UNIVERSITY OF BIRMINGHAM

Technological Maturity Assessment of Additive Hybrid Manufacturing Technology

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A thesis submitted to
The University of Birmingham
for the degree of
DOCTOR OF PHILOSOPHY

School of Mechanical Engineering
University of Birmingham
October 2022.

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ABSTRACT

Additive and hybrid manufacturing technologies have for a long time been referred to as new, emerging, relatively new technologies in all publications and references to date. The need to ascertain the level of technology advancement in the additive and hybrid manufacturing technologies (HMT), a data-based status, and the need to assure and reassure both the existing and prospective government agencies, academia, and industry investors of the reality has necessitated the need for research on the maturity assessment of the two emerging technologies. The research therefore aimed to develop and implement a technological maturity assessment model for HMT along three process capability variables: process product quality (PPQ), process efficiency (PE), and the process effectiveness (PEffec.) and to test the maturity compatibility of the processes. In doing so, a digital technology and artificial intelligence based semi-direct technological maturity assessment methodology (SDTMAM) was conceived, where some artificial intelligence (AI), fuzzy logic theory and set theory-based models were developed, progressively and systematically linked together to be applied as scientific tools to source and process research data for assessment of the maturity levels of individual additive and subtractive manufacturing technologies, as well as the hybrid manufacturing technology. The model was implemented on the technological maturity assessment of hybrid manufacturing technology (HMT) that integrates metal additive manufacturing, and a computer and numerical control (CNC) machining processes. A Capability Maturity Model Integration (CMMI) maturity profile of the Software Engineering Institute was adopted as a reference maturity profile for the technological maturity assessment results and ranking. The HMT after research and results simulation was found at the quantitatively managed maturity level of 4 of 5, where the individual

technological maturity levels of HMT based on PPQ, PE, and PEffec. are 63.5%, 67.75%, and 71.63% respectively. With the overall maturity level of 3.39, at 67.63%, which justifies, and thus represents the maturity level of HMT that integrates metal additive manufacturing and CNC machining processes. Subsequently, maturity compatibility test model for the HM processes was developed, designed and implemented based on processes union, complementarity, difference and intersection. The result suggests that the technologies maturity intersection is equivalent to the processes interface, which is the hybrid manufacturing technology maturity level.

DEDICATION AND ACKNOWLEDGEMENT

On behalf of my family and I having acquired more knowledge and experience, I dedicate my PhD thesis to God for his ever presence and great work in my life. Especially each time I am amidst all troubles and hopelessness of the world. However, I wish to thank Thee for providing me with a Lead Supervisor, Prof. Stefan Dimov, a Professor of Micro and Nano Manufacturing, whose support is instrumental to the progress and success of my research. The same goes to my Second Supervisor, Prof. Khamis Essa too, a Professor of Digital Manufacturing. Also acknowledged are my parents, Mr and Mrs Charles and Gloria Dim, both retired teachers, for their legacy and preference to our education first before any money or material wealth. Also, my grandmothers, Mrs Luisa Dim (P) and Mrs Akuezuo Okpalanwaka (M) for their protective roles in my life growing up. Moreover, my son Victor Chukwuzitelu Dim in Nigeria, is acknowledged, especially for his patience and prayers for Daddy throughout his six years of absence from home in pursuit of more knowledge in England, United Kingdom. My immense and unquantifiable thanks also go to a highly experienced and exposed scholar Dr Terkimbi Atonde of the Birmingham City University, for his direct encouragement, technical support, and immense contributions to date. Inclusive as well are my friends and well-wishers, especially my colleagues and friends in ESUT who did encourage me both in words and in spirit from the beginning and throughout, and whose relationship is instrumental and contributed positively to my life and success in UK. More so, my profound gratitude to my research degree Examiners, Prof. Mahmoud Shafik, Professor of Intelligent Mechatronics Systems and Digital Technology (External) and Dr. Sein Leung Soo of Manufacturing and Mechanical Engineering (Internal), as well, the Chairperson, Prof. Athanasios Tsolakis, Professor of Thermodynamics, Daniels come to judgement, for their meticulousness and

restoration of the dignity of man. On your honour, The University of Birmingham, the global university of the Firsts, for their provisions, and justice well done. Finally, I will ever remain grateful to the Federal Government of Nigeria, through TETFund, and through my employer Enugu State University of Science and Technology (ESUT), Nigeria, for the opportunity, and sponsorship of the programme. May God continue to bless all of us as we shall continue to reap the fruits of our labour.

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NOTATIONS

3DMP – 3-Dimensional Metal Printing

AB – Acrylonitrile Butadiene

ABS - Acrylonitrile Butadiene Styrene

AHMT – Additive Hybrid Manufacturing Technology

AI - Artificial intelligence

Al – Aluminum

AM - Additive manufacturing

AMT - Additive manufacturing technology

ASTM - American Society for Testing and Materials

BT - Basic Technology

CA - Coordination Action

CMM - Capability Maturity Model

CMMI - Capability Maturity Model Integration

CNC – Computer and Numerical Control

CPP - Capability Performance Parameters

CTE - Critical technology elements

D – Dependable

DED - Direct energy deposition

DEF – Defined

DMLS - Direct Metal Laser Sintering

DOD - Drop on Demand

DT – Digital Technology

DTMAM - Direct technological maturity assessment methodology

EBM - Electron Beam Melting

EBM – Electron Beam Melting

EC - European Commission

EPD – Ethene Propene Diene

FDM - Fuse Deposition Modelling

FG – Fairly Good

FM - Fairly Mature

G – Good

H – High

HD – Highly Dependable

HDPE – High Density Polyethylene

HIP - Hot isostatic processing

HIPS – High Impact-resistant Polystyrene

HM - Hybrid manufacturing

HMPML – Hybrid manufacturing process maturity level

HMT - Hybrid manufacturing technology

ICTMAM - Indirect custom maturity assessment methodology

IM – Immature

IN - Initial

IS – IT Services

ISO/IEC - International Organization of Standardization/International Electrotechnical Commission

IT – Information Technology

ITIL - Information Technology Infrastructure Library

ITSM – IT Service Management

KPCA - Key Process Capability Areas

KT - Key Technology

L - Level

L – Low

LENS - Laser Engineered Net Shaping

LOM - Laminated Object Manufacturing

LPBF – Laser powder bed fusion

LPBF – Laser Powder Bed Fusion

LPBFPE – Laser powder bed fusion process efficiency

LPBFPEffec. – Laser powder bed fusion process effectiveness

LPBFPPQ – Laser powder bed fusion process product quality

M – Mature

M & N – Micro and Nano

MAHMT - Metal Additive Hybrid Manufacturing Technology

MAHMT - Metal additive hybrid manufacturing technology

MAMI – Maximini

MAN - Managed

MAX – Maximum

MIN – Minimum

ML – Maturity Level

MLs – Maturity Levels

MMA – Minimax

MMZ - Maximizing

MNM - Micro and Nano Manufacturing

MNTs – Micro and Nano Technologies

MP - Manufacturing Process

Mpa – Megapascal

MPE – Machining process efficiency

MPEffec. – Machining process effectiveness

MPPQ – Machining process product quality

ND – Not Dependable

NHD – Not Highly Dependable

NoE - Network of Excellence

NQD – Not Quite Dependable

NQG – Not Quite Good

NQL – Not Quite Low

NQM – Not Quite Mature

NQW – Not Quite Well

NVW – Not Very Well

NW – Not Well

OPTIM - Optimizing

OSCM - Operation and supply chain management

P – Poor

PA - Polyamide

PBF - Powder Bed Fusion

PBS - Product breakdown structure

PC - Polycarbonate

PCAs - Process capability areas

PE – Process efficiency

PEffec – Process effectiveness

PLA – Polylactide

PMI - Processes maturity indicators

PMMA – Polymethyl Methacrylate

PPQ – Process Product quality

PS - Polystyrene

PT - Pacing Technology

QMAN – Quantitatively Managed

QMMG - Quality management maturity grid

R & D – Research and Development

SDMAM - Semi-direct maturity assessment methodology

SDTMAM - Semi-direct technological maturity assessment model (SDTMAM)

SE – Software Engineering

SEI - Software Engineering Institute

SHS - Selective Heat Sintering

SLM - Selective Laser Melting

SLS - Selective Laser Sintering

SM - Subtractive manufacturing

SPICE - Software Process Improvement and Capability Determination

Ti-6Al4V – Titanium Alloy of Aluminium Vanadium

TMA – Technological Maturity Assessment

TML - Technology Maturity Levels

TP - Transition Phases

TRL - Technology readiness level

TRPM - Technology Readiness Pathway Matrix

UAM - Ultrasonic Additive Manufacturing

UV – Ultra Violet

UVL – Ultra Violet Light

VG – Very Good

VH – Very High

VL – Very Low

VW – Very Well

W – Well

WM – Well Mature

CHAPTER 1

BACKGROUND TO THE STUDY

1.1 Additive Manufacturing

Figure 1. An AM process directed energy deposition (DED) technology picture [1].

Additive manufacturing (AM) is a new manufacturing technology at the quantitatively managed capability maturity level of the Software Engineering Institute's Capability Maturity Model Integration (CMMI) profile. The history of additive manufacturing dates back to the 1980s when Dr Hideo Kodama, a researcher at the Nagoya Municipal Industrial Research Institute, laid the foundation for additive manufacturing (AM) take-off having filed the first AM technology patent. His idea was to expose a container of photopolymer material to light to form or produce prototypes. However, due to lack of funding, Kodama's project was not implemented [2, 3]. Nevertheless, Chuck Hull, the co-founder of 3D Systems, couple of years later, in 1986, invented a stereolithography (SLA) which is taken for the first rapid prototyping system [2, 3]. This was later followed gradually with the development of other additive manufacturing technologies overtime, until in the 1990s which is regarded as the decade of a very rapid growth for the then emerging technology. AM is used to produce or build high quality and high-performance engineering components or parts of complex geometries. AM is a term that broadens the scope of 3D Metal Printing to include a wide range of processes

that start with a 3D computer model, then incorporate an additive fabrication or building process, and finally end up with a creation of functional part or component in the machine which is only controlled by a computer which builds the model layer by layer. Where, the layer thickness dictates the final quality, though it depends widely on the machine and process. Meanwhile, some people these days understand the term 3D printing, but what many mean when talking about 3D printing is actually one of the several additive manufacturing processes. This is because the distinction between 3D printing and AM processes is dim due to the rapid development of competing methods used to produce a 3D part. Hence, additive manufacturing (AM) refers to a large and complex field encompassing model-based design engineering, computer-aided design (CAD) and computer-aided manufacturing (CAM) software, process engineering and control, material science and engineering, then comes industrial practice [4]. Procedure involves first create a 3D model of the part to be printed with CAD, secondly, convert the CAD file to a standard additive manufacturing file format (STL file) afterwards. Then, the STL file is transferred, and setting up the computer-controlled machine that builds the model layer by layer as shown in figure 1 above. After building or producing the part and applying cooling and curing periods, the model can then be removed from the machine. Hence, extra work called post-processing such as cleaning, polishing, painting, and finishing of the surface depending on the desired standard can be done. Moreover, post-processing that involves tooling and machining may be required and carried out as well. [5].

1.1.1 Industry Applications of Additive Manufacturing Technology

There are domestic and industrial applications of AM. These cut across vast kinds of products, manufacturing technologies or processes. Ranging from, but not limited to aerospace, automotive, medicine, power, energy, construction, oil and gas, arts, fashion, prototyping, consumer goods, and toy industries. However, the choice of AM process for a product now does not solely depend on the capability in delivering high quality part of complex or intricate geometries, but inclusive are other factors such as the product need, use, efficient, effective or economic process, design, and manufacture as there are now many AM solutions in terms of quality control, post processing, system monitoring and assurance department. They play a huge

role in the industry. However, as illustrated in the figures 2, 3 and 4 below, though the industry application examples of AM are not limited to the very expensive and high-risk mechanical engineering fields of aerospace, medical and automotive industries, where there is no limit to efforts towards quality, ergonomics, and safety of life and property. Hence, the consequences of part malfunction, failure and losses are very heavy and catastrophic on occurrence. Thus, as it is a fact that part failure largely ascribed to the way it was manufactured, the advantages of AM technology in these industry areas are enormous, and cannot be overemphasized. Especially, its well suited and exploits in the manufacture of low machinability materials such as the heat resistant alloys, and high-hardness materials such as stainless steel, titanium, cobalt, chrome, steel, nickel, coper, Inconel (Nickel-Chrome Alloy), which are used in aerospace, automotive and medical industry applications, notwithstanding aluminium AM material [6]. Also, widely used in other industries including power and energy, oil and gas, though in various ways or processes as project demands.

Moreover, based on industrial releases and the increased rate at which the major world machine tool manufacturers; Yamazaki Mazak Corporation and DMG MORI et al invest in the AM and hybrid manufacturing solution machine technology production, coupled with the high demand for AM manufactured parts especially in the aerospace, medical, automotive, construction and power industries as shown in the appendices 1, 2, 3 and 4, is a significance that a lot of progress has been made in the additive and hybrid manufacturing technology.

Figure 2. Aerospace industry AM application (aircraft and engine pictures) [7, 8]

Figure 3. Medical industry AM application
(equipment and prosthetic human skeleton pictures) [9, 10]

Figure 4. Automotive industry AM application (car and engine pictures) [11, 12]

1.1.2 Categorization of Additive Manufacturing technology

The American Society for Testing and Materials (ASTM) group code named "ASTM F42 – Additive Manufacturing" [13], formulated a set of standards that classified the range of additive manufacturing processes into seven (7) categories [13]. These are namely, the VAT Photopolymerization, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion (PBF), Sheet Lamination, and Directed Energy Deposition (DED) [5]. However, for the purpose of process definition or characterization, and steps, dependent materials and selection, technical information and relationships, pros and cons, additive manufacturing processes are further explained below.

1.1.2.1 *VAT Photopolymerization*

Vat photopolymerization is the type of AM process that makes use of vat of liquid photopolymer resin from which part is built or constructed in layer-by-layer method. As illustrated in the figure 5 below, the process working energy is an ultraviolet (UV) light which is directed and used to cure the resin in the area or region where needed. This occurs as the build platform moves with the part under manufacture or being made downwards after each new layer is hardened. As the vat photopolymerization AM technology uses liquid as raw material to create solid objects, it has no structural support from the material during the manufacturing process. This is quite unlike the powder-based materials, where the unbound material give support to the model under manufacture. Whereas in this case, support structures will always be needed and have to be provided. In all, resins are cured by applying a photo polymerisation process [5, 14] or an ultraviolet light, where the light energy is directed over across the surface of the resin using mirrors that are controlled by motor [5]. Hence, the resin cures or hardens once it contacts the light.

The stereolithography additive (SLA) process: The SLA possesses and delivers a high degree of accuracy and good surface finish [5]. Meanwhile, it usually requires support structures and post curing for a strong manufactured product, enough for structural applications. Process of photopolymerization can be achieved with a single laser and optics. Thus, blades [14] are to pass over across previous layers to ensure that there are no defects in the resin for the building of the succeeding or following layer. This is a precautionary measure as sometimes, the photopolymerization process and support material may have likely caused defects like air gaps. Hence, there will be a need for the gaps to be filled up with resin to deliver a quality model or part. Normally, layer thickness for the vat photopolymerization process is 0.025 – 0.5mm [5].

Post Processing: At this manufacturing stage, part shall be removed from the resin, where any excess or unused resin will be fully drained from the vat build platform. However, supports can be removed with knife or any useful sharp implement. But care should be taken to avoid contaminating the resin, hence appropriate safety measures must be established and observed. Meanwhile, the methods for removing resin and supports include application of an alcohol rinse along with a water rinse. The vat photopolymerization

process takes a long time as products do sometimes require extra treatment or scrubbing to entirely remove material. As well, parts can be treated naturally by open air drying or by using air blower or hose. Ultraviolet light is mostly used for the post process curing to ensure a high performance and quality part. Example of the vat photopolymerization machine is the 3D Systems ProX 950, with a build area of 1500mm x 750mm x 550mm, and Maximum part weight of 450kg. The process uses plastics and polymers, ultraviolet (UV) curable photopolymer resin, Resins Visijet range (3D systems).

Step by step operation and principle of VP

Figure 5. Vat photopolymerization process [5, 14]

Step 1. The build platform is lowered downwards from the top of the resin vat based on the material layer thickness.

Step 2. A positioned ultraviolet light or laser energy hardens the resin layer after layers as the build platform continues to move downwards. Thus, additional layers are then built on top of the preceding layer.

Step 3. A blade moves between layers depending on the machine, providing a smooth resin build base for the next layer.

Step 4. Vat is drained off the resin on completion, and the built part is removed.

Advantages

It delivers a high degree of accuracy and good surface finish

It has a large build area: 1000: 1000 x 800 x 500 and a maximum model weight of 200kg

The process is relatively a fast process

Disadvantages

The vat photopolymerization AM process is relatively costly

There is obviously record of prolonged post processing time including removal from resin

There is limited material use of photo-resins

The process usually requires support structures and post curing to deliver a strong part capable of structural applications.

1.1.2.2 *Material Jetting*

Material jetting process builds parts in a method that resembles a two-dimensional ink jet printer. Here, either a continuous or Drop on Demand (DOD) approach is applied to jet material onto the build platform surface. As illustrated in the figure 6 below, the material is jetted onto the build surface, where it solidifies on cooling, and the part is built upon layer-by-layer basis. Material is deposited from a nozzle which moves horizontally over across the build surface. However, material jetting machines vary in complexity and in their ways of controlling material deposition. Ultraviolet light is used to harden or cure material layers afterwards. Meanwhile, as the materials should be deposited in drops, the variety of materials available for production is limited. Also, multiple materials can be used in one process and the material can be changed during the build period. Polymers and waxes are often used and are suitable due to their viscous nature and ability to form or produce droplets.

Drop on Demand (DOD): This is used to deliver material onto the appropriate surface point or region. The droplets formed are positioned and dropped unto the build surface of the platform, in order to build the part being printed. It continues with more droplets added on previous layers until the entire part is completely made. However, idea or phenomenon of using material droplets to build is a limitation to type of materials, the number and availability. Meanwhile, viscosity is the causal or determining factor of the process, and there is a need to refill the reservoir very fast, which obviously causes interruption, thus affecting the print speed. Contrary to a continuous material streamflow, droplets are only delivered when needed. The drops are effected or activated due to pressure change in the nozzle by the thermal or piezoelectric actuators. Actually, the actuators drop the material droplets at a high rate, while using a thin film resistor to produce or make the droplets. The piezoelectric method is however often taken as better and preferred one because of its disposition to a wider usage or range of choice of materials. The designs of a normal DOD print head vary with the machines, but according to Ottnad, mainly include a reservoir, sealing ring, Piezo elements, and silicon plate with nozzle, held together with a high temperature glue.

Post processing: The material jetting supporting material can be taken out using a sodium hydroxide solution or water jet. Moreover, due to the high degree of accuracy of the process technology, the amount of the post processing required to be carried out to enhance the properties is limited. Also, the functional and aesthetic qualities of the manufactured parts are mostly determined during the printing stage. For instance, Stratasys Polyjet technology hardens or cures material using an ultraviolet light. Therefore, no post curing process is needed.

An example of the material jetting machine is the Object 500 Connex 3, with a 490 x 390 x 200mm Build area, Layer thickness of 16microns, and 46 number of colours. Material jetting process makes use of polymers and plastics materials. Polymers include Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, EDP.

Step by step operation and principle of MJ

Figure 6. Material jetting process [5, 14]

Step 1. The machine print head is located in position above the build platform

Step 2. Applying either a thermal or piezoelectric method, the material droplets are delivered from the print head onto the build surface at the exact point required.

Step 3. The first material droplets solidify to form the initial layer.

Step 4. Then layers continue to be built on top of the preceding layers in the same manner.

Step 5. The layers formed are allowed some time to cool and hardened or cured by the UV light. Thus, the removal of the support material is part of the post processing.

Advantages

There is advantage of low waste generation on production because of high accuracy of deposition of droplets by material jetting process.

There is a low material waste or lost due to the accuracy of deposits.

The technology allows and builds multiple material parts and colours under one process.

Disadvantages

Material jetting mostly requires support material to succeed.

There is a production challenge of limited materials as only polymers and waxes are available for use.

1.1.2.3 *Binder Jetting*

The binder jetting process is an additive manufacturing process that operates on just two materials such as a material powder and a binder. The binder here is an adhesive substance that binds the powder material. It is normally applied in between power layers and continues as such. The binder is normally in a liquid state, while the build material in a powder form. As illustrated in the figure 7 below, the binder jetting print head in operation, moves horizontally along the X and Y axes of the build platform, and delivers or deposits alternating layers of the build material (powder) and the binding material successively. However, the part being produced or printed will continue being lowered while on the platform after each laid layer. Nevertheless, due to this method of binding, the characteristics, and properties of the material, they are not often suitable to serve as structural parts. Also, despite its considerable speed of printing, the additional post processing necessity means extra time of the whole production cycle. Thus, with reference to other powder-based printing methods, the part or object under production is self-supported within the powder bed and is separated or removed from the unbound powder once through or done with.

Binder jetting technology works with metal, polymers, and ceramic materials, more so permits colour printing. It is generally quicker than other AM processes. The production cycle or time can further be quickened by simply increasing the number of the printing head holes that deposit material. Its ability for two material made part provides opportunity for a good number of different binder-powder mixtures and many mechanical properties of the final products to be gotten by changing or influencing the ratios and properties of each of the two different materials. Binder jetting process is however very suitable in a situation where different sections of the part to manufacture material structure needs a special or certain quality based on design specification. Meanwhile, the layers of build material, mostly in granular and powder form are bound together by applying adhesive binder. The machine print head deposits the binding material in

micro quantities, while the powder material is majorly deployed in creating the block of the entire part mass. However, the speed of the printing process can be improved by rise in the temperature of the build chamber and resultant increase in the viscosity of the materials [5].

Post Processing

The entire processing cycle of the binder jetting is higher due to the time allowance provision for the binder to set. Also, the product is normally allowed some cooling time in the machine to evenly harden or solidify for that desired a better-quality finish [14]. The post processing here is required mostly or mainly to deliver a stronger part, while the binder material is given better mechanical structural properties [5, 14]. An example of a binder jetting machine is the Spectrum Z 500. It delivers a material thickness of range 0.089 – 0.203mm, and print speed of 2layers/minute. The raw materials include metals such as stainless steel, polymers like ABS, PA, PC, and ceramics such as glass. Hence, all these three types of materials can be applied in the binder jetting (BJ) AM process.

Step by step operation and principle of BJ

Figure 7. Binder jetting process [5].

Step 1. A roller is used to spread the powder material over the build platform

Step 2. The print head delivers and deposits the binder adhesive on top of the powder material where required.

Step 3. The build platform is then lowered down based on the model's design layer thickness.

Step 4. A new amount of powder material is spread over the preceding for another layer. Then the component forms as the powder is bound by the liquid adhesive.

Step 5. The unbound powder material remains unutilized surrounding the part.

Step 6. The process continues repeatedly until the part is made

Advantages

Its part products can be created with more than one colour

It uses a variety of materials which includes metals, polymers, and ceramics

The manufacturing process is faster than the rest generally.

The hybrid or biomaterial method creates room for a higher number of different binder-powder combination and more engineering material properties.

Disadvantages

The binder jetting process is not really recommended for structural engineering parts due to the use of binder that will fail under certain stress condition.

The process adds up post processing time, which results in increase in the overall technology production cycle or time.

1.1.2.4 *Material Extrusion*

A prevalent or common material extrusion AM process is the Fuse deposition modelling (FDM) as trademarked by the manufacturing company, Stratasys. In the material extrusion process material is drawn through a nozzle, where it is heated and deposit layer by layer. As illustrated in the figure 8 below, the nozzle normally moves horizontally to and fro, while the build platform moves vertically up and down after each new layer is deposited. However, this process technique is mostly or commonly used on some less costly,

inhouse or domestic, pleasure or hobby 3D printers. Meanwhile, there are some factors that affect the final part quality, but it is of great utility and advantage when these factors are adequately and well managed successfully. Although, the FDM has large similarity with all the rest of the AM processes, hence it builds parts on a layer-by-layer basis, but still differ with the fact that material is applied or added through a nozzle, and under a regulated constant pressure which ensures and maintain a continuous material stream flow throughout the deposition process. Meanwhile, sure must be specially made that this pressure is maintained at steady pressure, and at a constant speed too, to be able to achieve accurate results [14]. These material layers bonding capability can be achieved by controlled temperature or using chemical agents. Normally, material is fed the machine in a cylindrical drum or spool form. Some of the advantages of the material extrusion process in the application of ABS plastic material. It is readily available and can produce parts of a very good mechanical structural properties of a near net product. The process can be of greater economic advantage method than the use of injection moulding, especially in low product volume situation. In order to deliver or achieve a desired high-quality finish, the process needs many factors to be managed and controlled. For example, the nozzles operate with a radius or round outlet orifice, and it will be difficult or impossible to have a perfect square nozzle outlet which deposits material. Thus, this fixed nozzle characteristic affects the final part quality as there is a need for flexibility nozzle architecture or geometry [5]. The built speed and accuracy of the process when compared to others is low, also with the quality of the final part, which depends solely on the nozzle and material thickness [5].

Post Processing

A method through which post processing can improve the physical appearance of part is by the improvement of the material transmissivity. Some methods have been studied by Ahn [5], including increase in temperature and the application of resin. Experiment often used to improve the strength of manufactured parts using cyamo acrylate resin, resulted in a 5% increase in transmissivity after 30seconds, and still standing [5]. Then, a vast consideration must be taken in design about the required tolerance regarding most temperature-based post processing where there is occurrence of part shrinkage. Likewise, when a material

extrusion process is used for a very high tolerance demand part, the effects of the force of gravity and surface tension acting on the part must be determined and resolved [14]. The layer thickness ranges from 0.178mm – 0.356mm [5]. Example of the material extrusion AM process machine is the Insstek MX3 of size (area), 1000 x 800 x 650mm, built volume, 520 L, and the layer thickness same as Al, Cobalt, Copper, and Nickel alloys materials. The material extrusion (ME) process uses polymers and plastics. Where the polymers include ABS, Nylon, PC, AB.

Step by step operation and principle of ME

Figure 8. Material extrusion process [5].

Step 1. The first layer is built when the nozzle delivers and deposits material on the cross-sectional area of the first component slice.

Step 2. Other layers are added on top of the previous layers as follows.

Step 3. The materials are in a melted state, hence the layers are fused together upon deposition.

Advantages

The technology is common and widespread, thus not an expensive process.

The material applied such as the ABS plastic has a very good mechanical structural properties, and it is readily available and accessible.

Disadvantages

The nozzle geometry or architecture in terms of the radius, limits and affects the manufactured part quality.

There are records of low process speed and accuracy of final when compared to other AM processes. Hence, the accuracy is limited to the material nozzle thickness.

The material extrusion process requires constant and even pressure on material to be able to achieve or improve quality finishes.

1.1.2.5 *Powder Bed Fusion*

The powder bed fusion (PBF) AM process such as the Direct metal laser sintering (DMLS), Selective laser sintering (SLS), Selective laser melting (SLM), Selective heat sintering (SHS), and the Electron beam melting (EBM), are the commonly used printing technologies. PBF processes use a laser and electron beam heat or energy to melt and fuse material powder together. The EBM process requires a vacuum. It can be used with metals and alloys in the making or manufacture of functional parts. However, as illustrated in the figure 9 below, all the PBF processes make use of peculiar or suitable systems including a blade or a roller, which enable the spreading of powder material over previous layers. Normally, a hopper or a reservoir located by the side of the bed feeds fresh material supply.

Meanwhile the Direct metal laser sintering (DMLS) and Selective laser sintering, are the same with respect to the use of metals, but not plastics. Here, the powder is sintered layer by layer, by the process, and a good range of metals are readily available for engineering application. Moreover, the Selective heat sintering is different from other processes as it uses a heated thermal print head to fuse powder material together. As usual, layers are added with a roller at the interval between the fusion of layers, while the build platform continues to lower the built part as requires in each time or cycle.

The SLS machines are made up of three systems [5, 14], which include (1.) a heat energy source required to fuse the material, (2.) a system that controls the source of the heat energy, and (3.) a system that adds new layers of material over the previous ones. For the fact that the powder material provides enough support to

the built part throughout the period of manufacture, the Selected laser sintering takes the advantage and benefits as it does not require an extra support structure. The build platform is within a temperature-controlled chamber whose temperature is normally some degrees below the material melting point. However, this lowers the reliance or dependency of the laser to fuse layers together. Moreover, nitrogen sometimes is added to the chamber to enhance oxidation process and the quality of the part finally manufactured also. Then, due to the need for high tolerance and quality of fusion, the part shall be allowed some period of time to cool down. In order to improve quality of part too, the temperature is monitored by some machines layer by layer to adapt the power and wattage of the laser energy.

The SLM process, when compared to the SLS, is most time quicker [14], but it needs an inert gas, with a more energy consumption. Its energy efficiency is as low as between 10 - 20% [5]. Either a roller or a blade is normally used by the process to spread new layers of powder material over previous layers. Hence, the blade system sometimes made to vibrate in operation to ensure and assure a better even powder material distribution [5, 14]. A fresh powder material is fed the machine by the hopper or a reservoir system component of the process.

The SHS process is the method that uses a heated thermal printhead to fuse powder material together. In this process, the layers are usually added or fed with a roller at the interval between fusion of layers. It is used in producing or building part prototypes, and products components of low structural application or value. SHS uses a thermal printhead instead of laser heat energy, thereby gains by taking the advantage of the lower heat and power requirement of the process. It uses thermoplastics powder which normally does the work of a support material at the same time. Example is a Blue printer which is a desktop 3D printer with a build chamber, 200mm x 160mm x 140mm, a layer thickness of 0.1mm, and print speed of 2 – 3mm/hour, that uses the SHS technology [15].

In the EBM process, layers are fused by using an electron beam to melt the metal powder. However, the beam and the vacuum pressure of 1 x 10^{-5}mba is controlled by the machine manufacturers Arcam using electromagnetic coil [5]. Electron beam melting delivers parts of good mechanical strength which is ascribed

to the even temperature condition of the process and especially during fusion [5]. EBM is recommended as suitable for high performance engineering components or parts for high-risk field of aerospace, automotive, and medical applications due to its very high quality and standard manufacturing capability. Hence the process has some advantages over the conventional or traditional methods of implant production among is the hip stem prothesis [5]. Meanwhile, when compared to the CNC machining, applying the EBM with Titanium of layer thickness of 0.1mm would deliver better result, in a shorter time and at a reduced cost by up to 35%.

The post processing in EBM process requires removal of the surplus or excess powder, deep cleaning, then the computer and numerical control (CNC) machining operation. The prevalent aim of post processing in the EBM process is to increase the part density, hence the resultant improved structural property of the manufactured part. This is one of the advantages. However, the liquid phase sintering process that employs a method of melting metal powder, mixture or powder combination aimed at achieving a homogeneous and continuous microstructure all through material and manufactured part. Notwithstanding, the shrinking behaviour of material during and much after the process must be considered and provided for. There is also a hot isotactic pressing, which is one of the methods used to increase manufactured part. Here, a vacuum chamber is meant to exert high pressure and increase the temperature of the material. However, there is no doubt that this process is effective with respect to manufacturing of part of improved strength, but the fact remains that it takes longer production time which means or incurs extra cost.

One of the examples of EBM machines is the 3S Systems ProX 500, covering an area of 381 x 330 x 457mm, print layer thickness of 0.08 – 0.15mm, and a print speed, 2litres/hour. The powder bed fusion can use and well deliver very well any powder-based material, though the common metals and polymers applicable are, Nylon for the SHS, then, Stainless steel, Titanium, Aluminium, Cobalt Chrome, Steel, for the DMLS, SLS, SLM, and Titanium, Cobalt Chrome, Stainless steel, Aluminium and Copper, for the EBM [5].

Step by step operation and principle of PBF

Figure 9. Powder bed fusion (PBF) process [5, 14]

Step 1. Normally, material layer of 0.1mm thickness is spread over the surface of the build platform.

Step 2. A positioned laser fuses the first layer or the first cross section of the part model.

Step 3. A roller spreads a new layer of powder across the preceding layer.

Step 4. More layers and cross sections are added and fused.

Step 5. The process continually repeated until the whole part is produced. However, the remaining loose and unfused powder that are still in positions are to be removed during the post processing.

Advantages

PBF AM Technology is relatively costly.

It is suitable for producing prototypes and visual models.

It has a wide range of materials and choice.

The powder structure of PBF acts and gives support to the part under manufacture.

The PBF's SHS can bring down technology into a very small rating office size machine.

Disadvantages

The speed of PBF's SHS is relatively slow.

Materials in use has no structural properties.

The process consumes much power, and high energy consumption too.

In the PBF, the powder grain size determines the surface finishes quality.

There is also the issue posed by the build volume and part size limitations.

1.1.2.6 *Sheet Lamination*

The sheet lamination processes are the ultrasonic additive manufacturing (UAM) and the laminated object manufacturing (LOM). Sheets or ribbons of metal are used in the UAM process. As illustrated in the figure 10 below, they are bound together using an ultrasonic welding technology. This process does not require post processing by way of additional CNC machining need, and the removal of the unbound or excess metal mostly during the welding operation. In the UAM, the metal cannot be removed easily manually by hand unlike the LOM, thus unwanted material must be removed by machining. Standard material saving metallic tape of 0.150mm thick and 25mm wide does lead to less material to be cut on post processing. However, milling can be carried out at intervals or at the end of the entire process. However, the metals used by UAM are Aluminium, Copper, Stainless steel, and Titanium [5]. The process requires low energy to run, hence the metal is not melted. Also, the process operates under low temperature. It allows for creation of internal geometries and can bind different material effectively.

Whereas the LOM operates a layer-by-layer alike process, where the materials used are paper and adhesive rather than welding, hence are readily available and costly. Here, a cross hatching method is used by the LOM process during printing to provide for easy and safe removal. Laminated objects are not meant or

suitable for structural applications, rather they are mostly used for aesthetic and visual models and purposes. The LOM process set up is a simple one as it is not a difficult in relation to other processes.

Post processing in sheet lamination process is concerned with the separation and extraction of the manufactured part from the edge or boundary of the left over, unwanted, or unutilized areas of the sheet material. In the LOM, cross hatching used is to make the process easier. Although as paper is inclusive, it does not require any special tools to be removed and saves time too ass the product lacks structural properties.

An example of a sheet lamination process machine is the MCor Matrix 300 plus, of area 256 x 169 x 150mm, and material layer thickness is within the range of 0.1mm – 0.19mm. In terms of materials, any sheet material whether paper such as the common A4 paper, plastic, and some sheet metals that can be rolled, can be used in sheet lamination process.

Step by step operation and principle of SL

Figure 10. Sheet lamination process [5].

Step 1. The material is placed in position on the cutting bed

Step 2. Applying adhesive, the next material is bonded in place over the preceding one

Step 3. A laser or knife is used to cut the required shape from the layer.

Step 4. Then, the next layer is added.

Advantages

Sheet lamination process is fast, it is affordable based on its low cost. There is ease of material handling, and the strength and mechanical structural integrity of the part is dependent on type of adhesive utilized [5].

Cutting off process material is very fast because the cutting route is only that of the shape outline, and not the entire cross-sectional area.

Disadvantages

Finishes of the sheet lamination process is dependent on the paper or plastic material utilized. Part may require post processing depending on the desired quality.

The process processing material is limited.

The sheet lamination fusion processes need more research to reposition the technology to a position of more prominence.

1.1.2.7 *Directed Energy Deposition*

Directed energy deposition (DED) is a very complex additive manufacturing or printing process that is mostly used to fill, add, or repair parts, by simply adding material to an already existing component [14]. This can be carried out as a repair or maintenance, refurbishment or a post manufacturing, or processing operation on structural parts. The DED harbours a number of nomenclatures or technical terms, which include (i) 3D laser cladding, (ii) Laser engineered net shaping, (iii) Directed light fabrication. However, as illustrated in the figure 11 below, a normal DED machine system is made up of a nozzle, which is located in position on a multi axis arm. The nozzle deposits melted material onto a particular or specified build surface, where is cools and solidifies. Meanwhile, the process method is similar to that of the material extrusion, but the difference is that the nozzle has more degrees of freedom, thus can move in many directions, as it is not permanently fixed to one or specific axis. Also, in DED, the material is melted on its deposition either with a laser or an

electron beam energy. Hence, the method of material melting is not the same, though all take place within a controlled chamber. Moreover, the DED material deposition can be achieved or delivered from any angle because of a system of up to 4 and 5 machine operating axes. With the 4 or 5 axis machines, the movement of the feedhead will not affect the rate of material flow or transmissivity. Nevertheless, just as applicable to the milling and turning machines, it is the arm that moves in most cases while the object or part is fixed or remains in a fixed position. The system can be reversed when required such that the build platform can be moving instead, while the arm remains in a fixed position too, though the time and choice depends on the product and process design. This is quite unlike in the fixed, and vertical deposition method [14]. Although DED process can be used with polymers and ceramic materials, but it is mainly used in metal part processing in the form of metal powder or wire feedstock. The wire feedstock, because the nature of its preformed shape, delivers less accurate, but it utilizes less material and saves more material than the powder application [14]. Also, the material cooling time of the DED process is very fast, and normally between 1000 – 5000^{0}C/Sec. [5]. Thus, the cooling time interval affects the grain structure of the deposited material. Especially, when considering the effects of temperature differences between previous layers and subsequent overlying deposited material layers. The underlying material grain structure is altered due to reheating or remelting occurrence. This situation can be carefully monitored and controlled, hence can lead to an even or uniform but alternating micro-structure. A typical layer thickness for DED process material is within 0.25mm – 0.5mm [5]. An example of a DED process machine is the Insstek MX3, of area 1000 x 800 x 650mm, and the layer thickness is between 0.089 – 0.203mm, then the print speed at 2layers/minute. The EBM process makes use of metals, and never polymers or ceramic material. Thus, the metals include Cobalt Chrome, Titanium [5].

Step by step operation and principle of DED

Figure 11. Directed energy deposition (DED) process [5].

Step 1. A 4 to 5-axis arm with nozzle goes around an object fixed in position.

Step 2. Material is delivered through the nozzle and deposited the existing surface of the object where required.

Step 3. The material utilized is either in powder form or a wire feedstock

Step 4. Either a laser, electron beam or a plasma arc is directed to melt the material while on delivery and deposition.

Step 5. More material is continued to be applied or added layer upon layer, then solidifies creating new part, repairing or introducing new feature on the existing component, by way of maintenance or modification as shown in the figure 12 and 13 below.

Figure 12. A Lasertec 3000 DED Hybrid – additive manufacturing machine performing repair and modification job [16].

Figure 13. Shows the DED HMT flexibility by the pairing or combination of the additive and the subtractive turning machining process for a high quality 3-D part finishes [16].

Advantages

DED process has the capability to control the material grain structure to a considerable grade. This ability gained the process a lot of advantage and upper hand in the repair or maintenance of high-quality functional parts.

It delivers parts of high quality and accuracy, and of a predetermined microstructure.

DED process is also a very fast method, but the options of quality and speed needs of manufacturing operation are always available, and the choice each time depends on the scale of preference or priority.

Disadvantages

The surface finishes of the DED process depend on whether paper or plastic material was utilized, and post processing may be required for a better result.

The DED process material use is limited.

More research is needed to be carried out in the DED material fusion process to further improve or advance the process into a position of prominence in additive manufacturing technology.

1.1.3 AM Materials

The first-hand materials for additive manufacturing are but not limited to metals, plastics, and ceramics. Then, one may ask what is 3D metal printing, and how does it differ from 3D plastic printing, 3D ceramic printing or 3D printing with other engineering materials? Also, how can one create complex metal objects and forge ahead the limitations of the conventional or traditional subtractive metal processing? Moreover, how can one study and understand the rudiments, finds out, and decide on a particular metal additive manufacturing process that is suitable for his design for manufacture?

The three types of materials can be utilized in additive manufacturing. They are often produced in powder form, or I wire feedstock. Thus, all the seven individual AM processes cover the use of metals, polymers, and ceramics. Although polymers are the most used, but some additive manufacturing techniques tend more

towards the use of certain materials over others. There are other materials that are used which include papers, and adhesive materials. However, it is possible to print any materials in layer-by-layer method, but the quality will largely depend on the material. Meanwhile, due to high temperature and pressure, some AM processes can change the microstructure of material. Therefore, properties of materials may not be entirely the same post manufacture when compared to others.

1.1.3.1 *Metals*

There exist a number range of metals that can be used in the AM processes. Also, there are several suitable choices for both structural and integral parts. They include Steel, Titanium, Aluminium, Cobalt, Chrome, Chrome alloy such as Inconel (alloy of Nickel and Chrome) [5]. Thus, maraging steel 1.2709 (Tensile Strength 1100Mpa), Titanium alloy Ti6Al4V (Tensile Strength 1150Mpa)15-5ph, Stainless steel (Tensile Strength 1150Mpa), Cobalt chrome alloy, Co28Cr6Mo (Tensile Strength 1300Mpa), Aluminium AlSi10mg (Tensile Strength 445Mpa), Gold and Silver.

1.1.3.2 *Polymers*

There are common plastics such as the Polycarbonate (PC), and the Acrylonitrile butadiene styrene (ABS), that can be used in 3D printing. Also, common structural polymers, Polylactide (PLA), including the soft PLA, Glass filled nylon (12.48Mpa), Nylon 12 (Tensile strength 45Mpa), Polyamide (Nylon,) waxes and epoxy-based resins (Epoxy resin), can be used.

1.1.3.3 *Ceramics*

There are ceramic powders which can be used in the AM processes because they can be printed. These include the porcelain, silicon-Carbide, silica, or glass.

1.1.4 Advantages of Additive Manufacturing Technology

1. AM technology promotes special design skills. Hence it makes it possible for part assemblies to be printed as a unit just in one manufacturing process, and organic objects of shapes to be produced

easily. In the AM, the conventional or traditional manufacturing challenges or limitations are eliminated.

2. No tooling is required in AM unlike in other conventional manufacturing technologies like injection moulding. Hence the tooling need can be a hinderance to production because of the cost implication.
3. AM designed part can be manufactured anywhere as the model can be dispatched digitally, then printed in any desired location, home, aeroplane, space, home, even near the market or consumers. This can reduce the requirements, also, dependence on transport.
4. Unlike the traditional subtractive manufacturing technology, AM has no geometrical limitations. In fact, the technology is purposely to be able to produce parts or components of complex geometries which conventional manufacturing technologies cannot produce better.
5. AM technology requires less personnel, small or a few skilled labour and resources to run machines than the traditional manufacturing technologies.
6. AM technology is very useful in the customization of manufactured parts. Especially in medicine where parts can be specially built and customised to the patient, and according to their peculiar or individual requirement
7. AM maintains efficient use of materials as there is no excesses or waste of materials unlike in the subtractive manufacturing technologies. Hence, materials required are normally measured to match the one utilized, and any extra material can be recycled and reused.
8. AM supports sustainability programmes for environment as the need for transport is reduced because of the capability to operate and manufacture anywhere eliminates usual vehicular emissions.
9. With more people gradually going into the production of AM machines, the technology is gradually becoming more affordable, while others like the injection moulding machines remain relatively costly and even inaccessible.

1.2 Additive Hybrid Manufacturing Technology (AHMT)

The study of the state-of-the-art additive manufacturing technology became more interesting as the quest for more information and deeper knowledge about the additive manufacturing technology (AMT), the industrial application, achievements, limitations, and challenges continued increasing. Then, came about hybrid manufacturing technology (HMT), and hybrid manufacturing of high-performance metallic engineering components. Hence, as an innovative effort to solve or resolve some of the problems faced with the AMT figures, emerged the idea to develop a platform solution of two integrated CNC machining (subtractive) and additive manufacturing technologies that operate as a hybrid manufacturing technology in a single machine platform to resolve the AMT inherent process and product issues. As illustrated in figures 14, 15, 16, 17, 18, 19 below, this phenomenon presents in real sense that hybrid processes that combine both Computer and Numerical Control (CNC) machining and AM methods may all fall under the category of additive manufacturing [4].

However, at a stage in the industrial application, it was found that irrespective of the fact that both the additive and hybrid manufacturing technologies are in their various improvement stages, are still faced with some carry over technology, material, product, personnel, machine, and environmental challenges of manufacturing processes. However, due to the clear enormous advantages, the attention of manufacturers has been drawn to the strong emerging millennial technology for continuous improvement, hence the reason for industrial demand for additively and hybrid manufactured products, especially those of high-risk operating areas or fields of aerospace, medicine, defense, automotive, and energy industry for high performance engineering parts are at the increase over time.

Figure 14. Additive hybrid manufacturing cell schematic

Figure 15. A Mazak Integrex i-400 AM, 5-Axis, Hybrid Multi-Tasking machine.
It applies its additive manufacturing capability to seamlessly produce near-net-shape parts, and finishes up with a high-precision post-processing machining. Some more of the products pictures are in the appendix 1 [17].

Figure 16 Shows the integration of additive manufacturing technology and a multi-tasking machining in a laser metal deposition of very expensive materials applied in medical, energy, aerospace, automotive, construction and power industry for production of near net part shapes [17].

Figure 17. Shows a Lasertec 12 SLM additive manufacturing machine by selective laser melting (SLM). Whereas appendix 4 contains some of the powder bed fusion AM products examples and application industry. More of the products pictures are in the appendix 3 [16].

Figure 18. Illustrates a DMG MORI additive manufacturing by selective laser melting in powder bed diagram [16].

Figure 19. Hybrid manufacturing technology: Direct energy deposition and CNC milling processes picture [16].

The innovation of HMT came about because of the advent of additive manufacturing technology, where several production economic advantages were discovered but needed to be exploited. These include the manufacturing capability of metal parts of complex geometries, metal part of different materials and sections. Though AMT is characterized by some limitations and challenges of speed of manufacturing process, product surface finishes, dimension accuracy, product size or volume, product quantity or volume of product. While the Subtractive manufacturing technology, being the traditional or conventional method with its own proven merits, which include precision capability, fine surface finishes, speed manufacture, mass production, accurate dimension has its own major limitations especially in the manufacture of metal parts of intricate or complex geometries.

Comparing just a few of the potential complementary advantages between the subtractive and additive manufacturing technologies, and the available resources, the need for integrated manufacturing systems in one production cell arose. That is the hybrid manufacturing technology platform as illustrated in figure 14 above. Founded in 2012 to introduce additive manufacturing into the main stream of CNC machines, and subsequently, the first commercially available mainstream CNC machine equipped with additive manufacturing facility and capabilities was launched one year later.[18] However, by more innovations and technologies, hybrid manufacturing has continued to evolve trying to harness fully the comparative advantages of the two manufacturing processes and optimizing productivity, production and quality, complex geometries, lead time, cost reduction, increase speed of manufacture, diversification of materials and applications, improve surface finishes, dimension accuracy, increase tool degrees of freedom, homogeneity of part and improved regions of interface.

Moreover, the success and challenges recorded so far show that hybrid manufacturing technology is still a development solution platform for additive manufacturing technology challenges and limitations. This is evident in the product surface integrity of metal parts manufactured, low production, high cost of products, limited industrial application, existence of a repeat work in the form of post process services, low number of professionals and experts, that have continued to manifest globally both in the industry and academia to

date. However, so long as subtractive metal manufacturing technology with its traditional attributes has never caused any threat to the practice, the major challenges of hybrid manufacturing technology are still observed in the aspect of performance of the complementary additive manufacturing process. Especially, the product anomalies such as the residual stress formation, part distortions, and a need for post machining process to end each production cycle as illustrated in the figures 20 and 21 below.

Figure 20. Additive hybrid manufacturing technology and post-processing schematic

Figure 21. Shows how processes, from machining to 3D additive manufacturing are integrated in one machine platform [17].

At present, Hybrid manufacturing basically operates in a complete cycle of product and process planning, design, manufacturing, and post manufacturing phases, to yield a finished product. The figures 20 and 21 above represent the ideal hybrid manufacturing technology or process and product cycle of subtractive processing – additive processing – post-processing only. However, efforts are being made towards technology performance optimization through study and improvement of the process product quality,

process efficiency, and process effectiveness capability areas. Thus, intensifying efforts in minimizing or eliminating a need for post-processing part of the manufacturing cycle. These are not limited to the post-processing technology of chemical, mechanical, and thermal parameters such as the temperature or thermodynamic post processing, heat treatment, stress relieving, annealing cycles, hot isostatic processing (HIP), and mechanical post processing steps. In addition, thin oiling, powdering, painting, all forms of wrapping either for protection or otherwise are also in the category of post-processing.

However, certain considerations are being made in the hybrid manufacturing process product planning and design with respect to the product parameters, product and process interface parameters, material parameter, process parameter, process implementation parameter, economic parameter. These are found in more university modules, some experimental research publications, workshops, seminars and conferences, awareness by the people in other disciplines like the medical doctors that know additive manufacturing as just a 3D-Printing technology.

1.2.1 Applications of Metal Additive Hybrid Manufacturing Technology

In the metallic additive manufacturing processes, the Laser Metal Deposition (LMD) also known as the direct energy deposition (DED) is applicable in the additive manufacturing or creation of new parts. But it is most effectively and advantageous in maintenance, remanufacturing, hard facing, coating, repair of existing or legacy parts. It has fast deposition rate, produces less complex geometry parts, has fewer material resources. Whereas the laser PBF hybrid manufacturing technology is advantageously applied for parts of high complex geometries. PBF can process a single part of multi-materials. The built process is slow and used mainly for producing complete new parts directly from 3D data file or built on top of a substrate. It has a better surface finish, a small built chamber. Post processing job is a must, especially in terms of preparation and removal of support structures and cutting off parts from the built platform.

1.2.2 Most Challenges of Metal Additive Hybrid Manufacturing Technology

Obviously, there are some identified sources of concern associated with the hybrid manufacturing process including possible solutions of various approaches [6].

1. The process planning issues are poised by the kinematics and dynamics of the processes, workpiece, and environment. Presently, there is yet no standard or best methodology or process planning aimed at hybrid machine. Although, there are proposed ones and ongoing research for a better methodology for process planning. However, decision and process planning for hybrid solutions are the outstanding areas progress needs to be made. Also, the main threat now is in the development of a software tool that will allow design of an optimized process plan that comprised of enhanced additive and subtractive processes that can be alternately run by switching between and among additive and subtractive processes.

2. Secondly, hybrid processes as well require the use of engineering computational frameworks in other to optimize additive and subtractive hybrid processes.

3. Monitoring and control issues; Process parameters need to be controlled instantaneously or predicted, depending on external variables. The introduction of parametric monitoring and control mechanisms in the hybrid process is very crucial. This will enable ability to detect and regulate process variables such as the melt pool temperature, layers thickness etc, at every manufacturing process bit successive step while observing the earlier sign or indications of possible deviation from the set standard. Meanwhile, Araujo J. R. et al [19], suggested integration of imaging sensors into the nozzle with aim to control the width of the melt pool and, consequently, the quality of the deposition. Whereas Hofman et al [20], developed a feedback control algorithm that enables adjustment of process parameters in the real time in other to control the melt pool size, and measure the clad height also in the real time. Moreover, considering effort to control the microstructure of deposited material, Farshidianfar et al [21], also processed the thermal information in the real time. Based on

the high interest drawn in the monitoring and control in hybrid process, it is believed that it will be necessary to research to develop and implement process monitoring into different additive manufacturing processes. Thus, these systems can only act or report on the process once a deviation is detected from the set values. However, for hybrid parts of high integrity, devoid of waste, a future or predictive monitoring and control system should be developed, which not only acts on the process variables based on real time measurement but can as well predict what will happen ahead steps and indicate or report immediately. Definitely, the development of monitoring and control systems will enable enhancement and process stability.

4. Cutting fluid problem in metal hybrid manufacturing processes; there is a need to study and reduce environmental impact of the machining processes in other to adapt the technology to the current industrial demand, hence the adverse effect of the cutting fluids and vapour, metal powder contamination by carbon and humidity, evacuation, and reclamation on the additive process. Obviously, the remains of the cutting fluids from the machining process influence the subsequent additive environment, process, and products. When the cutting fluid is in contact with the metal powder, they react and produce moisture which hinders laser beam energy and the filler material within the substrate. Also, the cutting fluid vaporizes during additive process, and results in porosity, then settles and coats optical surfaces within the system. To prevent or solve this problem of metal powder contamination, evacuation and reclamation or recycling, they should from inception, be part and parcel of process planning, and to make sure that the workpiece and the machining environment is dry cleaned before switching for additive process and subsequent switchings. This will also help to eliminate existence of cracks and porosity as possible, while ensuring building a quality part top and joined region of high-quality additive delivery.

Furthermore, Lei Yan et al [22] in their “investigation of machining coolant residue cleaning methods for

Ti6Al4V part fabrication through hybrid manufacturing process" tried to look at dry machining as an option but feasibility research shows that it was poised with some disadvantages such as lower feed rate, lower plunging depths, higher tool wears and breakages. They then, used laser rastering and compressed air in a cleaning effectiveness study with oil and water-based coolant residue. The cleaning effect was evaluated on the parts and compared with the ones built on dry machining surface, indicates that the laser heating for thing oil-based coolant residue and laser heating, then cleaning with compressed air blowing for water-based coolant residue yield good cleaning effectiveness. So, there is need to research on the effect of various cutting fluids and residues on the additive process and their cleaning methods. Hence, the present hybrid manufacturing process does not have provisions for a dry-cleaning system in between the additive and subtractive process. However, there is no clue or lead effort yet on how to proceed with such important process requirement, though there are studies carried out on "the control and management of cutting fluid resulting from machining, as it affects the additive raw materials, process and influences the product quality", also the development of pores and surface roughness. Hence, there is a need for design considerations for ventilation, blower or compressed air, moisture dryer, extractor, slant or perforated built platform for hybrid set up.

5. The effect of the residual stress and high distortion of the built components or parts geometry because of high thermal energy of the additive process and subsequent deformation resulting from post processing. Generation of residual stresses also results in distortions of part geometries in which the machining tool may encounter different plunging depths to the ones programmed. In other to minimize the residual stress occurrence, the distortion, and the subsequent effects on the manufactured parts, there will be a post-processing heat treatment to restore the microstructure and mechanical properties of built parts. However, in Kobryn and Semiating [23] study of the influence of a post processing stage on a Ti-6Al4V part produced by Laser Engineered Net Shaping (LENS) and conclusion that a Hot Isostatic Pressing (HIP) operation can increase ductility from 0.8% to values of almost 12%, but there is no internal provision yet for the thermal energy requirements

of some post processing heat treatments in the case of the hybrid manufacturing process. Therefore, there is a need for independent or external furnace system for such heat treatments, which negates or challenges the philosophy and principles of hybrid manufacturing process set up as a single unit system or machine. Hence there is a need for further research on the ways to achieve all the post processing heat treatment with laser energy within hybrid manufacturing set up.

6. Tool path optimization, in which more needs to be done on the planning for complex geometry parts manufacturing especially for five-axis machining operations.
7. Non-accessible space or geometries of built parts under remanufacturing or repair process, and processes interchangeability during remanufacturing or recycling of legacy parts are also part of the challenges of the hybrid process.
8. The challenge of the exact selection of the best part zero or program zero for or in hybrid part manufacturing process considering complex geometries of parts.
9. In terms of the maturity of hybrid processes, the machining process is evaluated and rated as mature, but all the additive processes are still termed not mature, based on the present challenges and limitations it still faced with, irrespective of their already industrial uses and exploits. Research has been carried out on the maturity and maturity levels of other related manufacturing processes and technologies such as the technology maturity assessment of micro and nano manufacturing processes, by E. B. Brousseau et al [24, 25], using a model, technology readiness level (TRL). The technology maturity assessment of micro and nano manufacturing processes and process chains, by Pierre C. Vella et al [26] using a capability maturity model (CMM). But none has been carried out or recorded on the side of the advancing hybrid or integrated Additive and subtractive manufacturing process to ascertain present state or status, the technology maturity level(s) and rankings for possible optimization. Thus, it has been observed that the following evolutionary models; Capability Maturity Model Integration (CMMI) or the Technology Readiness Pathway Matrix (TRPM) can be applied in

the technology maturity evaluation of the HMT.

10. There is also a need for research on the inspection and user safety standard in the additive and hybrid manufacturing operations.

11. It is true that when a single set up is used for both additive and subtractive operations, the part positioning error is minimized, also, it results in higher final product accuracy. Also, in a single zero set up per part or set of parts based on the part (s) x and y point zero co-ordinate axes, non-productive time due to zero marking is reduced to the minimum. And there is no need to change part zeros or Program Zeros during the manufacturing process [6].

1.2.3 Proposed Solution to Some of the Metal Additive Hybrid Manufacturing Technology

Now, the question remains how to start looking into, and solving these problems to be able to get to the technology desired destination. Then, here comes the sayings that, ''One who was not present at the place of interment normally starts exhumation from the leg''. Also, ''he who does not know where rain started beating him will not know where it stopped. Finally, ''what one does not know is beyond him''. Therefore, it is good to have adequate knowledge of what is to be improved, how to improve it, and where to start from to improving it to achieve the desired results.

While the research proposal skewed towards the technology maturity assessment of hybrid manufacturing technology to establish and fill gaps as part of solutions to the metal additive manufacturing process shortcomings, the initial idea and plan was to determine some industry choice additive hybrid manufactured products. Then, to source and subject them to certain agreeable possible empirical and qualitative laboratory processes capability and performance tests. Mostly mechanical and physical properties, and characteristics This will be a direct methodology of laboratory experimental research on sets of hybrid manufactured metallic parts produced over given periods of noted industry evolvement, all things being equal. This research will help to assess, find out, define, and establish the improvement or development progression trajectory of the processes that produced those tested products over time. However, due to

the limitations, and yet perceived business nature, cold war, competition, and secrecy among the industry players, including consultants, access to industry research resources was sensed difficult and impossible, though the method would be very demanding and expensive, also slow and limited to materials. Hence, the idea of the alternative, machine intelligence semi-direct method of sourcing research resources, information, and data arose. This was followed with the thinking of the possible limitations in sourcing and processing the research working data in such a manner that will give near or accurate results of good precision. It was suggested, discussed, and decided to be embarked upon.

Thus, the semi-direct methodology for technological maturity assessment is an alternative to practical or empirical experiment. Which means that, instead of sourcing research data directly from the hybrid manufacturing technology materials resources of the machines or manufacturing processes and products laboratory, it now becomes through the technology human resources and knowledge of the industry technology, data from professionals and experts survey.

Getting started, the additive manufacturing technology as a new technology became a problem as an integral part of the hybrid manufacturing technology. Hence, lack of exposure and adequate knowledge about the additive manufacturing poised a serious challenge to the proposed alternative research methodology. Study of additive hybrid manufacturing technology of metallic components was carried out with the intention to find out the inside out level or number of advancements of the new technology. This gave birth to the thinking about defining and designing a generic model to execute or assess the level of the technological development.

Nevertheless, there are some known methodologies for assessing growth, maturity of organisations, companies, and industries. Also, services, products, development, and process. It was observed that all relied on data collected through questionnaire administration. It was also observed that each researcher had different kinds of data, focus areas and method of data collection, processing, and analysis. They are seen

fall within the named semi-direct and indirect custom methodologies, such as those of [24, 25, 26, 27], are similar to SDTMAM, while [28, 29, 30], are similar to the ICTMAM in the literature review, for example. Thus, these depend on the researchers' discipline and the interests, guided by the aims and objectives. Most approaches are academic and more of surveying and statistical analysis of data, considering the process areas, the analogy, and data characteristics. Notwithstanding, the termed limited direct practical experiment approach on the hybrid manufactured products was proposed right from the beginning, but was discouraged and discontinued with by perception of business secrecy and inaccessibility of the industry for working information and documents.

1.3 Maturity Profile of the Metal Additive Hybrid Manufacturing Technology

Maturity in hybrid manufacturing technology is a measure of its process and products performance at a particular industry evolvement. It is also the degree of formality, growth, and optimization of HMT. Maturity levels of hybrid manufacturing are well-defined evolutionary steps towards achieving an advanced or developed manufacturing process [31, 32]. Where maturity profile can be viewed as a set of structured state levels that describe how well hybrid manufacturing technology can reliably, availably, dependably, capably, well and sustainably produce the required outcomes ratings. It is used as a benchmark for comparison and aids understanding and comparative assessment of different technologies of common or related characteristics and parametric variables.

Among the choice maturity profiles considered for references to enable assessment of the technological maturity of HMT is the capability maturity model (CMM). CMM is part of the maturity assessment tool developed by Watts Humphrey of the Software Engineering Institute in the 1980s and applied successfully in assessing the capabilities of the software engineering contractors and organizations that are doing business with them at a time. Actually, it is a development model formed from the knowledge and experience from data collected from organizations that contracted with the U.S. Department of Defense who incidentally funded the research. However, it was later in 2006 upgraded to a staged Capability Maturity

Model Integration (CMMI) by the institute at the Carnegie Mellon University. The CMMI model was studied very well with respect to the earlier CMM model before the profile only was proposed, and was adopted to be used in the manufacturing engineering industry technological maturity assessment research programme, precisely in the additive hybrid manufacturing technologies maturity investigation. Hence, the decision was informed by its coverage or scope as in the table 1 below. Hopefully, it will more likely provide that theoretical continuum along which the hybrid manufacturing processes maturity can be developed incrementally and assessed from one level to the next.

Table 1. The Capability Maturity Model (CMMI) Profile [31, 32]

S/No	Levels	Maturity	Maturity Levels Definition and Qualification in Manufacturing technology
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

This capability maturity model profile is adopted for the HMT maturity strata to represent the bases for maturity and ranking in nomenclature, meaning, scope and strata. However, it is important to know that CMMI is not, and never a standard but mere reference strata upon which maturity assessment and the activities are read. This implies that, it specifies a general intent and criteria for different levels of maturity for the areas of application. It does not provide a prescription on how to achieve the levels. This is where the wide study of the research focus area is crucial. Although, it does provide definition of the terms with

examples, these serve as guidelines to understanding and application, but the way or methodology of implementation majorly depends on the researcher's experience, knowledge and skills.

1.3.1 Analysis of the CMMI Maturity Profile of the Metal Additive Hybrid Manufacturing technology

From the practical and industrial phenomena, the term maturity, development, growth etc used in the works are human linguistic variables. It was observed that, none of the researchers shows how the vagueness of the human words are treated from the questionnaire development and design stage to ensure more definite and accurate research data and results.

The CMM, CMMI and other sister models tried to resolve this in their models by the stratification of their maturity levels, but unfortunately, the first source of bias in their methodologies is that all the strata are also linguistic variables. Thus, all are still vague terms.

In order to resolve and check this potential source of error and concern, it was decided to deviate from the conventional binary system of survey questionnaire administration by Pierre et al. [26], for example, to a nonpolarized fuzzy questionnaire answer or response system where there are considerations to factor in various intermediate opinions and positions of the expert and professional respondents about the developing technology under assessment. Hence, for wisemen, experts and professionals do not believe or depend entirely on a binary system situation, judgement or vision of just two limiting consequential alternative options of a ''yes or no, [0,1]'' answers or responses only. This is because of the strong believe that there is always a third angle or alternative to it or a balance about it, or everything, thus decision cannot be right or wrong if people are not consulted, ensure equalization of opinions under the rule of law [33]. That third alternative to going to jail or paying a fine of $10000, is justice [34]. It is the justification point, it is conditional. This point can be found outside, within, and around the two alternatives. Hence, the fuzzy logic theory and a rough set theory [29, 35, 36].

1.4 Research Gap

Observations were made at pre-research topic hunt and checks discussions, and similarly during literature review about the research area and topic proper. However, it was noticed and found out that;

1. For over two decades and a decade of additive and hybrid manufacturing respectively, the technologies have continued to be addressed as emerging technology without any maturity status or obvious effort towards the development of the maturity assessment tools for the developing technology.
2. Some qualitative laboratory experiments are going on with the products, but I think that they are limited to a very small areas of the processes, materials and products properties. This I think will not be enough to drive the industry, development and investment demand of the technology. Hence, a quicker, more encompassing and prolific quantitative artificial intelligent (AI) and digital industrial research approach is required to meet the need.
3. Industry, academia, and research community members have continued to make some unverifiable statement and claims about the capabilities in terms of the attained processes and products characteristics, tactical availability, dependability or operational reliability and performance capability. These made it very necessary to study to x-ray the advancements, the challenges, and the actual achievements of AM and HMT to date. Hence, the result of the study will enable the two technologies and performances to ever be described or discussed by the stakeholders based on their maturity levels or status within process capability areas of product quality, efficiency and effectiveness.
4. Bias issue was observed in research by other scholars who utilized maturity assessment models in their work. Hence, resulting from the vagueness of the linguistic maturity profiles of the models they applied in the research. The artificial intelligence fuzzy logic theory was introduced to cover the gap and effectively deal with the problems associated with an ambiguous linguistic profile of the models.

5. There is no maturity assessment methodology and models established as means of systematically measure, document and guide the development of additive and hybrid manufacturing technology.
6. Additive hybrid manufacturing technology is a cutting-edge manufacturing technology I found new in the mechanical engineering curriculum of the university during my consideration PhD study and research proposal. With the intention of moving from the traditional mechanical engineering domain to a cutting-edge industry digital technology zone
7. There is lack of genuine discussion of the accomplishments and challenges of additive and hybrid manufacturing technology required to instruct, motivate, create and draw a devoted group of followers, learners, and new leaders to ignite and fuel that desire or AM passion.
8. There is lack of quantitative maturation data and status for additive and hybrid manufacturing technologies for researchers, manufacturers and prospective or potential investors.
9. Additive and hybrid manufacturing technology (AHMT) has not been domesticated in Africa in academia, industry, and government institutions.
10. There is high-cost commercial additive manufacturing machine ranging from hundreds of thousands of dollars to millions of dollars. Also, there is a limited number of the industry experts, but one must not have to invest on high-cost of professional engineering software, and a million-dollar 3D Metal printer or additive manufacturing machines first, to reach the cutting-edge of additive manufacturing
11. International business implications and opportunities in the areas of aerospace, medicine, automotive, and defence. Thus, high population implies high need and demand for good public health, high need for transportation, industries, schools and research institutions, infrastructure, security, and high AM product and service market demand potentials of the Africa. Hence, Africa is the future destination for additive manufacturing, and I wish to acquire as much knowledge and skill as required for further research, teaching the young and future engineers, support learning for the large population, infrastructure, and businesses demands to come.

12. There has not been a documented holistic examination report neither on the technology maturity assessment of additive manufacturing processes nor the emerging Hybrid Manufacturing Technology (HMT).

Thus, it was very inspiring having understood that it would make a revolutionary research thesis if these gaps could be walked through successfully with appreciable results and recommendations that will contribute meaningfully to closing them.

1.5 Research Programme Aim, and Objectives

The aim of the research is to develop a new and generic hybrid manufacturing technological assessment model, to assess the technological maturity of metal additive hybrid manufacturing technology for improvement and optimization, to design and develop a new hybrid manufacturing technological maturity compatibility test model, and to test the technological maturity compatibility of the metal additive hybrid manufacturing technology for improvement and optimization.

Whereas the objectives of the research include.

1. Identify the process areas and the variables, then the parameters and their performance indices (PI)
2. Develop, plan, and design artificial intelligence fuzzy logic-based questionnaire for experts' survey.
3. Generate sets of result-oriented research survey statements, propositions, or questions as suitable, for the questionnaire.
4. Assess the maturity level of the subtractive manufacturing (machining) technology in the process areas of the process product quality, process efficiency, and the process effectiveness maturity, and their aggregated maturity.
5. Assess the maturity level of the additive manufacturing (PBF) technology in the areas of the process product quality, process efficiency, and the process effectiveness maturity, and their aggregated maturity.

6. Use digital technology to assess the maturity level of the hybrid manufacturing (HMT) technology in the areas of the process product quality, process efficiency, and the process effectiveness maturity, and their aggregated maturity.
7. Simulate a quantified maturity assessment procedure and results for probable or possible achievement of the same maturity outcome.
8. Determine the technological maturity compatibility of metal additive hybrid manufacturing processes union, complementarity, intersection, and the differences based on the product quality, processes efficiency, and processes effectiveness maturity levels.

1.6 Scope of the Study

The laser-based additive manufacturing (AM) of metal parts made a significant progress in the last two decades, especially in advancing Laser-PBF, Electron Beam Melting (EBM), and the Wire-directed energy deposition (DED) AM technologies. Also broadening the range of materials available for them and as well in developing the necessary data pre-processing tool. However, the AM technology especially the Direct energy deposition (DED) technology has matured to reach a level where it can be considered as a viable alternative for producing net shape metal components for relatively small markets, mostly for prototyping and small batch manufacture [6]. The development of hybrid solutions that combine the AM technologies with other complementary processes can broaden their application areas and address some of inherent AM limitations associated with ''design to piece'' lead time and cost. In this context, this research is focused on studying and designing a new generic technological assessment model and using same in assessing the maturity of hybrid manufacturing (HM) solutions that combine the capabilities of metal AM technologies with the complementary CNC machining or subtractive manufacturing (SM) (pre- and post-processing) technologies, with respect to their individual and combined process product quality, process efficiency, and the process effectiveness capability performance areas.

1.7 Significance and Key Contribution to knowledge of Study

1. Owing to my continuing professional and academic development ambition, especially in the Cutting-Edge Technology of AM. Thus, additive hybrid manufacturing technology is a cutting-edge manufacturing technology I found new in the mechanical engineering curriculum of the university during my consideration for my PhD study and research proposal. With the intention of moving from the traditional mechanical engineering domain to the more current, and new era of industry digital technology zone, it was observed that the technology is posed to revolutionize the ways parts and components of complex geometries are developed, designed, planned, and qualitatively manufactured effectively and efficiently, while maintaining high and optimum standard and performance. I found the AM technology very interesting especially its capabilities in the high-risk areas and engineering applications of aerospace, medicine, automotive, and defence. Hence, I wish to join the technology industry and academia leads globally, participate, and contribute to the efforts in the manufacturing of high-performance engineering components or parts.

2. Lack of quantitative maturation data and status for additive and hybrid manufacturing technologies for researchers, manufacturers and prospective or potential investors is among the factors. Thus, there is a bright future and rewarding career in additive and hybrid manufacturing technology. The only way I think to enhance people's interest without losing the energy or drive is to strike a balanced view and approach towards the point where the technology is presently and where it can possibly be in future. As the producers or manufacturers, how do you prepare to benefit from this opportunity? Also, as the business owner, how can this industrial revolution affect or impact your investment, profit or earnings including those of your competitors or other businesses? Then, how mature is the technology and what long-term strategic advantages might it guarantee? Definitely, a genuine discussion of the accomplishments and challenges of additive and hybrid manufacturing technology is required to instruct, motivate, create and draw a devoted group of followers, learners, and new leaders to ignite and fuel the desire or passion and make the future of the additive and hybrid manufacturing technology [4].

3. In a regional context, additive and hybrid manufacturing technology (AHMT) has not been domesticated

in Africa in academia, industry, and government institutions. Although, high-cost commercial additive manufacturing machine can range in price from hundreds of thousands of dollars to millions of dollars, the limited number of the industry experts notwithstanding, but that does not mean that one cannot have the ambition to begin to study and acquire the AM knowledge and skills from elsewhere, then transfer and consolidate the technology in Nigeria, and Africa in general within a shortest period of time. Thus, there is nothing bizarre or inordinate about an African scholar's ambition to study AM and HM technologies as one must not even necessarily need a degree in engineering or invest in the high-cost of professional engineering software, and a million-dollar 3D Metal printer or additive manufacturing machines first, to reach the cutting-edge of additive manufacturing [4]

4. International business implications and opportunities in the areas of aerospace, medicine, automotive, construction, power, energy and defence. Hence, high population, which implies high need and demand for good public health, high need for transportation, industries, schools and research institutions, infrastructure, security, and high product and service market demand potentials of the Africa. Hence, Africa is the future destination for additive manufacturing, and I wish to acquire as much knowledge as possible, including the engineering, the technology, the business and technical skills required for further research, teaching the young and future engineers, support learning for the large population, infrastructure, and businesses demands. Also, carry out consultancy services to the government, companies, investors, developers, industries, and schools etc. Also, organizing local and international workshops, training, seminars, conferences within and outside Nigeria and Africa. I envisage a bright and rewarding career future in additive manufacturing.

Thus, regarding the metal additive hybrid manufacturing technology (MAHMT) and guided by the fact that every emerging technology or innovation has goals, but knowing the extent of accomplishment of these goals, the challenges, and the successes through system audit over time is very important.

Moreover, the research is very necessary as there has not been a documented holistic examination report

neither on the technology maturity assessment of additive manufacturing processes nor the emerging Hybrid Manufacturing Technology (HMT). Thus, if the model is implemented and validated, it will be available as a generic model for manufacturing processes, two or more process pairs maturity assessment tool or model.

1.8 Definition of Terms

1.8.1 *Process Area*

A process area is a group of phenomena and activities that is relevant to the system under study, with the aims and objective functions inclusive. The process area of contention is required to be identified and rigorously characterized further to determine the process areas that are most relevant to the manufacturing processes, from where performance indicators are ascertained for questionnaire development and experts' survey.

1.8.2 *Process Objective Evidence*

This is several practice implementation indicators or evidence that a given CMMI Practice that support a Goal has indeed been carried out or implemented. The idea is that performing a practice will leave a footprint or evidence that the practice is performed. Thus, objective evidence is a body of obvious indicators which automatically prove that certain practice has been implemented to achieve a definite goal of a process area. Hence, performing a practice, leaves behind some trace of signs or facts that show that such practice was performed. Objective evidence can be a document or a material object (Artifacts) and a spoken statement or voice (Affirmation) that is directly drawn from a practice within a process area. [31, 32]. However, to carry out or attempt a technology maturity assessments questions, experts and professional appraisers first look for or reflect on memory to the best of their knowledge and identify various performance issues statements, the objective evidence, or the practice implementation indicators that will back their answer or claim.

1.8.3 *Maturity assessment tool*

Capability maturity model Integration (CMMI) maturity profile was proposed to be utilized in the maturity

assessment methodology for hybrid manufacturing technology. However, for the CMMI model being made up of linguistic variables, and due to the structural progression or developmental characteristics of its variables, which are in human language or words, it was discovered that the imprecision of application leaves doubts that the model lacks the full capacity to achieve the desired tight result due to gaps already existing in the linguistic nature and the vagueness of the ''maturity'' variables which is relative, and will affect survey outcome. Thus, with the knowledge of digital technology principles and application, as well, artificial intelligence (AI) fuzzy logic system was considered and introduced in the design of questionnaire. They are seamlessly integrated with the CMMI maturity profile as shown in the tables 3, 4, and 5 below. Hence, the Fuzzy logic application is essential for determining the relationships within the base CMMI model and the technology parameters. This is to ensure the applicability and validity of the combined model, hence the accessibility and assessibility of the maturity levels. The role of AI in these tools is the ability to generate and process unbiased or definite numerical and quantifiable data from the blurred human words, linguistic process capability variables, and that of the evolutional CMMI model and profiles. Thus, no one needs to go to the laboratory, which wastes a lot of time, scarce human and material resources, and low output.

1.8.4 *Fuzzy Logic*

Fuzzy logic like other artificial or machine intelligence tools is important for processing and making decisions based on research data and information outside the conventional qualitative approach.

However, it has also been realized that the capability maturity model integration (CMMI) can be implemented by employing linguistic variables and the fuzzy theory should be applied to process them and obtain numerical or quantifiable variables.

Thus, designing a hybrid manufacturing technology (HMT) maturity assessment and improvement questionnaire interview model requires some rigorous process of choice and considerations to be able to generate an unbiased research data set for fuzzy logic and set theory applications.

1.9 Thesis Structure and Organization

Step 1: Data collection and the basic statistical data processing and result analysis of manufacturing processes A and B in hybrid manufacturing solution.

Step 2: Further processing or iterative post basic statistical data processing and result analysis of manufacturing processes 1 and 2, by applying the fuzzy logic and set theory for membership function, then establishing the technological maturity of the individual processes.

Step 3: Specialist mechanical engineer or AM, HMT expert's inference rule results (output) of hybrid manufacturing processes 1 and 2.

Step 4: Simulation of the technological maturity assessment results in a fuzzy logic tool-box in MATLAB, for engineering mathematical model results confirmation and more results accuracy.

Step 5: Development and design of processes compatibility test model for hybrid manufacturing.

CHAPTER 2

LITERATURE REVIEW

Literature review was carried out on advanced manufacturing technologies of the subtractive CNC machining and additive manufacturing technologies for the purpose of learning and understanding the idea, system, aims and objectives, innovation, principles, applications, and limitations. Thereby creating general background to the technological research. This is with the intention to be able to have adequate information requirement, likely process areas and the key performance indices for the design consideration and the modelling proper.

Also, literature review was carried out on maturity assessment programmes, where certain maturity models were shown, referenced, adopted, adapted, and utilized in some other maturity assessment projects performed in the past.

2.1 Model and Maturity Profile Adoption

Maturity model is a framework or set of structured levels that is used to describe and measure how well the behaviours, practices and processes of a system reliably and consistently produce required expected outcomes [31, 32]. It can be used as a benchmark for development, comparison, and as an aid to understanding for continuous improvement of systems or processes.

There are many models available for assessing maturity, be it of organization, man, machine, material, technology, process, product, and services. The models include the capability maturity model (CMM), capability maturity model integration (CMMI), and technology readiness levels (TRLs). The use of the models depends on the project area and the requirements for the assessment. Hence, any model can be adopted, adapted, or an entirely new model introduced for research survey appraisals.

However, the capability maturity model (CMM) is a development model formed in 1986 after examining the data collected from various organizations or companies that do contract businesses with the U.S. Department of Defense, who incidentally funded the project. The aim of the model is to improve the existing

software development processes of the U.S. Military, though it can as well be applied in other processes. Thus, the word maturity has to do with the degree or measure of stability and optimization of processes from ad hoc practices, to a formally defined steps, to managed result metrics, to active optimization of the processes.

Years later in 2006, the Software Engineering Institute (SEI) of Carnegie Mellon University developed the capability maturity model integration (CMMI), where several developments, product, and services process areas, practices and goals are allotted certain maturity levels along a complete maturity profile through experts' survey. Obviously, the prevailing CMMI has largely superseded the CMM having addressed some of its limitations and challenges.

Moreover, Philip B. Crosby [37] earlier conceived the quality management maturity grid (QMMG). An organizational maturity matrix which he first published in his book, Quality is free. The quality management maturity grid describes 5 maturity levels through which an organization or business will go through the maturity profile of evolutional linguistic variables or nomenclatures such as the 1st, Uncertainty, the 2nd, Awakening, the 3rd, Enlightenment, the 4th, Wisdom, and the 5th maturity level, Certainty.

Hence, Pierre et al [26] adopted a CMM model of the Software Engineering Institute (SEI). With their replacement of the maturity level (L2), Managed by a Repeatability with respect to the CMMI maturity profile. Two approaches were followed, namely the top-down approach, where the process maturity assessment is based on the process work area maturity indicators, and the bottom-up approach, where the supposed process maturity assessment is based on the process capabilities of product quality. Till Albert et al [28] adopted their maturity assessment model of Technology Lifecycle and states of the Pacing Technology (PT), Key Technology (KT), and the Basic Technology (BT) under which the various terms are grouped. The model they further tinkered and reduced to just two technology lifecycle of Pacing and Basic Technology states, like binary set and logic systems along which their products maturity indicators were assessed and

ranked. Similarly, Rodrigo Goyannes et al [29] moreover, adapted the OSCM4.0 maturity levels as thus, None-existent (ML0), Conceptual (ML1), Managed (ML2), Advanced (ML3), Self-optimized (ML4). Meanwhile, Cengiz and et al [38] were able to come up with a good number of classified areas of industrial engineering research activities, topics, journals, and books. Also, Andrzej SKRZAT et al [36] adapted the input and output variables by using the extension principle and alpha -optimization method. Where, in 2016, Pierre C. Vella et al [26], adopted the capability maturity model with a minor tinkering at the maturity level 2 as follows; Initial, Repeatable, Defined, Managed, Optimized, thereby, still standing out clearly from the CMMI maturity profile. Fatih Yucalar et al [39] combined the CMM and the CMMI models (Continuous representation capability levels and Staged representation maturity levels).

Moreover, E.B. Brousseau et al [24, 25] reported and as an alternative, explained how a Nine (9) maturity steps Technology Readiness Level (TRLs) model was adopted and transformed through the adapted Six (6) steps Transition Phases (TP) model to finally form a Seven (7) Maturity Phases model. The seven maturity phases of technology development were identified and classified with the nomenclatures as: Maturity Level (ML) 1. Basic Technology Research, ML2. Feasibility Study, ML3. Technology Development, ML4. Technology Demonstration, ML5. System Development/Integration, ML6. Integration in a Production Environment and Validation, and ML7. Mass Production/Serial Production. Thus, the number of maturity levels is a matter of individual choice driven by the research environment and semantics. Also, Till Albert et al [28] applied the model devised by Sommerlatte and Deschamps, with its three clearly defined states of Pacing technology, Key technology, and the Basic technology. A technology lifecycle model, with well-defined states of maturity as developed by Sommerlatte and Deschamps was adopted [40]. The definitions of these states of maturity helped them to operationalize the model and match term candidates as thus, Pacing Technology, Key Technology, and Basic Technology. Meanwhile, Colin Rudd and John Sansbury [27] as reported by Axelos Limited 2013, aligned with the CMMI definition based on the ITIL framework of, Initial, Repeatable, Defined, Managed and Optimized. Moreover, Alison Olechowsk et al [41] for convenience and as a matter of semantics, changed from using TRLs, and used Technology Maturity Levels (TMLs) instead, in practice.

2.2 Choice of Process Capability Area and Application of Model

Obviously, the nature and choice of the process area depends on the researcher's aim and objective, the kind of data focus et al. This implies the type of data peculiar to the need of the assessment project. They include the data focus area, the methodology, the model proposed, the research approach, aim and objective of research, the product, services, process, and development, while the guiding principle is based on the performance indicators, and the objective evidence.

The SEI CMM model as part of the maturity assessment tool developed and applied successfully in assessing the capabilities of the software engineering contractors and organizations that were doing business with them at the time. This model helped them to establish the level of maturity, qualification, trust or reliability of their suppliers and contractors in the business and service delivery during products and services procurement planning, bidding, and award administration exercise of the organizations. It enables them to measure and clearly select their vendors objectively with evidence and justifications without guess. The CMM was originally intended as a tool to evaluate the ability of government contractors to perform a contracted software project. Though it comes from the area of software development, it can be, has been, and continues to be widely applied as a general model of the maturity of the process (e.g., IT services management processes) in IS/IT (and other) organizations [31, 32].

The Quality Management Maturity Grid (QMMG), a business matrix, is used by a business or organization as a benchmark of how mature their processes are, and how well they are embedded in their culture, with respect to service or product quality management. The Crosby's QMMG is credited with being the precursor maturity model for the Capability Maturity Model (CMM) created a decade later that also has five levels of maturity.

The Pierre et al [26] model was designed for manufacturing industry, and to be applied as a maturity framework for technology maturity assessment of micro and nano manufacturing processes pairs and

chains. Eight (8) different MNM processes and process chains were tested to assess their individual process and pair maturity and to judge about their respective Key Process Capability Areas (KPCA). The technology maturity assessment of micro and nano manufacturing processes and process chains research work is widely seen composed of and bound by a micro and nano products design, manufacturability, micro and nano manufacturing processes design, processes selection and planning activities which dominate the research data source. Till Albert et al [28] were focused on product technology.

Similarly, Rodrigo Goyannes et al [29] proposed a novel model to assess the I4.0 coded maturity of manufacturing companies based on a fuzzy probabilistic expert system to overcome the inaccuracy and uncertainty of previous maturity models (MMs). It addresses the complexity of digitalization level perception across all operations and supply chain management. Hence, takes charge or control of the management of all the activities of the organization which are directly concerned with the acquisition and utilization of resources, production, and the distributive functions for products and services. The study centres on addressing the question of how to measure readiness digitalization in manufacturing organizations. Meanwhile, Cengiz Kahraman et al [38] tried to define a fuzzy set theory, stating the importance and its degree of usefulness in industrial engineering. The aim and objective of the research is to show the level of utilization of fuzzy set theory in the industrial engineering by researchers, journals, and book authors. They were able to come up with a good number of classified areas of industrial engineering research activities, topics, journals, and books where the fuzzy set theory was applied in industrial engineering phenomena. Thus, recent research findings in each area of IE reviewed, show that extensive work has been done on applying fuzzy set theory to research problems in IE. Andrzej SKRZAT et al [36] introduced fuzzy logic as relatively a new concept in science which might be used for the analysis of mathematical models which contain some uncertainties. Analysis of fuzzy set theory with some mathematical representations were made. These were used to illustrate some fuzzy set operations such as the addition and multiplication of fuzzy sets, the determination of membership functions for fuzzy input and output variables by the extension principle and alpha -optimization method. Fatih Yucalar et al [39] adopted the maturity level 2 process area

of a CMMI model, which was used to assess a maturity of five Turkish software companies at the maturity level 2. They defined the CMMI model and its capacity in assessing maturity levels of software companies. However, E.B. Brousseau et al [24, 25], reported and explained the application of the new model at the European Commission (EC) sponsored life project of the technology maturity assessment of a micro and nano manufacturing technology.

Meanwhile, Colin Rudd and John Sansbury [27] embark on a management maturity model that assesses the service management capabilities of organizations, and the maturity of their governance structure and management system. Their purpose of the self-assessment service is to allow organizations to understand the maturity of their IT service management processes and functions. A kind of the Institute of Leadership and Management (ILM) apprenticeship of the organization. The model is for the organizational internal use. Hence, inculcating and promoting organization's procedural core value and image among staff. Meanwhile, the ITIL Maturity Model released in 2021, as an IT service management (ITSM) assessment tool with five maturity levels of nomenclatures ML0. Chaotic, ML1. Reactive, ML2. Proactive, ML3. Service, ML4. Value. It can be used by teams at any time in their ITSM programme to weigh their organization, set baseline, as well identify improvement opportunities. Moreover, Alison Olechowsk et al [41], adopted NASA Technology Readiness Levels model scale.

2.3 Methodologies Applied by other Scholars

In the various approaches of the maturity assessment studied, it is still observed that technological maturity assessment approaches mainly depend on what the researcher chooses as the process area, based on what he knows or what he is thinking about. The process areas may be generic, common, familiar, customized, abstract in nature. It may be bespoke, and personalized areas around which research prepositional statements are formulated and generated. Then, coined as required or suitable for experts' survey questionnaire, data sourcing and collection.

In Pierre et al [26], the capability maturity assessment model (CMM) was adopted with a minor tinkering of the maturity level 2 of the CMM compared to the CMMI maturity model as thus, Initial, Repeatable, Defined, Managed, Optimized. Pierre et al [26] also adopted and applied a combined top-down and bottom-up approaches by Becker et al [42], and Lahrmann et al [43, 44, 45] respectively. In the top-down approach, three sets of survey questions totaling 55 in number, were adopted, and were grouped under three management categories of their Key Process Capability Areas of, dynamics, capability and documentation for convenience, better research management. Whereas in the bottom-up approach also adopted are some pairs of the micro and nano manufacturing technology industry parametric quantitative values and data information which said were got directly from the research and development (R & D) department. The categorized questions were used to design an expert survey questionnaire of crisp binary 'yes' or 'no' for the research information target group. The same questionnaire was independently administered on the two technologies. Data were collected, processed, and the results were able to rank each of their categorized key process capability areas along the adapted CMM profile. Whereas the obtained quantitative parametric values of the MNM processes pairs were used to compare the complementarity, and compatibility of the processes in pairs. Hence the meta parametric results of processes compatibility and complementarity were analyzed and discussed.

However, since the aim of the survey is to find out if a specific process key performance indicator is achieved, it means that the binary response of 'yes' or 'no' are not representing the true state of the (PMI), hence there is probability or certainty that there could be some of the process capability areas which can still be at their intermediary state or level of the maturity.

Where, Till Albert et al [28] used web and online blog publication texts as the sources of research information and data collection. It was noticed that certain terms are more commonly associated with a particular technology state than the other over and in a particular time. Hence, the use of terms and the number of occurrence or frequency of such terms in a page is used to determine the maturity state of such technology. However, like in the case of Pierre's binary questionnaire answers, their products maturity indicators

assessment results were ranked just along the two technologies lifecycle of pacing and basic technology states. Whereas it is obvious that there is a lot of room for bias and non-encompassing results. But notwithstanding, it is most likely because of the situation that prompted their introduction of fuzzy logic theory at the middle stage of the research to transform the statistical crisp data sets to fuzzy sets and assigning some membership values to the applied lifecycle states. Yet, I think that they were not able to capture the fuzziness of their model and its components. Especially, where developmental and none-clear or obvious variables, and sets of nondefinite activities and results are involved in their study.

Then, Till Albert et al [28] based on Blog Analysis, applied the knowledge of standardized short technology maturity report where they got their data directly from the industry technology blog publications, the patents and scientific literature reports etc. Followed by expert survey exercise, which helped to compare the maturity, monitor development speed, as well the maturity state changes and identifying emerging basic technologies. Moreover, they adopted and used the technology and its related lifecycle, which represents the evolutionary maturity profile, to show that maturity can be assessed and represented as it is positioned or by its position within a technology lifecycle. Thus, the technology lifecycle models of three to six maturity states and describing the maturity or maturity process of the technology from the discovery of the underlying scientific principles to its introduction to the market and beyond that. However, it was reported according to Tiefel [46], that the current or available technology lifecycle models are characterized by some shortcomings, which include lack of methodologies to operationalize the model parameters. So, in other to overcome these challenges, the lifecycle of the real-world technologies later was operationalized by way of corresponding lifecycle of text data as suggested by Martino [47], Porter and Cunningham [48], and Jarvenpaa and Makinen [28, 49].

Till Albert [28] did apply blogs as source of information for assessing technology maturity, where online visibility of a technology and the internet audience awareness of its existence contents change with the maturity of the technology (Ansoff 1984) [28]. Although they highly believe that a blog-based indicator allows for increased precision of technology lifecycle state identification, yet web content-based research is

scarce. Hence, can be gathered from the results of a survey. Research information was sourced from the blog. The information of the technologies was categorized and used to generate statistical data that was later transformed into fuzzy sets with membership values. Till Albert et al [28] on the other hand used patents for the purpose of assessing a technology maturity. Although patents are early indicators, but normally, they involve a delay of 18 months between filing and disclosure [50]. Patents must be clearly distinguished as concept, product, and process patents [40].

However, there is no category for concept patents in patents system. But in some cases, patents compromise both product and method claim as it is difficult to separate them. Hence, patents are useful for identifying pacing technology, and difficult to be applied in other lifecycle states, like key and basic technologies. Moreover, from observation, it seems that the combination of patents, scientific and web base informetric will yield better results in maturity assessment and recommended that a larger number of maturity states be applied instead of the just two technology lifecycle model or structure; pacing and basic technologies states utilized [28]. Meanwhile, Rodrigo Goyannes et al [29] generated up to 24 OSCM maturity indicators, which were used to produce research questions. Further in the design of the questionnaire and administration, they were divided into seven maturity dimensions, namely (1) consumer (2) logistic (3) supplier (4) integration (5) production, planning, and control (6) quality (7) maintenance.

However, considering the uncertainty and impreciseness, Rodrigo designed an expert system composed of fuzzy inferential systems (FISs) with two key elements; fuzzy rules and membership functions (Zadeh, 1965) to model the experts' perception in decision-making judgments. To process the results, the construction of FISs relied on Mamdani-style fuzzy inference [30], and its setting is segmented into four stages: fuzzification, rule evaluation, aggregation and defuzzification [51]. Section 4.2 describes the FISs modelling and its elements. They did not make any reference to any research or working data set utilized in their explanations. However, some mathematical relationships of fuzzy sets were shown, but the paper is not centred on any engineering system or project. The paper is not solving any mentioned problem or executing any project. Just introduced and illustrated some formula used in fuzzy set operation. There is no information about the

nature and source of data used in the expressions or illustrations. The paper is more of teaching and reporting how fuzzy set theory can be used to solve a simple mathematical or statistical operational problem. As there was no project mentioned, or even an area of application mentioned.

Hence, there is no objective evidence for the comparison between the extension principle and the alpha-optimization method since they were applied under an unknown real time or practical research results source and condition. However, they are saying that the extension principle is not effective for mapping models that have some form of complex numeric algorithm, whereas the alpha-optimization method is rather more suitable in the situation. This article may guide a researcher who is trying to analyse and operationalize research fuzzy data sets and the results for a better and guided decision in his work. Thus, the statement should be experimented with a live data. Though finally, in their advice or recommendation, the fuzzy logic was used for simply solving problem, that in further research, fuzzy theory will be applied for a specific engineering problem. The question is, what will guide and lead such research project and the researcher to the point of fuzzy system, the required data sets and the mathematical formula recognition, applications, or utilization. Thus, there is still a gap (no connection or relation) between the theory and the intending project area or application, the aim and objective. Fatih Yucalar et al [39], showed how a set of 39 questionnaire with five possible answers to each question, and each being allotted certain numerical point value. Having explained the relationship with the original CMM model, and the International Organization of Standardization/International Electrotechnical Commission ISO/IEC 15504 information technology process assessment standards. Also known as Software Process Improvement and Capability Determination (SPICE)**.** It constitutes a set of technical standards documents for computer software development process and related business management functions.

The five software companies were assessed for maturity level 2 only, and the appraisal was limited to the process area within the ML2. Nothing was considered from the below and above process area. Seven samples of the questionnaire questions were shown and with assigned weight to the possible answer options or choices of; Definitely yes, Usually, planned but not applied, Not sure, Definitely no. The survey was carried

out, and the results processed. There was no close or direct study about the companies. The questionnaire was developed from the process area, practice, and goals for the maturity level 2. However, the illustration did not handle the effect of the vague linguistic variables of the CMM, CMMI models, which makes the entire exercise seem ineffective**.** Moreover, in the results assessment, the company whose assessment value is greater than 80% is classified as being at the maturity level 2, whereas those below are required to put up a little more effort to get to the maturity level 2. The results of the assessment were coming out like that because the appraisal was conducted for the maturity level 2 benchmark.

However, in the maturity survey literature proper, it is observed that the CMMI expert was more of the principal stakeholder in the exercise, rather than the software experts whose domain and expertise are being assessed. Hence, it is the companies' software capabilities that are being assessed with the adopted CMMI model. Also, expertise in CMMI does not qualify one to design a valid questionnaire and assess a system he is not one of the stakeholders or knowledgeable, hence the result will be unreliable. Thus, software industry supposed to have its peculiar process area, and the process area, after the assessment should be placed each on their appropriate maturity levels accordingly. This will represent a discrete maturity ranking.

Finally, the study seems to be more of an illustration than research as there is no real-life and real time data sourcing, collection, and analysis. Hence the article focused more on the characterization of the CMM and CMMI models and shows how it can be used to generate set of survey questions required for appraisal and applied on the same system that invented it. This shows that the study is still within the information technology system which is the original CMMI area of application. E.B. Brousseau et al [24, 25], report shows that the services of the technology experts and professionals are well utilized where required at every stage of the study. From the maturity indicators drive to the design of questionnaire, administration, and data collections. Also, through a Crisp survey answers or responses, they were able to collect data which was ranked along the maturity phases. However, it was seen that they did not consider and deal with the ambiguous, vague nature and characteristics of the linguistic variables of the model throughout the project, hence it is not in the report. Emmanuel Brousseeau et al [24, 25], reported and described the original study

which was conducted in collaboration with two networks funded through the Sixth framework programme (FP6) of the European Commission (EC), namely, the Multi-Material Micro Manufacture (4M) Network of Excellence (NoE) and the µSAPIENT Coordination Action (CA). Their research data was sourced from existing R&D Projects that were carried out in the MNTs industry domain by partner organizations in two consortia. Where the maturity phases targeted by each project could be evaluated, and as a result, the maturity profiles for given technologies were extracted.

However, the aim and objective for their research, report and description of the projects is not to find lapses or establish gaps, neither is it to redesign or innovate another methodology, rather, to help inform the industry, the global research community and policy makers about the current level of maturity reached by MNTs as developed and shown in R&D Projects, and briefly shown how it was done including the identification of maturity indicators, design of experts' survey questionnaire and administration, also the adapted seven (7) phases of the technology development on which the rankings were based. R.V.S. Lalitha et al [35], both from the Sri Sai Aditya Institute of Science and Technology, Surampalem [52] explained the relationship between Fuzzy Logic theory and the Probability theory, as both having values that lie between 0 and 1. Analysis was made using existing data from a database, where degree of membership values was assigned to the elements of the subset based on the stipulated numerical quantity. However, the source and methodology for generating such data was skipped.

Though it may not be important as the interest is on the belongingness or degree membership of the subsets. Colin Rudd and John Sansbury [27], which is the same to the Pierre's, CMM maturity models and profiles, but notwithstanding, the Information Technology Infrastructure Library (ITIL) is a set of best practices for delivering IT services—it standardizes the selection, planning, delivery, and support of IT services to maximize efficiency and maintain predictable levels of service. The model is currently divided into five broad stages or categories namely, Service Strategy, Service Design, Service Transition, Service Operation, and Continual Service Improvement. Thus, the ITIL processes are organized and focused around the five stages or specific phase of the five-service lifecycle. It helps businesses improve service levels and reduce costs of

IT operations. The primary or main goal of ITIL is to provide high-quality service while enhancing business efficiency.

Meanwhile, the Colin Rudd and John Sansbury [27] self-administered maturity survey or assessment service was classified into two, the high-level self-administered maturity survey or assessment, and the full self-administered maturity survey or assessment. Where the difference between the two is the number of questions utilized in the survey exercise. The latter is expected to be far higher than the other. However, the information required for the process and function assessments questionnaire come from the organization demographics and IT demographics, which are organized by either lifecycle or capability view. However, all questions have two possible responses of Yes and No. Each question also corresponds to one of the five levels of maturity. Hence, there is no option to partially meet the requirement, as the full self-assessment service comprehensively covers the requirements of a particular process or function at all maturity levels. Thus, the system is designed such that by answering a set of questions related to a process or function, the self-assessment service will calculate a value for the maturity of that process or function within the range of 0 – 5 levels.

Now, considering the relations, ITIL model was introduced as a subject for the self-assessment exercise, but the model or states, the terms capabilities, functions, and processes were neither shown nor defined. Rather, the Pierre's CMM and CMMI models were just adopted and utilized in the self-assessment programme. This implies that the study and the literature did not include the five states of the ITIL maturity model capability, function and the processes, and lifecycle-based profile. Nevertheless, a model supposed to be a guide, and it depends on what the user wants to achieve with it. Also, in Alison Olechowsk et al [41], the TRLs model was reviewed by using it to assess the readiness maturity of seven industrial organizations with the intent to finding the deficiencies of the model asper the phenomenal capabilities, processes and functions areas left out or not considered in the technology readiness assessment project design. These phenomenal areas are found to be what they referred to as, the integration and connectivity, in terms of environment, the interface maturity, both the physical and signal, the scope of TRLs assessment, in terms of product breakdown

structure (PBS), and the critical technology elements (CTE), the influence or effect of new component, or subcomponent and environment on TRLs. Also, the prioritization of technology development effort (''Weakest Link'') method.

Thus, the fault-finding study was carried out by implementing the supposed nine TRLs model by means of a semi-structured interview with the employees from the 7 different organizations and examined documentation collected from industry standards and organizational guidelines related to technology development, and demonstration. Hence, their findings consist of 15 challenges observed in the TRLs implementations. These challenges were further categorized into 3 groups: system complexity, planning and review, validity of assessment. The challenges are presented as areas of further research opportunities to be explored and addressed for an improved decision process and performance outcomes of TRLs model in complex engineering projects.

Thus, the article is seen to be more of a critical review of the TRLs model with respect to the unveiled 15 deficiencies of the model. I think it is trying to say that the model does not clearly consider the three identified categories. Meanwhile, it was also observed in further information that most of the 15 challenges established by the study are matters of semantics, and as well individual or personal perspectives, which may be because of the vague nature of its linguistic variables and the resultant human biases and imperfection. These perceived gaps might be resolved or addressed by introducing some simple elements of fuzzy theory in the design, planning and management stages of the development and production. Otherwise, the challenges are supposed to be revealed and addressed by an experts' questionnaire, and expert survey implementation method.

Nevertheless, models have no definite shape, structure, and characteristics. Hence, invented models are prone to innovations and re-innovations. Also, they are subject to adoption or changes by adaptation during application, depending on the suitability of the process area, the aim and objective of study.

However, it is important to note that TRLs is simply a model and not a standard. This implies that, for each

area of practice it specifies a general intent and different levels of maturity in abstract terms, it does not provide a prescription how to achieve those levels. Hence, it does provide detailed abstract information and examples which serve as guidelines to understanding and implementations, but the way or methodology of implementing depends on the researcher.

2.4 Summary of the Literature Review

2.4.1 Definition and Classification of Maturity Assessment Methodologies

From the literature review so far, one can say that there are many methodologies that can be applied on a maturity assessment programme. These methodologies seem to be driven by the ideology and interest of the researcher. Reports, experience, and observation show that these methodologies can be, categorized into three groups namely, the direct, semi-direct maturity, and the indirect custom or personalized technological maturity assessment methodologies. Governed by the availability, ease, and accessibility of research materials resources and information or data, but driven by researcher's ideology, experience, skills set, research data source, scope. Also, by the means of data collection, and finally the theory of model employed.

2.4.1.1 *Direct Technological Maturity Assessment Methodology (DTMAM)*

The DTMAM is the act of physical preparation and scientifically carrying out technological assessment through the gathering of physical data about technology and products empirical engineering laboratory tests. Gather directly, measurements and information about physical processes, production, market and consumer or users' through systematic and strategic investigation processes and results analysis for the process capabilities of product quality, efficiency, and reliability of the manufacturing processes respectively over some given industry evolutional periods of time. Although some additive hybrid manufacturing processes and products experiments have been conducted in the past with results and analysis, but not specifically for the purpose of technological maturity assessment of the AM and HMT. This method is limited

and will be very expensive, hence requires a lot of resources, very slow as it can hardly cover more than one parameter at a time. Mostly products physical characteristics and properties of materials, such as the laboratory investigation of the technological maturity of processes based on the product surface integrity, dimensional accuracy, presence and effects of residual stress, tolerance and precision, mechanical properties analyses, post processing needs over time.

2.4.1.2 *Semi-Direct Technological Maturity Assessment Methodology (SDTMAM)*

The SDTMAM is an alternative to practical experimental studies and methodology similar to the methods [24, 25, 26, 27]. As the name implies is the act of preparation and carrying out generic technological assessment of manufacturing processes through both direct and indirect remote method, but efficiently collect information and data in smart ways. Also processing it in smart ways. It is a physical and scientific sourcing and using relevant available academic and industry management and technical resources, product, and market information. Mostly by answering questions based on objective evidence in the subject. SDTMAM is more encompassing, but tedious, as it requires artificial intelligence and absolute carefulness in handling human bias, the vagueness and unprecise human words or language barriers, the environmental differences in survey practice. Thus, there is a need for professional and expert views, and contributions to a dedicated and committed research team to implement effectively. However, the methodology can still be employed alongside the laboratory DTMAM for the purpose of comparison but limited to the only laboratory achievable process product quality capability maturity assessment programmes. This is because of its direct and laboratory testable physical, mechanical, electrical, and chemical properties and characteristics. Moreover, the validity of this SDTMAM will depend on the important factors to be considered by the researcher and ensured considerably below.

i. The amount of resources and variables the assessor is prepared to include, and the degree of rigor of the appraisal exercise, the data size. It can be highly demanding. Hence a resilient researcher is needed. Therefore, sure must be made during preparation, budgeting and planning that all the research requirements and demands are tried to be met and adequately provided to

avoid situations of deficiency or lack.

ii. The level of expertise of the appraisal team or participants involvement, hence the more, the more validation results get.

iii. Clarity of the performance indicators and the objective evidence as the is a need for good understanding of the process capability areas.

iv. The amount of the researcher's knowledge about the technology and process to assess. This is very crucial to the entire project.

v. Research data target, and the method of collection must be well known to avoid west of time and resources.

vi. How to process the data to achieve the desired results as some tools and methodologies are better and more suitable for a particular project.

vii. Analysis and further application of the statistical results to further research as the results can still be used to energize subsequent or adjoining process model.

Thus, it is expected that the university should undertake and upgrade second implementation of the model after validation of the methodology to a postdoctoral or research fellowship project.

2.4.1.3 *Indirect Custom Technological Maturity Assessment Methodology (ICTMAM)*

The ICTMAM is the act of using any other possible artistic technological maturity assessment means. A kind of approach [28, 29, 30], where researchers apply some kinds of personalized or individual novel or genre concepts that deem logical and meaningful for mostly custom set objectives. A situation whereby any imagined or abstract phenomena can be substantiated and adapted as variables to make sense of the research data and collection. The custom here implies as concerns or suits the researcher to express or communicate his ideas. In this methodology, a researcher chooses not using smart variables of direct engineering or economic relevance to define his data, type, and parameters.

Moreover, the methodology applied by the authors above really depends on the aim and objectives of their individual research project, what they want to achieve and how to go about it. Hence, the type or nature of

data, the method or techniques of data collection, data processing and analyses. However, in the case of the SDTMAM, the process product quality, process efficiency, and the process effectiveness are studied, investigated and evaluated systematically for the desired outcome. Otherwise, outside these three focused variables of the technological maturity assessment, what research variable could have been smarter. Hence, the research data type, source and information were observed revolving around and within three major process areas of concerns and interests in the manufacturing technology. Thus, embedding all information and material resources for the technological maturity assessment model, and widely seen composed of and bound in hybrid manufacturing technology products design, manufacturability, hybrid manufacturing technology process design, processes selection and planning activities, which dominate the research information and data source of hybrid manufacturing processes resources.

2.4.2 Technological Resources for the modelling

Additive and hybrid manufacturing technologies are certainly integral parts and major factors in the TMA modelling project. Having given a good background to the study, which is the outcome and measure that ensures a more direct and comprehensive HMT maturity model and application. Thus, state-of-the-art technology capabilities, exploits, and challenges ascribed to processes and products are established. Also, the technology capability areas, parametric variables and key performances indices from hybrid manufacturing technology research and findings are articulated as in the appendices 5, 6, 7, 8, 9. Subsequently, from where the research propositions required to guide and drive the design, questionnaires, data and implementation of the new model are generated as in tables 12, 22 and 32.

2.4.3 Observation from Literature Review and Background of Studies

Several models have been developed and employed in the recent years based on process-product-market economy. But the capability maturity profile, Technology Readiness Levels, and the Technology Lifecycle States are all in human language or words. They are vague and ambiguous, which means that there is a need to first defuzzify to be converted to near or some quantified numerical values. Then, applying the fuzzy logic

in developing a strict but more encompassing experts survey questionnaire that will lead to a very tight scientific and classical numerical data values required for the appraisal.

However, in all the methodologies stated above, it is observed that none of the researchers considered the linguistic nature or phenomena of the subject maturity with respect to the models' structural components. Both maturity and the profile are vague to such that they are required to be defuzzified for a more precise expert survey questionnaire result. Thus, the Crisp and binary logic applied in the models are not enough for a thorough or realizable assessment. This is considering and providing for the intermediary states of maturity of some process areas and maturity or performance indicators.

Therefore, to capture and consider the vagueness of the human words characteristics of the word maturity, and the maturity profile right from inception, artificial intelligence fuzzy logic theory is applied in the design of the questionnaire to cover and take care of all the lapses resulting from the human linguistic variable of the models as possible. This action will naturally create reference and solid foundation for the subsequent degree of belongingness or degree of membership function during the data processing and analysis of the maturity ranking. However, as the process quality approach has come to dominate the industry rather than the product-market-customer economy, hence the quality of a product depends on the how the process that produced it was conceived, designed, or prepared, and managed. It is by this knowledge that the maturity assessment of hybrid manufacturing technology is decided to be focused on the hybrid manufacturing process, but in relation with the product cum market situation report of the time. Finally, the Fuzzy Set Theory is used to check for the compatibility, complementarity, and the unionism of the naturally and carefully selected process areas of product quality, efficiency, and effectiveness capability performance variables.

Also, the compatibility and complementarity assessed by Pierre's was based on the products perceived current data from the Research and Development (R&D). When the assessment would have been better carried out with the results or the data from the expert's survey as in SDTMAM instead of quoting a probable outdated product parametric value of a time.

CHAPTER 3

PROPOSED ASSESSMENT MODEL OF ADDITIVE HYBRID MANUFACTURING TECHNOLOGY

The idea of a Semi-Direct technological maturity assessment methodology (SDTMAM) was conceived and proposed for development. It is the process that guided the development and design of the generic model for technological maturity assessment of hybrid manufacturing technologies. An artificial intelligence semi-direct approach, which combines the functions of the capability maturity model integration (CMMI), fuzzy logic and fuzzy set theories in the strategic maturity assessment of a hybrid manufacturing technology. Thus, it is called a semi-direct in the sense of the nature and type of research data, the source of data, and the method of data collection. However, as illustrated in Figure 22 below, the proposed two manufacturing processes operating in a single hybrid manufacturing cell.

3.1 Process assessment consideration

During the process assessment planning, the following factors were determined and considered.

1. The scope of the technology under study. In this case, a hybrid metal manufacturing to start with.

2. The processes to be considered are the CNC Machining and PBF manufacturing processes, prompted by industry attention on the PBF AM having been having more process and product challenges.

3. Process variables, parameters, performance indicators and the key performance indices

4. The membership of the appraisal team. In this case, a mixed (internal and external).

5. Project to be named, a hybrid manufacturing technology that integrates metal additive manufacturing

and CNC machining processes.

6. Target individuals to be interviewed. In this case, about 150 respondents among experts and professionals, researchers including engineers and technologists in the additive and hybrid metal manufacturing, and related fields, mostly from academia, industry and technology research institutes.

Thus, the assessment method is designed to provide benchmark quality ratings of Hybrid manufacturing processes, and the expected outcomes will be,

1. Capability maturity level ratings

2. Findings that describe the strengths and weaknesses of the hybrid manufacturing processes.
3. Consensus with respect to technology key process issues or limitations.

4. An appraisal database that can continue to be used to monitor process improvement progress and to support future assessments.

Figure 22. Hybrid manufacturing technology

Thus, capabilities of each of the hybrid manufacturing processes in figure 22 above, or technologies are classified into a single or a few variables or process areas, depending on the expected research scope. Each of the process areas is defined based on the aim and objective of the research and linked to the associated capability parameters which show or measure the process capability performance as in the table 2 below.

Table 2. Identification of process capability area and performance indicators

Serial No.	Manufacturing Process Capability Area
	Capability Performance Parameters
1	CPP1
2	CPP2
3	CPP3
4	CPP4
5	CPP5

They serve as the industry process performance index or the process capability performance indicators. Under the process area and process performance indicators are verifiable research investigative propositional statements. The statements are derived from the process present state and militating conditions or recorded challenges and wins of the technology over time. They revolve around or cover all aspects of manufacturing engineering practices, 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 process capability area. This is purposely to conduct a survey for the primary research data collection. Fuzzy logic theory is applied considering the methodology and the desired result. Hence, since the maturity and the CMMI maturity profile are all in human words, which are all linguistic variables, there is a need to check the vagueness and imperfection of human bias decision and judgement. Hence, the maturity and the CMMI profiles are simplified or fuzzified as in the Table 3 below.

Table 3. Fuzzification of Maturity and question response

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

Syntax = A Set of the linguistic Terms and numerical figures adopted in the research as shown in the Table 4.

Below.

Table 4. Illustration of relationship between linguistic terms and numerical figures

Fuzzy Set Linguistic Variable (Maturity) Difuzzification					
CMM Terms	Initial	Managed	Defined	Quantitatively Managed	Optimizing
CMM 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

It relies on the technology typical work 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. The hybrid metal manufacturing process maturity assessment methodology is designed using the Capability Maturity Model Integration as a reference framework and Fuzzy System Theory evaluation and analysis. The process model is made up of major components which form the tools utilized in the implementation of manufacturing process appraisals.

A set of questionnaire propositions and statements from the process work areas was planned, designed, and developed based on the principles of Fuzzy logic as in Table 5. This is due to the human and linguistic nature of the maturity and the model's variables. The fuzzy theory was introduced in the definitions and sourcing of research data, analysis, and operation of the model.

MATURITY = Linguistic variable

Fuzzification of Linguistic Variables

Table 5. Fuzzy Expert's Survey Capability Maturity Questionnaire Model

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					

It explains the maturity based CMMI model, and the truth-based survey response model. The data collected were further processed and put to statistical analyses, followed with ranking along the CMMI profile as the base model to represent each process maturity assessment result. Each of the 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 6.

Table 6. Process maturity ranking framework

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

Survey conducted for each of the hybrid processes, the data collected was further processed on individual process bases. Hence, the maturity assessment results are 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) capability areas experts' survey data.

Having determined each class capability maturity levels for the processes, then the expected capability maturity levels 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, 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.

3.2 Determining the Membership Functions

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. Furthermore, a common universe of discourse (X) is decided and applied for each of the processes, as shown in the figure 23 below.

Figure 23. 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 HM processes as illustrated above.

Thus, a set of maturity subsets are established with some familiar descriptors, to determine the membership functions of the subsets as in the figure 4 above. Defining the membership functions for each set of the inputs and output descriptors, a triangular membership function is applied in 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. 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.

The criteria that guided the choice of a triangular membership functions include,

a. The nature of the variables
b. The resolution and level of details to be included
c. The nature of applications
d. The design and optimization suitability
e. The concepts to represent the variables

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 4 above. Where equations 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.

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

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

Therefore, for the Process Input (1) IM membership function (µIM),

If $y_1 = 1$, $x_1 = 0$, and $y_2 = 0$, $x_2 = x_1$

Then, µIM = $\frac{x_1 - x}{x_1}$ $[0, x_1]$

For the Process Input (1) NQM membership function (µNQM),

If $y_1 = 0$, $x_1 = 0$, and $y_2 = 1$, $x_2 = x_1$

Then, µNQM = $\frac{x}{x_1}$ $[0, x_1]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_1$, and $y_2 = 0$, $x_2 = x_2$

Then, μNQM = $\frac{x_2 - x}{x_2 - x_1}$ $[x_1, x_2]$ ---------- Second part

Which implies,

μNQM = $\frac{x}{x_1}$ $[0, x_1]$, $\frac{x_2 - x}{x_2 - x_1}$ $[x_1, x_2]$

For the Process Input (1) FM membership function (μFM),

If $y_1 = 0$, $x_1 = x_1$, and $y_2 = 1$, $x_2 = x_2$

Then, μFM = $\frac{x - x_1}{x_2 - x_1}$ $[x_1, x_2]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_2$, and $y_2 = 0$, $x_2 = x_3$

Then, μFM = $\frac{-x + x_3}{x_3 - x_2}$ $[x_2, x_3]$ ---------- Second part

Which implies,

μFM = $\frac{x - x_1}{x_2 - x_1}$ $[x_1, x_2]$, $\frac{-x + x_3}{x_3 - x_2}$ $[x_2, x_3]$

For the Process Input (1) M membership function (μM),

If $y_1 = 0$, $x_1 = x_2$, and $y_2 = 1$, $x_2 = x_3$

Then, μM = $\frac{x - x_2}{x_3 - x_2}$ $[x_2, x_3]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_3$, and $y_2 = 0$, $x_2 = x_4$

Then, μM = $\frac{x_4 - x}{x_4 - x_3}$ $[x_3, x_4]$ ---------- Second part

Which implies,

μM = $\frac{x - x_2}{x_3 - x_2}$ $[x_2, x_3]$, $\frac{x_4 - x}{x_4 - x_3}$ $[x_3, x_4]$

For the Process Input (1) WM membership function (μWM),

If $y_1 = 0$, $x_1 = x_3$, and $y_2 = 1$, $x_2 = x_4$

Then, μWM = $\frac{x - x_3}{x_4 - x_3}$ $[x_3, x_4]$

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 = $\frac{x - x_3}{x_4 - x_3}$ $[x_3, x_4]$

Thus, on the same hand for the membership functions of the Input (2) fuzzy subset, the same equation of straight line is applied accordingly as,

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

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

Therefore, for the Process Input (1) P membership function (μP),

If $y_1 = 1$, $x_1 = 0$, and $y_2 = 0$, $x_2 = x_1$

Then, μP = $\frac{x_1 - x}{x_1}$ $[0, x_1]$

For the Process Input (1) NQG membership function (μNQG),

If $y_1 = 0$, $x_1 = 0$, and $y_2 = 1$, $x_2 = x_1$

Then, μNQG = $\frac{x}{x_1}$ $[0, x_1]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_1$, and $y_2 = 0$, $x_2 = x_2$

Then, μNQG = $\frac{x_2 - x}{x_2 - x_1}$ $[x_1, x_2]$ ---------- Second part

Which implies,

μNQG = $\frac{x}{x_1}$ $[0, x_1]$, $\frac{x_2 - x}{x_2 - x_1}$ $[x_1, x_2]$

For the Process Input (1) FG membership function (μFG),

If $y_1 = 0$, $x_1 = x_1$, and $y_2 = 1$, $x_2 = x_2$

Then, μFG = $\frac{x - x_1}{x_2 - x_1}$ $[x_1, x_2]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_2$, and $y_2 = 0$, $x_2 = x_3$

Then, μFG = $\frac{-x + x_3}{x_3 - x_2}$ $[x_2, x_3]$ ---------- Second part

Which implies,

μFG = $\frac{x - x_1}{x_2 - x_1}$ $[x_1, x_2]$, $\frac{-x + x_3}{x_3 - x_2}$ $[x_2, x_3]$

For the Process Input (1) G membership function (μG),

If $y_1 = 0$, $x_1 = x_2$, and $y_2 = 1$, $x_2 = x_3$

Then, μG = $\frac{x - x_2}{x_3 - x_2}$ $[x_2, x_3]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_3$, and $y_2 = 0$, $x_2 = x_4$

Then, μG = $\frac{x_4 - x}{x_4 - x_3}$ $[x_3, x_4]$ ---------- Second part

Which implies,

μG = $\frac{x - x_2}{x_3 - x_2}$ $[x_2, x_3]$, $\frac{x_4 - x}{x_4 - x_3}$ $[x_3, x_4]$

For the Process Input (1) VG membership function (μVG),

If $y_1 = 0$, $x_1 = x_3$, and $y_2 = 1$, $x_2 = x_4$

Then, μVG = $\frac{x - x_3}{x_4 - x_3}$ $[x_3, x_4]$

Therefore, the membership functions for each of the input (1) 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 of the Output fuzzy subset, are equally determined using the same equation of straight line as applied to others.

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

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

Therefore, for the Process Output IN membership function (μIN),

If $y_1 = 1$, $x_1 = 0$, and $y_2 = 0$, $x_2 = x_1$

- Then, μIN = $\frac{x_1 - x}{x_1}$ $[0, x_1]$

For the Process Output MAN membership function (μMAN),

If $y_1 = 0$, $x_1 = 0$, and $y_2 = 1$, $x_2 = x_1$

Then, μMAN = $\frac{x}{x_1}$ $[0, x_1]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_1$, and $y_2 = 0$, $x_2 = x_2$

Then, μMAN = $\frac{x_2 - x}{x_2 - x_1}$ $[x_1, x_2]$ ---------- Second part

Which implies,

μMAN = $\frac{x}{x_1}$ $[0, x_1]$, $\frac{x_2 - x}{x_2 - x_1}$ $[x_1, x_2]$

For the Process Output DEF membership function (μDEF),

If $y_1 = 0$, $x_1 = x_1$, and $y_2 = 1$, $x_2 = x_2$

Then, μDEF = $\frac{x - x_1}{x_2 - x_1}$ $[x_1, x_2]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_2$, and $y_2 = 0$, $x_2 = x_3$

Then, μDEF = $\frac{-x + x_3}{x_3 - x_2}$ $[x_2, x_3]$ ---------- Second part

Which implies,

μDEF = $\frac{x - x_1}{x_2 - x_1}$ $[x_1, x_2]$, $\frac{-x + x_3}{x_3 - x_2}$ $[x_2, x_3]$

For the Process Output QMAN membership function (μQMAN),

If $y_1 = 0$, $x_1 = x_2$, and $y_2 = 1$, $x_2 = x_3$

Then, μQMAN = $\frac{x - x_2}{x_3 - x_2}$ $[x_2, x_3]$ ---------- First part,

and if $y_1 = 1$, $x_1 = x_3$, and $y_2 = 0$, $x_2 = x_4$

Then, μQMAN= $\frac{x_4 - x}{x_4 - x_3}$ $[x_3, x_4]$ ---------- Second part

Which implies,

μQMAN = $\frac{x - x_2}{x_3 - x_2}$ $[x_2, x_3]$, $\frac{x_4 - x}{x_4 - x_3}$ $[x_3, x_4]$

For the Processes Output OPTIM membership function (μOPTIM),

If $y_1 = 0$, $x_1 = x_3$, and $y_2 = 1$, $x_2 = x_4$

Then, μOPTIM = $\frac{x - x_3}{x_4 - x_3}$ $[x_3, x_4]$

Therefore, 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

$\mu FM = [x_3 - x/x_3 - x_2 = x_3 - \dot{x}_1/x_3 - x_2]$ and $\mu M = [x - x_2/x_3 - x_2 = \dot{x}_1 - x_2/x_3 - x_2]$ --------- Process A

$\mu FG = [x_3 - x/x_3 - x_2 = x_3 - \dot{x}_2/x_3 - x_2]$ and $\mu G = [x - x_2/x_3 - x_2 = \dot{x}_2 - x_2/x_3 - x_2]$ ----------Process B

3.3 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 7 Below

Table 7. 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

3.4 Implementation of TMA Fuzzy Inference Rules

Therefore, to determine what the output will be for each mapping, a rule base is developed and run based on the HMT professional and expertise hypothetical knowledge of the compatibility and complementarity of the Inputs (1) and (2), and the corresponding expected output.

Hence, each of the three sets is represented by its descriptors in table 8 as follows,

Table 8. Implementation of AHMT Professionals and Experts
TMA Fuzzy inference rules

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 (1)	QMAN (2)	OPTIM	**DEF**
G	IN	MAN	DEF (3)	QMAN (4)	OPTIM	**QMAN**
VG	IN	MAN	DEF	QMAN	OPTIM	**OPTIM**

Remembering that 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 FG and G. Then, fuzzification and evaluation of the rules imply.

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

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

3.5 Graphical Technique Inference for the Inputs and Output

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

Figure 24. 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.

$\frac{y_2-y_1}{x_2-x_1} = \frac{y-y_1}{x-x_1}$, 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

3.6 Presentation of Results

Thus, results will be presented as summarized in the table 9 below.

Table 9. Presentation of TMA of Machining-LPBF Additive HMT Results

Processes Capability Performance Maturity Assessment																	
Process Product Quality Maturity Level						Process Efficiency Maturity Level						Process Effectiveness Maturity Level					
LPBF		*Machining*		*HMT*		*LPBF*		*Machining*		*HMT*		*LPBF*		*Machining*		*HMT*	
ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage

3.7 Algorithm of a Generic Technological Maturity Assessment of Hybrid Manufacturing Technologies

Figure 25. Algorithm of generic TMA of HMT as explained in steps in table 10 below.

3.8 The Schematic Representation of The Semi-Direct Technological Maturity Assessment Research Methodology

For the newly designed generic model for technological maturity assessment of hybrid manufacturing technology the steps shown in table 10 were taken from the SDTMAM algorithm illustrated in figure 25 above.

Table 10. Schematic Representation of the Semi-Direct Technological Maturity Assessment Research Methodology

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 maturity results were independently fuzzified into five subsets each*
10.	*Step10.*	*Membership functions were created and assigned to the Inputs and Output fuzzy subsets.*
11	*Step11.*	*Manual execution of Fuzzy inference rules processes subsets*
12	*Step12.*	*Defuzzification of each of the results was carried out with engineering mathematical model for exact maturity level results by applying a centroid defuzzification method*

13	*Step13.*	*Simulation of results in fuzzy logic system by artificial intelligence (AI) fuzzy command line functions, and by using a graphical user interface for the simulated results from AI*
14	*Step14.*	*Presentation and analyses of results*

The model is to be implemented on a hybrid manufacturing technology that integrates laser powder bed fusion manufacturing and CNC machining technology, for possible validation.

Then, the fuzzy set theory is used in the second phase of the research to determine the operational compatibility test models for the processes under hybrid manufacturing technology. They shall include the processes complementarity, union, intersection, and differences. The compatibility is a very important factor in HMT. It is normally referred to during hybrid manufacturing process design stage.

3.9 Design and Development of a Compatibility Test Model for Hybrid Manufacturing Technology

3.9.1 Hybrid Manufacturing Processes Compatibility Test Model

The need to make the right or best choice of processes for hybrid manufacturing platform has led to the thinking of developing and designing of an applicable hybrid manufacturing processes compatibility test model. However, the compatibility in this study is based on the maturity levels of the two manufacturing processes, and their subsequent results or outputs. This model when completed will be useful in the industry hybrid manufacturing technologies processes and products design, operations management for the technological and product improvement, productivity, and sustainability.

3.9.2 Research Methodology for HM Processes Maturity Compatibilities

The maturity parametric compatibility test model of the hybrid manufacturing processes by the application of the fuzzy logic and sets theory on the capability maturity results. Hence, the compatibility depends on the outcome of their union, complementarity, intersection or interface, and differences in their maturity levels. However, when the compatibility is based on the maturity levels of the two manufacturing processes, and the corresponding result or output of their union (U)

This implies that $MP_1ML_1UMP_2ML_2$ = HMPML

Where MP_1ML_1 = Manufacturing Process (1) Maturity Level (1)

And MP_2ML_2 = Manufacturing Process (2) Maturity Level (2)

Then, HMPML = Hybrid Manufacturing Process Maturity Level (the output of the union).

Also, based on the complementarity of the complements of the maturity of the same two manufacturing processes, it will imply,

1 - MP_1ML_1, and 1 – MP_2ML_2, respectively, and each representing the membership function (μ) or value of each of the manufacturing process maturity value or level.

Whereas the maturity intersection (∩) of the two manufacturing processes will also imply, $MP_1ML_1 \cap MP_2ML_2$ = HMPML

Hence, the maturity complementarity of the union of the manufacturing processes, and that of the intersection of the manufacturing processes are to be considered for determination.

Thus, the difference between the maturity levels of the two manufacturing processes (A and B) as well will imply, $MP_1ML_1 – MP_2ML_2$

But for the difference between the maturity levels of the two manufacturing processes (B and A) will now be, MP_2ML_2 - MP_1ML_1, which is entirely a different outcome.

Meanwhile, in the design and implementation of a model for testing the compatibility of hybrid manufacturing technology, introducing fuzzy logic, and set theories to the conventional arithmetical or numerical formulae will energize and enhance the process quality and outcome model.

Thus, considering the hybrid manufacturing process maturity level (HMPML) output of the union of two fuzzy inputs (1) and (2) of the manufacturing processes (A) and (B) respectively, where the membership functions (μ) lie between 0 and 1, such μ = {0 ≥ Ƶ ≤ 1}, and Ƶ = μ

Figure 26. The Output of the compatibility test by graphical technique of inference model for hybrid manufacturing processes of fuzzy sets Input (1) and Input (2).

From the above, figure 26 is an integrated graphical representation of fuzzy logic and set theories applications whereby the compatibility of the two fuzzy sets (Input (1) and (2)) in the universe of discourse (X) Є [0, x1, x2, x3, x4, x5] can be defined by the output of the union, complementarity, intersection, and differences of the hybrid manufacturing processes maturity fuzzy sets input (1) and input (2) with the subset descriptors; A, B, C, D, E and K, T, H, G, F respectively for the output; IN, MAN, DEF, QMAN, OPTIM

Therefore,

3.9.3 The Union of Maturity Levels of Hybrid Manufacturing Processes

The output of the union of the fuzzy sets of Input (1) and Input (2) above in the universe of discourse (X) Є [0, x1, x2, x3, x4, x5] is defined as follows,

$\mu_{Input\ (1) \cup Input\ (2)}(x) = \max[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (i)

3.9.4 The Complement of Maturity Levels of Hybrid Manufacturing Processes

The Output of the Complement of the Fuzzy sets of Input (1) and Input (2) above,

(i) Independently defined as the fuzzy set Input (1) complement in the universe of discourse (X) Є [0, x1, x2, x3, x4, x5] whose membership function is defined as follows;

$\mu_{Input\ (1)\ complement}(x) = [1 - \mu_{Input\ (1)}(x)]\ \forall_x \in X$ ---------- Eqn. (ii)

and;

$\mu_{Input\ (2)\ complement}(x) = [1 - \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (iii)

The complement of a fuzzy set should contain all elements along with their membership values from the universe of discourse (X)

(ii) Applying the DE Morgan's Law of union for fuzzy sets Input (1) and Input (2) with the universe of discourse (X) Є [0, x1, x2, x3, x4, x5], the complement of the union of the fuzzy sets Input (1) and Input (2) implies that,

Input (1)∪Input (2) complt = Input (1)complt∩Input (2) complt

Where the membership function values of, Input (1)∪Input (2) complt, and the Input (1)complt∩Input (2) complt, are defined as,

Input (1)∪Input (2) complt = $1 - \max[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ------- Eqn. (iv)

and;

Input (1)complt∩Input (2) complt = min[$\mu_{Input\ (1)\ complt}(x)$, $\mu_{Input\ (2)\ complt}(x)$] $\forall_x \in X$

---------- Eqn. (v)

(iii) Also, going by the DE Morgan's law of intersection, it implies that, for fuzzy Input (1) and Input (2) sets with the universe of discourse (X) Є [0,80], the complement of Input (1) and Input (2) intersection, ie;

[(Input (1)∩Input (2))complt] = Input (1)compltuInput (2)complt

Thus, the membership function values of,

[(Input (1)∩Input (2))complt] and Input (1)compltuInput (2)complt, are defined as;

[(Input (1)∩Input (2))complt] = 1 – min[$\mu_{Input\ (1)}(x)$,$\mu_{Input\ (2)}(x)$] $\forall_x \in X$

---------- Eqn. (vi)

and;

Input (1)compltuInput (2)complt = max[$\mu_{Input\ (1)\ complt}(x)$, $\mu_{Input\ (2)\ complt}(x)$] $\forall_x \in X$ ----------

---------- Eqn. (vii)

3.9.5 The Differences (A) and (B) between the Maturity Levels of Hybrid Manufacturing Processes

A. The Output of the Deference between the Fuzzy Input (1) and Input (2) sets above, with the membership function values $\mu_{Input\ (1)}(x)$ and $\mu_{Input\ (2)}(x)$ respectively in the universe of discourse (X) Є [0, x1, x2, x3, x4, x5] will imply;

$\mu_{Input\ (1)|Input\ (2)}(x) = \min[\mu_{Input\ (1)}(x), \mu_{Input\ (2)\ complt}(x)]\ \forall_x \in X$ ---------- Eqn. (viii)

B. The Output of the Deference between the Fuzzy Input (2) and Input (1) sets above, with the membership function values $\mu_{Input\ (2)}(x)$ and $\mu_{Input\ (1)}(x)$ respectively in the universe of discourse (X) Є [0, x1, x2, x3, x4, x5] will imply;

$\mu_{Input\ (2)|Input\ (1)}(x) = \min[\mu_{Input\ (2)}(x), \mu_{Input\ (1)\ complt}(x)]\ \forall_x \in X$ ---------- Eqn. (ix)

3.9.6 The Intersection of the Maturity Levels of Hybrid Manufacturing Processes

The Output of the Intersection of the Fuzzy Input (1) and Input (2) sets above with the membership function values $\mu_{Input\ (2)}(x)$ and $\mu_{Input\ (1)}(x)$ respectively in the universe of discourse (X) Є [0, x1, x2, x3, x4, x5] will represent all elements for which the corresponding membership values can be computed by;

$\mu_{Input\ (1) \cap Input\ (2)}(x) = \min[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (x)

CHAPTER 4

REQUIREMENT FOR IMPLEMENTATION OF GENERIC TECHNOLOGICAL MATURITY ASSESSMENT MODEL FOR HYBRID MANUFACTURING TECHNOLOGY THAT INTEGRATES METAL ADDITIVE MANUFACTURING PROCESSES

The implementation of the technological maturity assessment model of hybrid manufacturing technologies should commence with the introduction of the metal Hybrid Manufacturing Technology, and identification of the manufacturing process operational parameters for study and investigation. In this case, a CNC Machining-PBF Hybrid Manufacturing, process and product parameters. The choice of CNC machining and powder bed fusion (PBF) performance indicators are required to be guided by coordinated and articulate industry and commercial activities, practices and goals that target the manufactured products, economic and the machine or in more direct terms, the process effectiveness and efficiency performance capabilities based on prevailing parametric values. However, there should be characterization of process work areas through reading, workshops, and conferences, which must tend towards achieving the current capabilities of the state-of-the-art manufacturing technology. The process capabilities, which will be used as a measure of hybrid manufacturing technology or process industry performance in terms process product quality, process efficiency and process effectiveness as categorized. For example, the ability of the process to produce or attain products of desired or a particular level of product qualities, which manifest in the product dimensional accuracy, surface roughness, repeatability, precision, and tolerance. These form part of the process parameters, process performance indicators shown in the appendices 5 and 6, which were transformed or used to create the process key performance indices utilized in the construction of the questionnaires research statements for experts' survey. Hence, to achieve or attain any of these capabilities, there may exist some process or work areas that require more attention or a need for improvement.

Therefore, the key performance indices of the two hybrid processes as important are first determined. Then,

further categorized for reasons of clarity and ease of data management as relates under three independent process capability areas of (i) process product quality, (ii) process efficiency, and (iii) process effectiveness as shown in the appendices 7, 8, and 9 respectively for generation of independent maturity assessment research statement or propositions of questionnaires.

Meanwhile, Characterization of the CMMI model is necessary to be able to relate the maturity levels of each process capability performance indicator. Then, there is a need for a questionnaire as the research interface tools to be used in the experts' survey and research data collection programme.

These exercises will require expert and professional contributions, where responses that should be backed with the industry objective evidence will be collected and data synthesized. The statistical and mathematical analysis of data collected will be carried out and results to be shown. Here, the present process or technology state or maturity ranks and analysis are to be shown represented in the reference CMMI maturity profile utilized. However, the results obtained at this level is fuzzy, hence still not precise or accurate as desires to be. Therefore, there will be a need to use the statistical variables to create and simulate some fuzzy sets of terms and values. The fuzzy set of values are required to be first characterized and positioned symmetrically along the capability maturity model integration (CMMI) profile. Such as from the CMMI components linguistic variables to numerical variables. ie; Characterizing the CMMI model, fuzzy logic and set theory, then to simulate and run the new model. Also, there will be a need to determine the graphical properties and representations through the system's universe of discourse, degree of membership or belongingness, by applying the fuzzy logic toolbox in MATLAB. However, the same principles of fuzzy logic and set theory are to be extended in the design and development of the processes' compatibility test model, which will be conducted while trying to establish the compatibility, complementarity, Intersection or interface, union of the hybrid manufacturing processes. Finally, the models will be test run or implemented to find out the current maturity level of the process in terms of the product quality, efficiency, and effectiveness. Then, followed by the analysis of the results.

Therefore, by traversing the metal additive and hybrid manufacturing technology to identify, extract and collate the technology laboratory, process, material and human resources, design, product, commercial, customer and consumer information, various performance issues and gains statements. Those challenges that are preventing the attainment of the desired technology destination, the progresses and breakthroughs. Then, associating, grouping according to relationships and meanings of terms, and eliminating the same. Thus, they were afterwards, used to establish the technology performance indices. Incidentally, these challenges turned performance indicators were naturally observed came out revolving around the three process capability areas of product quality, process efficiency, and process effectiveness. With their independent phenomenal parameters, these performance indices, grouped, matched or mapped, were used to coin and generate constructive research statements or propositions that were applied in the expert's survey questionnaires, designed with the knowledge and principles of digital technology, artificial intelligence fuzzy logic theory, and set theory. Thus, representing the initial research survey interface tool for the technological maturity assessment of hybrid manufacturing technology. Thus, the aim is to find out which among these challenges still exists over certain period, and to what extent has each condition been either improved or deteriorated.

However, decision was first made on the data type and definition of data. Also, decided upon is the design for the interface tools as illustrated in the fuzzy maturity assessment questionnaire design framework table 11 below, as well the modelling scope, and the requirements for the proposed Semi-Direct technological maturity assessment methodology.

First, decision was made on the data type and definition of data. Also, decided is the design for the interface tools and modelling scope, as well, the requirements for the proposed Semi-Direct technological maturity assessment methodology.

4.1 Semi-Direct technological maturity assessment methodology

Whereas, in this research, the objective is to design a different or new systematic and strategic generic model for technological assessment of additive hybrid manufacturing technology. This means that the model will on completion have the capability of assessing every other manufacturing technology or technology in general once the process areas and performance indices of such technologies are known and established for the research. Thus, the model will be designed, and test run very good on the named technologies. Then, simulate the results afterwards for an expected outcome, which should be the same as with the manually or engineering mathematically calculated values.

The model designed and utilized is a procedural and iterative model that uses artificial intelligence (AI), knowledge of HMT data and software engineering to assess the technological maturity of metal additive hybrid manufacturing technologies. It combined the CMMI maturity profile, principles of statistical science, fuzzy logic system and set theory to source and process maturity information or data from the two processes individually, and in hybrid manufacturing process outcome.

In this research, CMMI maturity profile only is adopted and utilized as the criteria milestone for the semi-direct technological maturity assessment methodology. Where each of the CMMI stratum serves as reference criteria and qualification to provide for the technological maturity assessment rating. It also serves as a framework to optimize or improve on process stratum. Successful application of the model relies on the characterization of each of the components of the model to match research need and constraints. The SDTMAM model is very adaptive, hence can be rephrased or tinkered in more than one fuzzy form and set as might be required to cover about eight main stages or steps of the new additive HMT maturity assessment model namely, determination of the research parametric variables and scope, questionnaire development, design, and administration stage, research survey and collection of data, statistical processing, and analysis stage, building and simulating fuzzy logic system stage. All the same, it will be applicable to more technological areas, products, processes, systems, development et al of known performance indices. However, having compared with other models, components, especially the areas of application, capability

areas and parameters which detects the size and trajectory of the model, it was realized that none could drive my research and logic of my imaginative methodology and variable. Efforts were made outside the academia, towards getting critical clues from the industry professionals and experts about the logic behind the CMMI model software operations and application but failed due to the secrecy that is still shrouded in the industry. The CMMI model, being an advanced digital business model, also like the AM HMT, being a new and cutting-edge technology, it was a real fight and struggle among 'suspected jealous stakeholders or competitors' to enjoy the provisions by the diversity, inclusion and equality acts of the technology and business field. This was noticed leading to hoarding of knowledge, technical and material information of the additive and hybrid manufacturing technology. Also, the same with the CMMI expertise too, among the industry stakeholders. Thus, the CMMI software was not accessible, and efforts made to secure a training session from the CMMI consultants failed. With this experience, there was an attempt to dump the CMMI profile at a point for an entirely new and personal model, and maturity profile because of the frustration, but for more direct, clear terms, diversity and flexibility of procedure, the choice for only the CMMI strata was made. The CMMI maturity profile was then applied because of the SEI popularity, strategic application, and coverage, in other to draw much attention to the new SDTMAM model. The choice was as well guided by the observed SMART (specific, measurable, achievable, realistic, and timely) attributes. Also considered are the merits of the Semi-Direct technological maturity assessment methodology which include.

1. The historical background, the adopted CMMI maturity profile having been developed by Carnegie Mellon University, Software Engineering Institute (SEI), and sponsored by the U.S. Defence Department. It has since been applied at a very high industry and global stage with results.
2. The set of the strata and variables are more meticulously articulated.
3. It is real, with clear or familiar industry terms and condition, composed of measurable and monitorable variables.
4. It is more comprehensive and demonstrates some validity through the second round of expert survey.

5. The structure is made of real and imaginable components that guide sound unbiased judgement.
6. The number of the model strata is five. It is moderate, hence makes a sizable and manageable statistical data analysis.
7. The model is inclusive in nature.

Table 11. Fuzzy Maturity Assessment Questionnaire Design framework

The Generic Technological Maturity Assessment of Hybrid Manufacturing Technology Data Interface/Tools (Questionnaire)							
S/No	*Survey Statements/Proposition*	Experts' Response/Answer					Maturity Level (ML)
		Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*	
1							
2							
3							
4							

4.2 A Generic Model for TMA of Additive Hybrid Manufacturing Technology

In the development and design of the technology maturity assessment model of the hybrid manufacturing technology, also for the obvious reasons, the capability maturity profile of the CMMI of the Software Engineering Institute is utilized as the reference strata for the design and implementation of the proposed model. The two manufacturing processes in hybrid manufacturing process are named as Process (A) and Process (B). The performance indices of the two processes are determined. From engineering and economic points of views as shown, they a classified under three process capability areas; (1) the process product quality, (2) process efficiency, and (3) process effectiveness.

However, due to the linguistic relationship between process efficiency and the process effectiveness, variables were strictly characterized, and each parameter also classified. Hence, the five membership functions of the fuzzy subset descriptors for process efficiency Input (1) are carefully and peculiarly defined and considered from Very Low (VL) to Very High (VH), and the Input (2) are chosen from Minimum (M) to Maximizing (MMZ). Whereas those for the five membership functions of the fuzzy subset descriptors for process effectiveness Input (1) are also carefully and peculiarly defined and considered from Not Well (NW) to Very Well (VW), while the Input (2) are chosen from Not Dependable (ND) to Highly Dependable (HD). Thus, these varied sets of descriptors each possesses some peculiar or unique quanta of guide and control

of experts' judgement and maintains right decision as close as possible in the survey throughout. Moreover, the vague nature of the linguistic variables of the CMM profile necessitated consideration for application of fuzzy logic in the development, planning, and design of multiple response or optional answers questionnaires. Commencing with certain number of process capability area-based research statements or propositions. These statements generated are to be classified under three categories of the process capability areas (PCA) of PPQ, PE, and PEffec., as observed relate at the time for a systematic and clearer expert survey programme. Also, to ensure a wholesome process and more valid data, the questionnaire will be jointly and directly administered to the AM and HMT professionals and experts' respondents across the academia, industry, and research institutes scope as planned to cover. The survey, when conducted, and the questionnaires returned, the data will be collected and segregated or classified on basis of the professionals and experts' respondent areas of specialties. This will be as suggested or shown by the three process capability areas or variables having made provisions for respondents' employment data. Thus, leveraging from the knowledge of principal component analysis, the returned questionnaires will be grouped under the quality and manufacturing engineers, production and cost engineers, and the design and process engineers' groups of respondents across the three industries of academia, industry, and the research institute. Finally, the survey data will then be processed either on individual independent or on a joint combined process capability area bases as shown in the last stage of the questionnaire administration and data schematic of figure 27 below. Therefore, for the purpose of this research as the first in the manufacturing domain of AM and HMT, and clarity reasons, the survey was opted to be carried out on the individual independent PCA bases, and data serially processed one after the other. Hence, the maturity assessment results are statistically analyzed and presented with the mean, median, mode, range, difference, standard deviation (S), and the variance etc., for each of the processes A and B capability areas experts' survey data.

Having determined each class capability maturity levels for the processes A and B, then the expected capability maturity levels of the hybrid process A + B, will imply that a set of each of the processes (A) and

(B) capability maturity variables, becomes the inputs variables, while the output variables by default will be the product of the hybrid manufacturing process. Hence, for segregation and clarity, the five subsets of each of the inputs and the output maturity variables were substituted and mapped with five sets of related descriptors each accordingly.

4.3 Questionnaires Administration and Data Plan

Figure 27. Questionnaires administration and data plan schematic

Where:

x, y, and z: Represent the Segregated Research Statements.

x_1, y_1, and z_1: Represent the Questionnaires

x_2, y_2, and z_2: Represent the Participants

x_3, y_3, and z_3: Represent the Returned Questionnaires

GX1, GX2, and GX3: Represent the 1st, 2nd, and 3rd Group Respondents for PPQ

GY1, GY2, and GY3: Represent the 1st, 2nd, and 3rd Group Respondents for PE

GZ1, GZ2, and GZ3: Represent the 1st, 2nd, and 3rd Group Respondents for PEffec.

However, to source and collect the primary data needed in the research, an online questionnaire was chosen, due to the COVID-19 pandemic total lockdown at the time. A pre-survey contacts of the identified recipients should be first made, followed by the questionnaires which will be emailed with a covering letter drafted, promising and assuring anonymity to the participants as in the appendix 10. Survey will be solely conducted electronically through a self-administered one hundred (100) internet mediated questionnaires having duly observed and ensured the general operating guidelines or netiquette.

4.4 Determining the Membership Functions

Thus, a set of maturity subsets are established with some familiar descriptors, to determine the membership functions of the subsets as in the figure 23 above. Defining the membership functions for each set of the inputs and output descriptors, a triangular membership function is applied in the three fuzzy subsets. The PBF process (Input 1) subset descriptors; IM, NQM, FM, M, WM. The Machining process (Input 2) subset descriptors; P, NQG, FG, G, VG. The Hybrid manufacturing process (Output) subset descriptors; IN, MAN, DEF, QMAN, OPTIM. 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.

The criteria that guided the choice of a triangular membership functions include,

1. The nature of the CMMI profile, and the process capability variables, which are in human words, linguistic and vague.
2. The resolution and level of details to be included are covered in the more detailed triangular membership functions, hence it was used in examples shown, which seems it is either the best or the easiest.
3. The nature of applications, well represent both fuzzy logic and set theory requirements of the research.
4. The design and optimization suitability having the triangular membership of fuzzy set descriptors of the elements stretched along but within the universe of discourse of maturity. This can be adjusted either by increasing the number of elements in the universe of discourse or vice versa.
5. The concepts and the capacity to physically show or represent the entire variables maturity levels.

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 23 above too. Where equations of the straight line are used to determine the membership functions for all the inputs and output descriptors and their corresponding membership values as follow.

4.5 Technological Maturity Assessment of Hybrid Manufacturing Technology that Integrates Metal PBF Additive Manufacturing and CNC Machining Processes

4.5.1 Product Quality

For the process product quality as one of the measures of process capability and maturity, covering the achievable dimensional accuracy, surface roughness, tolerance, repeatability status of the manufacturing

processes. It is as the degree whether good or bad in terms of physical appearance and related characteristics.

Thus, if the capability of machining technology or process is determined by its manufacturable or achievable product characteristics such as (i) dimensional accuracy (ii) surface roughness (iii) precision or repeatability and (iv) tolerance, they can be considered the technology capability parameters. Also considering the commonness of these machined product characteristics with that of the additively manufactured products, they also can be termed or taken as the interface, which can as well be the basis for measurement and comparison among manufacturing processes or technology capabilities. Thus, it is by this relationship and validity of the analysis that the capability maturity model integration (CMMI) is adapted as the maturity profile for a scientific technology maturity assessment of hybrid manufacturing technologies.

4.5.1.1 *Survey Questionnaire for Process Product Quality TMA*

As a result of the Semi-Direct technological maturity assessment methodology approach of the assessment, the vague nature of the linguistic variable product quality, and the maturity necessitated the introduction of artificial intelligence fuzzy logic principle in the design, planning and administration of a questionnaire for expert survey, and collection of research data in table 12 below. To take care of various degrees of technology developmental stages or states, which the binary questionnaire response cannot cover. The questionnaire is designed as a group based, such that each 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. To ensure and improve the reliability and confidence of research, the questionnaire was directly emailed to the targeted professionals and experts' respondents drawn from the field of additive and hybrid manufacturing. A situation where, based on the research variable of PPQ, and importance of specialty, the related quality and manufacturing engineers in the midst were marked and sub-grouped as main target. Then, with the knowledge of principal component analysis, and to achieve a better manageable data size, the 63 questionnaires returned within the stipulated time frame were sorted and classified under three employers' groups within the first; academia, second; industry, and third; research institutes of the

respondents. This was based on the employment data provided in the questionnaires, which includes current positions of the respondents. Thus, data collected was processed as presented in the appendices 11, 12, 13 and 17, for Powder Bed Fusion and appendices 14, 15, 16 and 17, for the CNC Machining processes under hybrid manufacturing cell. The algorithm of the maturity assessment of the PPQ for the metal AHMT is as shown in the schematic figure 28 below. Whereas the results and analyses of the initial experts' survey primary data are as represented and explained in the tables 13, 14, 15, 16, 17 and 18, and the figures 29, 30, 31, 32, 33, 34 and 35 below.

Table 12. Experts' Survey Questionnaire for Processes Product Quality TMA with research statements jointly produced from various AM and HMT publications referenced below. See appendices 5, 6, 7, 8 and 9 also.

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					

[18, 19, 20, 21, 22, 23, 24, 25, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 79, 80, 81, 82, 86, 87, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 102, 103, 104, 105, 106, 107]

4.5.1.2 *Algorithm of Process Product Quality Technological Maturity Assessment of HMT that Integrate Metal PBF Additive Manufacturing and CNC Machining Processes*

Figure 28. Product quality TMA of HMT as explained in the schematic illustration in table 10 above.

4.5.1.3 *Process Product Quality Maturity Profile of Each of The Technologies*

Table 13. Process Product Quality Capability maturity ranking framework 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**	
2 Process Managed	Basic Process Management	-	-
1 Process Initiated	Process is informal and Adhoc	No Process Area	

Table 14. Statistical results of Product Quality TMA

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

Figure 29. The normal probability test plot of LPBFPPQ maturity data on Minitab.

Figure 30. Histogram of LPBFPPQ maturity graph

Figure 31. Boxplot of LPBFPPQ maturity.

In summary, figure 29 as shown in the results for Anderson-Darling (AD), the probability value; P-Value is less than 0.05. This means strong evidence against the null hypothesis (H0). Also, the data do not follow a normal distribution and H0 is rejected. Thus, the test is statistically significant. However, figure 31 is showing the data spread. Whereas in table 14 above, the Minimum (mini) maturity level (ML), 1st Quartile (Q1), the

Median, 3rd Quartile (Q3), and the Maximum (max) ML, with a range of 1.3300, and the interquartile range (IQR), 0.4150. Which means that the middle 50% of the maturity spread only has a variability of 0.4150ML

Table 15. Process Product Quality capability maturity ranking framework 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	

Table 16. Statistical results of Product Quality TMA

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

Figure 32. The normal probability test plot of

CNC MPPQ maturity data on Minitab.

Figure 33. Histogram of CNC MPPQ maturity graph

Figure 34. Boxplot of CNC MPPQ maturity.

Figure 35. A double Boxplot for a set of LPBFPPQ maturity And CNC MPPQ maturity data.

Method

μ_1: population mean of LPBFPPQ Maturity
μ_2: population mean of MPPQ Maturity
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Table 17. 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

Summarily, in figure 32 as shown in the results for Anderson-Darling (AD), the probability value; P-Value is less than 0.05. This means strong evidence against the null hypothesis (H_0). Also, the data do not follow a

normal distribution and H_0 is rejected. Thus, the test is statistically significant. Whereas figure 34 is showing the data spread. When in table 16 above, the Minimum (mini) maturity level (ML), 1st Quartile (Q1), the Median, 3rd Quartile (Q3), and the Maximum (max) ML, with a range of 1.670, and the interquartile range (IQR), 0.745. Which means that the middle 50% of the maturity spread only has a variability of 0.745. Finally, the double boxplot of figure 35 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.

Thus, going forward from the statistical analysis results of the two technologies, the maturity levels and the percentage maturity of the processes are the two cluster means as in the Table 18 below

Table 18. Product Quality TMA Results

Process Product Quality Maturity Level			
LPBF		***Machining***	
ML	%tage	ML	%tage
3.16	63.2	3.94	78.8

Therefore, if both classical or crisp maturity levels are as obtained, then there is a need to also determine the degree or the extent of truth in it or the extent that it is true. This leads to the introduction of membership functions.

4.5.1.4 *Determining the Membership Functions*

Thus, a set of maturity subsets are established with some familiar descriptors, to determine the membership functions of the subsets as in the figures 36, 37, 38 and 39 below. Defining the membership functions for

each set of the inputs and output descriptors, a triangular membership function is applied in the three fuzzy subsets. The LPBF process subset descriptors; IM, NQM, FM, M, WM. The Machining process subset descriptors; P, NQG, FG, G, VG. The Hybrid manufacturing Output subset descriptors: IN, MAN, DEF, QMAN, OPTIM. 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.

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

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

Input (1)

Figure 36. Element of the PPQ Input 1 universe of discuss

Therefore, in determining the membership function (μ) for Immature (IM), with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

20μ = 20 – x

μ = 20 – x/20

Therefore, μIM = 20 –x/20 [0,20]

For the membership function (μ) for NQM, involves two cases.

Range from [0,20] and Range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x$

$\mu = x/20$

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, μNQM = x/20 [0,20], 40 – x/20 [20,40]

For the membership function (μ) for FM, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 20$

$\mu = x - 20/20$

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 60$

$\mu = 60 – x/20$

Therefore, $\mu FM = x - 20/20$ [20,40], $60 – x/20$ [40,60]

For the membership function (μ) for M, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

Therefore, $\mu M = x - 40/20$ [40,60], $80 – x/20$ [60,80]

For the membership function (μ) for WM, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 60$

$\mu = x - 60/20$

Therefore, $\mu WM = x - 60/20$ [60,80]

Summarily, we have.

- $\mu IM = 20 –x/20$ [0,20]
- $\mu NQM = x/20$ [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 37. Elements of the PPQ Input 2 universe of discuss

For the membership functions of the Input (2) fuzzy subset, the same equation of straight line is applied.

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

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

Therefore, in determining the membership function (μ) for Poor (P), with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

$20\mu = 20 – x$

$\mu = 20 – x/20$

Therefore, $\mu P = 20 –x/20$ [0,20]

For the membership function (μ) for NQG, involves two cases.

Range from [0,20] and Range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x$

$\mu = x/20$

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, $\mu NQG = x/20$ [0,20], $40 – x/20$ [20,40]

For the membership function (μ) for FG, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 20$

$\mu = x - 20/20$

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 60$

$\mu = 60 – x/20$

Therefore, $\mu FG = x - 20/20$ [20,40], $60 – x/20$ [40,60]

For the membership function (μ) for G, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

Therefore, $\mu G = x - 40/20$ [40,60], $80 – x/20$ [60,80]

For the membership function (μ) for VG, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 60$

$\mu = x - 60/20$

Therefore, $\mu VG = x - 60/20$ [60,80]

Accordingly, the membership functions of Input (2) are as determined and summarized below.

- 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).

If the maturity of the Input (1) is = 63.2%, then, the membership function (μ) from the graph will be at the 63.2% of 80 (Universe of discourse).

Which implies; 63.2/100 x 80 = 51

Thus, it falls between the range [40,60] as illustrated above

On the same hand, if the maturity of the Input (2) is 78.8%,

Then, the membership function (μ) from the graph will be at 78.8% of 80 (Universe of discourse) as thus,

78.8/100 x 80 = 64

Thus, as well, falls between the range [40,60] as illustrated above.

Therefore, striking out the rest in Input (1), it implies that,

- μFM = 60 – x/20 [40,60], where x = 51
- μM = x - 40/20 [40,60], where x = 51

On the same hand, striking the rest in Input (2)

- $\mu G = 80 – x/20$ [60,80], where x = 64
- $\mu VG = x - 60/20$ [60,80], where x = 64

Therefore, the membership functions of Input (1); FM and M will be as stated below.

$\mu FM = 60 – x/20 = 60 – 51/20 = 0.45$

$\mu FM = 0.45$

Then,

$\mu M = x - 40/20 = 51 – 40/20 = 0.55$

$\mu M = 0.55$

Whereas the membership functions of Input (2); G and VG are as well

$\mu G = 80 – x/20 = 80 – 64/20 = 0.8$

$\mu G = 0.8$

Then,

$\mu VG = x - 60/20 = 64 – 60/20 = 0.2$

$\mu VG = 0.2$

Therefore,

→ 63.2% of 80 = 50.56% ≈ 51%

Also,

→ 78.8% of 80 = 63.04% ≈ 64%

Figure 38. 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 19. below.

Table 19. 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 39. Membership functions of PPQ Output

For the membership functions of the Output fuzzy subset, the same equation of straight line is applied.

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

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

Therefore, in determining the membership function (μ) for Initial (IN), with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

20μ = 20 – x

μ = 20 – x/20

Therefore, μIN = 20 –x/20 [0,20]

For the membership function (μ) for MAN, involves two cases.

Range from [0,20] and Range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x$

$\mu = x/20$

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, $\mu MAN = x/20$ [0,20], $40 – x/20$ [20,40]

For the membership function (μ) for DEF, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 20$

$\mu = x - 20/20$

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 60$

$\mu = 60 – x/20$

Therefore, $\mu DEF = x - 20/20$ [20,40], $60 – x/20$ [40,60]

For the membership function (μ) for QMAN, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

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

For the membership function (μ) for OPTIM, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 60$

$\mu = x - 60/20$

Therefore, μOPTIM = x - 60/20 [60,80]

Summarily, we have.

- 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]

4.5.1.5 *Process Product Quality Professional and Expert Inferences*

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 professional and expert knowledge of the compatibility and complementarity of the two processes inputs, a rule base system is developed and applied as in the Table 20. below. The system enables one of the entrusted 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.

Table 20. 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 below to obtain the required maturity level of the Output.

Figure 40. 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 maturity value of the processes pair Inputs and Output value, a centroid method is applied as in the figure 41 below, and finally defuzzifying the value (Z*).

Therefore, applying the Centroid Defuzzification method;

Figure 41. 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

Therefore, **<u>ab</u>** implies,

$y_1 = 0$, $x_1 = 20$

$y_2 = 0.45$, $x_2 = 28$

Then, 8y = 0.45x – 9

y = 0.45x – 9/8 [20,28]

<u>bc</u> = y = 0.45 [28,48]

<u>cd</u> implies,

$y_1 = 0.45$, $x_1 = 48$

$y_2 = 0.55$, $x_2 = 52$

4y = 0.1x - 3

y = 0.1x - 3/4 [48,52]

<u>de</u> = y = 0.55 [52,68]

Then, for **<u>ef</u>**,

$y_1 = 0.55$, $x_1 = 68$

$y_2 = 0$, $x_2 = 80$

12y = -0.55x + 44

y = -0.55x + 44/12 [68,80]

4.5.1.6 *Process Product Quality Defuzzification of the fuzzy Set Inference Output Result*

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

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

Appendix 18 shows the engineering mathematical calculations and result for the complex system geometries. Hence the technological maturity for PPQ is the result of the defuzzification of the shaded portion of the graphical figure 41.

4.5.1.7 *Process Product Quality Maturity Assessment Results Simulations in Fuzzy Logic System*

Figure 42. The Rule Viewer Output format in a fuzzy logic system toolbox in MATLAB.

Figure 43. The Surface Viewer Output format in fuzzy logic system toolbox in MATLAB.

Figure 44. Surface Viewer: Processes PQ Maturity for two axes
CNC machining and HMT MLs only

Figure 45. Surface Viewer: Processes PQ Maturity for two axes
PBF AM and HMT MLs only

In summary, figure 42 above shows a dynamic inference process for the fuzzy process product quality 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. Whereas figure 43 that follows shows a static three-dimensional graphical mapping of combination of the Inputs 1 and 2, and the Output process product quality 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.

4.5.1.8 *Fuzzy Logic Command Line Functions for the AM (LPBF), Machining, and HM Processes Product Quality Maturity.*

```
[System]
Name='processes_product_quality_maturity'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=4
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='am_process'
Range=[0 80]
NumMFs=5
MF1='im':'trimf',[-20 0 20]
MF2='nqm':'trimf',[0 20 40]
MF3='fm':'trimf',[20 40 60]
MF4='m':'trimf',[40 60 80]
MF5='wm':'trimf',[60 80 100]

[Input2]
Name='machining_process'
Range=[0 80]
NumMFs=5
MF1='p':'trimf',[-20 0 20]
MF2='nqg':'trimf',[0 20 40]
MF3='fg':'trimf',[20 40 60]
MF4='g':'trimf',[40 60 80]
MF5='vg':'trimf',[60 80 100]



[Output1]
Name='hm_technology'
Range=[0 80]
NumMFs=5
MF1='in':'trimf',[-20 0 20]
MF2='man':'trimf',[0 20 40]
MF3='def':'trimf',[20 40 60]
MF4='qman':'trimf',[40 60 80]
MF5='optim':'trimf',[60 80 100]

[Rules]
3 4, 3 (1) : 1
3 5, 3 (1) : 1
4 4, 4 (1) : 1
4 5, 4 (1) : 1
```

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

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

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

4.5.1.9 *Analysis of Processes Product Quality ML*

The technological maturity level of the hybrid manufacturing technology with respect to the process product quality (PPQ) is as follows and in the table 21 below.

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

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

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

The HMT maturity for PPQ is therefore at 63.5%

Table 21. Processes Product Quality MLs

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

4.5.2 Efficiency

Process Efficiency as a measure of the manufacturing process economy of cost of production, quantity or volume of production, and production cycle or time effectiveness within a production cycle of hybrid manufacturing technology. It is as the degree, whether high or low in terms of productivity and gains. However, because of the indirect methodology approach of the assessment, the vague nature of the linguistic variable process efficiency, and the maturity. Fuzzy logic principle is applied in the design, planning and administration of a questionnaire to obtain expert survey opinion, and the collection of research data in table 22. below. This also takes care of various degrees of technology developmental stages, which the binary questionnaire answers cannot handle or will not be able to cover.

4.5.2.1 *Experts' Survey Questionnaire for Process Efficiency TMA of HMT*

A group-based questionnaire is designed such that each process efficiency capability performance survey statement has up to five-gravitating optional answers. These include the Not true, Not quite true, Fairly true, True, and Very true. To ensure and improve the reliability and confidence of research, the questionnaire was directly emailed to the targeted professionals and experts' respondents drawn from the field of additive and hybrid manufacturing. A situation where, based on the research variable of PPE, and importance of specialty, the related production and cost engineers in the midst were marked and sub-grouped as main target. Then, with the knowledge of principal component analysis, and to achieve a better manageable data size, the 63 questionnaires returned within the stipulated time frame were sorted and classified under three employers' groups within the first; academia, second; industry, and third; research institutes of the respondents. This was based on the employment data provided in the questionnaires, which includes current positions. Thus, data collected was processed as presented in the appendices 19, 20, 21 and 25, for Powder Bed Fusion and appendices 22, 23, 24 and 25, for the CNC Machining process under hybrid manufacturing cell. The algorithm of the maturity assessment of the PE for the metal AHMT is as shown in the schematic figure 46 below.

Whereas the results and analyses of the initial experts' survey primary data are as represented and explained in the tables 23, 24, 25, 26, 27 and 28, and the figures 47, 48, 49, 50, 51, 52 and 53 below.

Table 22. Experts' Survey Questionnaire for Processes Efficiency TMA with research statements jointly produced from various AM and HMT publications referenced below. See appendices 5, 6, 7, 8 and 9 also.

Survey Questionnaire for HMT Process Efficiency Capability Performance						
S/No	***Research Statement/Proposition***	***Not True***	***Not Quite True***	***Fairly True***	***True.***	***Very True***
1	Full implementation of additive manufacturing process in terms of process planning has been fulfilled					
2	Process operational space requirement has been minimized					
3	The number of personnel or operator requirement has reduced					
4	The investment capital rating and requirements has reasonably dwindled					
5	There are proven means of achieving a substantial reduction in the cost of final part					
6	The material efficiency target of 97% has been attained, in terms of reduction in energy demand, reducing the emissions and other environmental impacts of the industry					
7	There is enough investment in the approaches that optimise material management					
8	There are practices established to minimize the generation of waste in the manufacturing process					
9	There is a standard methodology for process planning in manufacturing					
10	There is a software tool solution in design, process planning and part inspection in the technology					
11	Engineers and designers mindsets have been focused on the priority area of product quality or customers based					
12	The process has been able to deliver or attained business values					
13	There are no potential financial risks associated with investing in the process					
14	There is a system in place to minimize down time					
15	The process has become off the shelve technology					
16	The cost of maintenance is at minimal					
17	There are now reductions in the cost of human and material resources					
18	There are systems available to enhance the performance of the manufacturing facilities					
19	The manufacturing process is coping with the growing product varieties					
20	The number of original equipment manufacturers (OEM) has gone more than 50					
21	The technology now require a low capital investment					
22	There is a recorded time reduction in production cycle					
23	The process manufactured products are readily available and affordable					
24	The industrial demand for the process is getting higher					
25	The process of introducing the technology and products into the general market has been successful					
26	There exists a financial risk assessment system for potential investors					
27	There are new application areas developed for the process					
28	The process make use of largely or mostly automatic equipment					
29	There is a systematic instrument to determine and evaluate the potential effects of an interruption to critical manufacturing operations as a result of fluctuation or failure of resources; power, energy etc					
30	The process quantitative production run or workproduct target has been attained					
31	The business need of the manufacturing process has been identified and well understood					
32	The measure of the process profitability has been satisfactory					
33	The number of the process manufactured product defect free unit or pieces is optimized					
34	Complex qeometric parts now produced without much human intervention					

[18, 19, 20, 21, 22, 23, 24, 25, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 79, 80, 81, 82, 86, 87, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 102, 103, 104, 105, 106, 107]

4.5.2.2 *Algorithm of Process Efficiency Technological Maturity Assessment of HMT that Integrate Metal Additive Manufacturing Processes*

Figure 46. Algorithm of efficiency TMA of HMT as explained in the schematics in table 10 above.

4.5.2.3 *Process Efficiency Technological Maturity Profile of Each of The Technologies*

Table 23. Process Efficiency capability maturity ranking framework for LPBF

Level	Focus	Process Capability Area	Result
5 Process Optimizing	Continuous Process Improvement	-	-
4 Process Quantitatively Managed	Process Quantitatively Managed	**2, 3, 5, 8, 10, 11, 12, 14, 18, 19, 24, 26, 27, 28, 29, 31, 32, 34**	
3 Process Defined	Process Standardization	**1, 4, 6, 7, 9, 13, 15, 16, 17, 20, 21, 22, 23, 25, 30, 33**	
2 Process Managed	Basic Process Management	-	-
1 Process Initiated	Process is informal and Adhoc	No Process Area	

Table 24. LPBF Efficiency TMA Statistical Results

Variable	Total Count	Percent	Mean	StDev	Variance	Sum	Minimum	Q1
LPBFPE Maturity	34	100	3.4215	0.4943	0.2443	116.3300	2.6700	3.0000

Variable	Median	Q3	Maximum	Range
LPBFPE Maturity	3.3300	4.0000	4.0000	1.3300

Figure 47. The normal probability test plot of LPBFPE maturity data on Minitab.

Figure 48. Histogram of LPBFPE maturity

Figure 49. Boxplot of LPBFPE maturity.

In summary, in figure 47 as shown in the results for Anderson-Darling (AD), the probability value; P-Value is less than Alpha value, 0.05. This means strong evidence against the null hypothesis (H_0). Also, the data do not follow a normal distribution and H_0 is rejected. Thus, the test is statistically significant. Where figure 49

is showing the data spread. Thus, in table 24 above, the Minimum (mini) maturity level (ML), 1st Quartile (Q1), the Median, 3rd Quartile (Q3), and the Maximum (max) ML, with a range of 1.3300, and the interquartile range (IQR), 1.0000. Which means that the middle 50% of the maturity spread only has a variability of 1.0000

Table 25. Process Efficiency Capability maturity ranking framework for CNC Machining

Level	Focus	Process Capability Area	Result
5 Process Optimizing	Continuous Process Improvement	**1**	-
4 Process Quantitatively Managed	Process Quantitatively Managed	**2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 17, 18, 20, 22, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33**	
3 Process Defined	Process Standardization	**13, 16, 19, 21, 23, 34**	
2 Process Managed	Basic Process Management	-	-
1 Process Initiated	Process is informal and Adhoc	No Process Area	

Table 26. Machining Efficiency TMA Statistical Results

Variable	Total Count	Percent	Mean	StDev	Variance	Sum	Minimum	Q1
MPE Maturity	34	100	3.7062	0.4473	0.2001	126.0100	2.6700	3.3300

Variable	Median	Q3	Maximum	Range
MPE Maturity	4.0000	4.0000	4.3300	1.6600

Figure 50. The normal probability test plot of CNC MPE maturity data on Minitab.

Figure 51. Histogram of CNC MPE maturity

Figure 52. Boxplot of CNC MPE maturity.

Figure 53. A double Boxplot for a set of LPBFPE maturity and CNC MPE maturity data.

Method

μ_1: population mean of LPBFPE Maturity
μ_2: population mean of MPE Maturity
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Table 27. Descriptive Statistics of HMTs

Sample	N	Mean	StDev	SE Mean
LPBFPE Maturity	34	3.421	0.494	0.085
MPE Maturity	34	3.706	0.447	0.077

Estimation for Difference

Difference	95% CI for Difference
-0.285	(-0.513, 0.056)

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
-2.49	65	0.015

In summary, figure 50 as shown in the results for Anderson-Darling (AD), the probability value; P-Value is less than Alpha value 0.05. This means strong evidence against the null hypothesis (H_0). Also, the data do not follow a normal distribution and H_0 is rejected. Thus, the test is statistically significant. Where figure 52 boxplot is showing the data spread. Then, in table 26 above, the Minimum (mini) maturity level (ML), 1st Quartile (Q1), the Median, 3rd Quartile (Q3), and the Maximum (max) ML, with a range of 1.6600, and the interquartile range (IQR), 0.6700. Which means that the middle 50% of the maturity spread only has a variability of 0.6700. Finally, the double boxplot of figure 53, means that the LPBFPE maturity with the bigger box shows that data is less concentrated in the area, therefore, has more variability than the MPE maturity. Thus, comparing their individual data spread, the Range shows that the CNC MPE has more spread out. Also, on their Interquartile Range (IQR), the LPBFPE data has more variability than the CNC MPE.

Thus, from the statistical analysis results of the two technologies under assessment, the maturity levels, and the percentage maturity of the two manufacturing processes are the two cluster means as in the table 28 below

Table 28. Efficiency TMA Results

Process Efficiency Maturity Level			
LPBF		***Machining***	
ML	%tage	ML	%tage
3.42	68.5	3.71	74.2

Therefore, if both classical or crisp maturity levels are as obtained, then there is a need to also determine the degree or the extent of truth in it or how true is it. This leads to the introduction of membership functions.

4.5.2.4 *Determining the Membership Functions of the Results*

To find the membership functions of the results, a set of maturity subsets are established with some related descriptors, to determine the membership functions of the subsets as in the figures 54, 55, 56 and 57 below. Defining the membership functions for each set of the inputs and output descriptors, a triangular membership function is applied in the three fuzzy subsets. The LPBF process (Input 1) subset descriptors; Very Low (VL), Low (L), Not Quite Low (NQL), High (H), Very High (VH). The Machining process (Input 2) subset descriptors; Minimum (M), Minimax (MMA), Maximin (MAMI), Maximum (MAX), Maximizing (MMZ). The Hybrid manufacturing Output subset descriptors: Initial (IN), Managed (MAN), Defined (DEF), Quantitatively Managed (QMAN), Optimizing (OPTIM). Where equation of the straight line is used to determine the membership functions for all the descriptors and their corresponding membership values as follows.

$\frac{y_2-y_1}{x_2-x_1} = \frac{y-y_1}{x-x_1}$ ----------(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 54. Elements of efficiency Input 1 universe of discuss

Therefore, in determining the membership function (μ) for (VL), with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

$20\mu = 20 - x$

$\mu = 20 - x/20$

Therefore, $\mu VL = 20 - x/20$ [0,20]

For the membership function (μ) for L, involves two cases.

Range from [0,20] and Range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x$

$\mu = x/20$

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, $\mu L = x/20$ [0,20], $40 – x/20$ [20,40]

For the membership function (μ) for NQL, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 20$

$\mu = x - 20/20$

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 60$

$\mu = 60 – x/20$

Therefore, μNQL = x - 20/20 [20,40], 60 – x/20 [40,60]

For the membership function (μ) for H, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

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

For the membership function (μ) for VH, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

20μ = x - 60

μ = x - 60/20

Therefore, μVH = x - 60/20 [60,80]

Summarily, we have.

- μVL = 20 –x/20 [0,20]
- μL = x/20 [0,20], 40 – x/20 [20,40]
- μNQL = x - 20/20 [20,40], 60 – x/20 [40,60]
- μH = x - 40/20 [40,60], 80 – x/20 [60,80]
- μVH = x - 60/20 [60,80]

Input (2)

Figure 55. Elements of efficiency Input 2 universe of discuss

For the membership functions of the Input (2) fuzzy subset, the same equation of straight line is applied.

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

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

Therefore, in determining the membership function (μ) for MIN, with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

20μ = 20 – x

μ = 20 – x/20

Therefore, μMIN = 20 –x/20 [0,20]

For the membership function (μ) for MMA, involves two cases.

Range from [0,20] and Range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

20μ = x

μ = x/20

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, μMMA = x/20 [0,20], 40 – x/20 [20,40]

For the membership function (μ) for MAMI, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 20$

$\mu = x - 20/20$

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 60$

$\mu = 60 – x/20$

Therefore, μMAMI = x - 20/20 [20,40], 60 – x/20 [40,60]

For the membership function (μ) for MAX, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

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

For the membership function (μ) for MMZ, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

20μ = x - 60

μ = x - 60/20

Therefore, μMMZ = x - 60/20 [60,80]

Accordingly, the membership functions of Input (2) are as determined and summarized below.

- μMIN = 20 –x/20 [0,20]
- μMMA = x/20 [0,20], 40 – x/20 [20,40]
- μMAMI = x - 20/20 [20,40], 60 – x/20 [40,60]
- μMAX = x - 40/20 [40,60], 80 – x/20 [60,80]
- μMMZ = 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).

It implies that when the maturity of the Input (1) is = 68.5%, then, the membership function (μ) from the graph will be at the 68.5% of 80 (Universe of discourse).

Therefore, 68.5/100 x 80 = 54.8 ≈ 55

Thus, it falls between the range [40,60] as illustrated above

On the same hand, if the maturity of the Input (2) is 74.2%,

Then, the membership function (μ) from the graph will be at 74.2% of 80 (Universe of discourse) as thus,

74.2/100 x 80 = 59.36 ≈ 60

Thus, as well, falls between the range [40,60] as illustrated above.

Therefore, striking out the rest in Input (1), it implies that,

- μNQL = 60 – x/20 [40,60], where x = 55
- μH = x - 40/20 [40,60], where x = 55

On the same hand, striking the rest in Input (2)

- μMAMI = 60 – x/20 [40,60], where x = 60
- μMAX = x - 40/20 [40,60], 80 – x/20 [60,80] where x = 60
- μMMZ = x - 60/20 [60,80]

Therefore, the membership functions of Input (1); NQL and H will be as stated below.

μNQL = 60 – x/20 = 60 – 55/20 = 0.25

μNQL = 0.25

Then,

μH = x - 40/20 = 55 – 40/20 = 0.75

μH = 0.75

Whereas the membership functions of Input (2); MAMI and MAX are as well

µMAMI = 60 – x/20 = 60 – 60/20 = 0

µMAMI = 0

Then,

µMAX = x - 40/20 = 60 – 40/20 = 1

µMAX = 1

Also, when µMAX = 80 – x/20 = 80 – 60/20 = 1

µMMZ = x - 60/20 = 60 – 60/20 = 0

Therefore,

Input 1 → 68.5% of 80 = 55

Also,

Input 2 → 74.2% of 80 = 60

Figure 56. Membership functions values of efficiency Inputs

Thus, forming the mapping between the different inputs, their membership values are associated and matched. Each of them to each other, and an eight-rule base is obtained as in table 29 below.

Table 29. Eight-rule base of Efficiency TMA Inputs

Rule 1	Input (1) NQL (0.25)	Input (2) MAMI (0)
Rule 2	Input (1) NQL (0.25)	Input (2) MAX (1)
Rule 3	Input (1) NQL (0.25)	Input (2) MAX (1)
Rule 4	Input (1) NQL (0.25)	Input (2) MMZ (0)
Rule 5	Input (1) H (0.75)	Input (2) MAMI (0)
Rule 6	Input (1) H (0.75)	Input (2) MAX (1)
Rule 7	Input (1) H (0.75)	Input (2) MAX (1)
Rule 8	Input (1) H (0.75)	Input (2) MMZ (0)

Output

Figure 57. Membership functions values of process efficiency TMA Output

For the membership functions of the Output fuzzy subset, the same equation of straight line is applied.

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

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

Therefore, in determining the membership function (μ) for Initial (IN), with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

$20\mu = 20 – x$

$\mu = 20 – x/20$

Therefore, μIN = 20 –x/20 [0,20]

For the membership function (μ) for MAN, involves two cases.

Range from [0,20] and Range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x$

$\mu = x/20$

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, μMAN = x/20 [0,20], 40 – x/20 [20,40]

For the membership function (μ) for DEF, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

20μ = x - 20

μ = x - 20/20

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

20μ = - x + 60

μ = 60 – x/20

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

For the membership function (μ) for QMAN, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

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

For the membership function (μ) for OPTIM, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 60$

$\mu = x - 60/20$

Therefore, μOPTIM = x - 60/20 [60,80]

Summarily, we have.

- 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]

4.5.2.5 *Process Efficiency Professional and Expert Inferences*

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 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: VL, LOW, NQL, H, VH

The Input (2) subset descriptors: MIN, MMA, MAMI, MAX, MMZ

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

Thus, with the metal additive hybrid manufacturing professional and expert knowledge of the compatibility and complementarity of the two processes inputs, a rule base system is developed and applied as in the table 30 below. The system enables one of the entrusted Production and Cost 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.

Table 30. Fuzzy inference rules of the TMA Inputs and Output

Input 1/2	**VL**	**L**	**NQL**	**H**	**VH**	Output
MIN	IN	IN	IN	IN	IN	**IN**
MMA	IN	IN	MAN	MAN	MAN	**MAN**
MAMI	IN	IN	MAN	MAN	MAN	**DEF**
MAX	IN	MAN	DEF	QMAN	OPTIM	**QMAN**
MMZ	IN	MAN	DEF	QMAN	OPTIM	**OPTIM**

Hence, the membership functions of Input (1) are within the range of NQL and H, while the membership functions of Input (2) are within the range of MAMI, MAX and MMZ.

Then, fuzzification and evaluation of the rules imply.

Rule 1: If the Input (1) is NQL, and the Input (2) is MAMI, then the Output, which is the hybrid Inputs (1) and (2) efficiency maturity is Managed (MAN).

Rule 2: If the Input (1) is NQL, and the Input (2) is MAX, then the Output, which is the hybrid Inputs (1) and (2) efficiency maturity is Defined (DEF).

Rule 3: If the Input (1) is NQL, and the Input (2) is MMZ, then the Output, which is the hybrid Inputs (1) and (2) efficiency maturity is Defined (DEF).

Rule 4: If the Input (1) is H, and the Input (2) is MAMI, then the Output, which is the hybrid Inputs (1) and (2) efficiency maturity is Managed (MAN).

Rule 5: If the Input (1) is H, and the Input (2) is MAX, then the Output, which is the hybrid Inputs (1) and (2)

efficiency maturity is Quantitatively Managed (QMAN).

Rule 6: If the Input (1) is H, and the Input (2) is MMZ, then the Output, which is the hybrid Inputs (1) and (2) efficiency maturity is Quantitatively Managed (QMAN).

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

Figure 58. Manual graphical technique of inference of process efficiency 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 maturity value of the hybrid process Inputs Output value, a centroid method is applied as in the figure 59. below and finally, defuzzifying the value (Z*).

Therefore, applying the Centroid Defuzzification method.

Figure 59. Fuzzy process efficiency 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

Therefore, **<u>ab</u>** implies,

$y_1 = 0$, $x_1 = 0$

$y_2 = 0$, $x_2 = 20$

Then, 20y - 0 = 0

y = 0 [0,20]

<u>bc</u> implies,

$y_1 = 0$, $x_1 = 20$

$y_2 = 0.25$, $x_2 = 25$

5y = 0.25x – 5

y = 0.25x – 5/5 [20,25]

<u>cd</u> implies,

$y_1 = 0.25$, $x_1 = 25$

$y_2 = 0.25$, $x_2 = 45$

20y = 5

y = 0.25 [25,45]

<u>de</u> implies,

$y_1 = 0.25$, $x_1 = 45$

$y_2 = 0.75$, $x_2 = 55$

10y = 0.5x – 20

y = 0.5x – 20/10 [45,55]

<u>ef</u> implies,

$y_1 = 0.75$, $x_1 = 55$

$y_2 = 0.75$, $x_2 = 65$

10y = 7.5

y = 0.75 [55,65]

Then for **<u>fg</u>**,

$y_1 = 0.75$, $x_1 = 65$

$y_2 = 0$, $x_2 = 80$

15y = -0.75x + 60

y = -0.75x + 60/15 [80,65]

4.5.2.6 *Process Efficiency Defuzzification of the fuzzy Set Inference Output Result*

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

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

Appendix 26 shows the engineering mathematical calculations and result for the complex system geometries. Hence the technological maturity for PE is the result of the defuzzification of the shaded portion of the graphical figure 59.

4.5.2.7 *Process Efficiency Maturity Assessment Results Simulations in Fuzzy Logic System*

Figure 60. The Rule Viewer output format in a fuzzy logic system toolbox in MATLAB.

Figure 61. The Surface Viewer output format in fuzzy logic system toolbox in MATLAB.

Figure 62. Surface Viewer: Processes efficiency maturity for two axes LPBF and HMT MLs only

Figure 63. Surface Viewer: Processes efficiency maturity for two axes CNC machining and HMT MLs only

To summarise, figure 60 above shows a dynamic inference process for the fuzzy process efficiency 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. Whereas the following figure 61 shows a static three-dimensional graphical mapping of combination of the Inputs 1 and 2, and the Output process efficiency 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.

4.5.2.8 *Fuzzy Logic Command Line Functions for the AM (LPBF), Machining, and HM Processes Efficiency Maturity*

```
[System]
Name='process_efficiency_maturity'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=6
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='lpbf_additive_process'
Range=[0 80]
NumMFs=5
MF1='vl':'trimf',[-20 0 20]
MF2='l':'trimf',[0 20 40]
MF3='nql':'trimf',[20 40 60]
MF4='h':'trimf',[40 60 80]
MF5='vh':'trimf',[60 80 100]

[Input2]
Name='machining_process'
Range=[0 80]
NumMFs=5
MF1='min':'trimf',[-20 0 20]
```

```
MF2='mma':'trimf',[0 20 40]
MF3='mami':'trimf',[20 40 60]
MF4='max':'trimf',[40 60 80]
MF5='mmz':'trimf',[60 80 100]

[Output1]
Name='hybrid_manufacturing_technology'
Range=[0 80]
NumMFs=5
MF1='initial':'trimf',[-20 0 20]
MF2='managed':'trimf',[0 20 40]
MF3='defined':'trimf',[20 40 60]
MF4='quantitatively_managed':'trimf',[40 60 80]
MF5='optimizing':'trimf',[60 80 100]

[Rules]
3 3, 2 (1) : 1
3 4, 3 (1) : 1
3 5, 3 (1) : 1
4 3, 2 (1) : 1
4 4, 4 (1) : 1
4 5, 4 (1) : 1
```

Therefore, by the model implementation results, the percentage (%) process efficiency maturity of Machining-Additive LPBF hybrid manufacturing technology, implies

$$\frac{\mathbf{54.19}}{\mathbf{80}} \times \mathbf{100} \;=\; \mathbf{67.77\%}$$

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

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

$$\frac{\mathbf{54.2}}{\mathbf{80}} \times \mathbf{100} \;=\; \mathbf{67.75\%}$$

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

4.5.2.9 *Analysis of Processes Efficiency MLs*

The technological maturity level of the hybrid manufacturing technology with respect to the process efficiency (PE) is as follows and in the table 31 below.

PBF: the maturity level is 3.44/5 representing 68.75%

Machining: the maturity level is 3.75/5 representing 75%

HMT: the maturity level is 3.39/5 representing 67.75%

The HMT maturity for PE is therefore at 67.75%

Table 31. Processes Efficiency MLs

Process Efficiency Maturity Level					
PBF		***Machining***		***HMT***	
ML	*%*	*ML*	*%*	*ML*	*%*
3.44/5	68.75	3.75/5	75	**3.39/5**	**67.75**

4.5.3 Effectiveness

Process Effectiveness is a measure of the manufacturing process performance capability, operational reliability, dependability, and process tactical availability in hybrid manufacturing technology [54]. It includes the prolificacy and stability of the machine utilities or infrastructure such as the processing temperature, power, energy, build volume, supporting structure, cutting fluid, and raw materials concerns or resources. Each of the characteristics can be expressed as a probability of system successful fulfilment of requirements

when operating within specified design limits. Hence, it is the degree or a measure of how well it does its job when working properly. However, HMT performance capability is concerned with the probability that the machine will meet or satisfy task performance requirements when operating within specified design limits. Hence, a measure how well it does its job when working properly. On the same hand, operational reliability is the probability that the HMT will maintain a specified level of performance throughout a given task. Hence, a measure of how long it can work without failure. Also, the tactical availability, which means an operational readiness, is the probability that at any point in time the HMT will be ready to operate at a specified level of performance, on demand. Hence, a measure of how often the machine is ready when needed. Thus, the HMT operational effectiveness implies the product of these three characteristics; performance capability, reliability, and availability. Therefore, operation effectiveness of an equipment or system is then the probability that it can successfully meet an operational requirement, for the duration of the need, when the need arises. However, because of the indirect methodology approach of the assessment, the vague nature of the linguistic variable process effectiveness, and the maturity. Fuzzy logic principle is applied in the design, planning and administration of a questionnaire to obtain expert survey opinion, and the collection of research data in table 32 below. It takes care of various degrees of technology developmental stages, which the binary questionnaire answers do not cover.

4.5.3.1 *Experts' Survey Questionnaire for Process Effectiveness TMA*

A group-based questionnaire is designed such that each process effectiveness capability performance survey statement has up to five-gravitating optional answers. These include the Not true, Not quite true, Fairly true, True, and Very true. To ensure and improve the reliability and confidence of research, the questionnaire was directly emailed to the targeted professionals and experts' respondents drawn from the field of additive and hybrid manufacturing. A situation where, based on the research variable of PPEffec., and importance of specialty, the related design and process engineers in the midst were marked and sub-grouped as main target. Then, with the knowledge of principal component analysis, and to achieve a better manageable data size, the 63 questionnaires returned within the stipulated time frame were sorted and naturally classified

under three employers' groups within the (1.) academia, (2.) industry, and (3.) research institutes of the respondents. This was based on the employment data provided in the questionnaires, which includes current positions. Thus, data collected was processed as presented in the appendices 27, 28, 29 and 33, for Powder Bed Fusion and appendices 30, 31, 32, 33, for the CNC machining processes under hybrid manufacturing cell. The algorithm of the maturity assessment of the PEffec. for the metal AHMT is as shown in the schematic figure 64 below. Whereas the results and analyses of the initial experts' survey primary data are as represented and explained in the tables 33, 34, 35, 36, 37 and 38, and the figures 65, 66, 67, 68, 69, 70 and 71 below.

Table 32. Experts' Survey Questionnaire for Processes Effectiveness TMA with research statements jointly produced from various AM and HMT publications referenced below. See appendices 5, 6, 7, 8 and 9 also.

Survey Questionnaire for HMT Process Effectiveness Capability Performance						
S/No	*Research Statement/Proposition*	*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
1	Vibration tendencies during machining operation are now minimized					
2	There is now a seamless switching between processes and materials during manufacturing operation, and without causing defects					
3	Environmental impact analysis has been conducted on the process, and it is certified passed.					
4	There is a permanent solution to the cutting fluid and the reminant effects on the additive powder material and product					
5	The relationship between material deposition and the geometry of the region where the material is being deposited, the surface finish etc has been established					
6	The Safety and risk assessment concerns of powder handling and laser is acceptable					
7	There is a universal methodology for managing or handling the process residues					
8	The powder remains of the process is confirmed recoverable, recyclable and reusable					
9	There is a best processing velocity or speed determined for specific machine operation					
10	The melt pool width size and temperature monitoring and control can be carried out remotely					
11	There are means of controlling the macro and microstructure of the deposited material					
12	Deviation from the set parametric values of process such as layer size and thickness can be detected during operation					
13	There is a look ahead process monitoring system in place					
14	There is possibility of maintaining a constant gap between the nuzzle and the substrate or preceeding layer during manufacturing					
15	There are experimentally obtained database to correlate process parameters					
16	There are provisions for power blowing and laser cleaning of the build volume before additive process					
17	There are enough research, publications and discussions about the process and application					
18	There are existence of a unified operational procedure and standard for the process					
19	Additive manufacturing technology is compatible with the standard data handling software					
20	The technology has the ability to convert data files to specific data format					
21	The process database is documented in data management system for research and industrial accesses					
22	The technology has provisions or accommodation for new materials and application					
23	There are numerical or other measurable parameter or factor that define the process or sets the condition of operation					
24	There are training and retraining programmes designed for the personnel					
25	There are universal or internationally agreed set of procedures for process operation and safety					
26	There are adequate teaching and learning of the process in the universities and colleges					
27	There is a regulated auditing mechanism or procedure for quality management in use					
28	The process is mature for both laboratory and industrial applications					
29	The effects of individual process parameters on the performance are widely known					
30	The technology has a well defined or calculated process characteristics					
31	There is a study and result for the source of measurement error and process uncertainty					
32	There is a specific implementation methodology that turns plan into action in order to accomplish process strategic objectives and goals					
33	There are defined aim and objective of process improvement and optimization					
34	There is a record of continuos process performance improvement through scientific research and innovations					
35	There are new applicable materials findings in the process					
36	Operators skill and knowledge contrubute significantly to the process performance and capabilities					
37	The process has attained its potential values					
38	The process yield has been applied to measure the performance of the process to determine the percentage of the products that pass through compliance check					
39	The process measurement system is available					
40	There are known effects of process parameters on products characteristics					
41	There is a precise process that can give inaccurate results due to system error					
42	There are difference between process simulation and the actual physical performance					
43	The accuracy of the process model simulation is based on the actual performance					
44	There is a universal process analytical model for the process simulation					

[18, 19, 20, 21, 22, 23, 24, 25, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 79, 80, 81, 82, 86, 87, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 102, 103, 104, 105, 106, 107]

4.5.3.2 Algorithm of Process Effectiveness Technological Maturity Assessment of HMT that Integrate Metal Additive Manufacturing Process

Figure 64. Algorithm of Effectiveness TMA of HMT as explained in the schematics in table 10., above.

4.5.3.3 Process Effectiveness technological maturity profile of each of the technologies

Table 33. Process Effectiveness Capability maturity ranking framework for LPBF

Level	Focus	Process Capability Area	Result
5 Process Optimizing	Continuous Process Improvement	-	-
4 Process Quantitatively Managed	Process Quantitatively Managed	**1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 14, 16, 20, 22, 23, 24, 25, 27, 29, 30, 31, 32, 33, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44**	
3 Process Defined	Process Standardization	**4, 12, 13, 15, 17, 18, 19, 21, 26, 28, 37**	
2 Process Managed	Basic Process Management	-	-
1 Process Initiated	Process is informal and Adhoc	No Process Area	

Table 34. LPBF Effectiveness TMA Statistical Results

Variable	Total Count	Percent	Mean	StDev	Variance	Sum	Minimum
LPBFPEffec. Maturity	44	100	3.6364	0.4305	0.1854	160.0000	3.0000

Variable	Q1	Median	Q3	Maximum	Range
LPBFPEffec. Maturity	3.0825	4.0000	4.0000	4.0000	1.0000

Figure 65. The normal probability test plot of LPBFPEffec. maturity data on Minitab.

Figure 66. Histogram of LPBFPEffec. maturity

Figure 67. Boxplot of LPBFPEffec. maturity.

In summary, figure 65 as shown in the results for Anderson-Darling (AD), the probability value; P-Value is less than Alpha value, 0.05. This means strong evidence against the null hypothesis (H_0). Also, the data do not follow a normal distribution and H_0 is rejected. Thus, the test is statistically significant. Whereas, figure 67 is showing the data spread. Hence, in table 34 above, the Minimum (mini) maturity level (ML), 1st Quartile (Q1), the Median, 3rd Quartile (Q3), and the Maximum (max) ML, with spread, Range of 1.0000, and the interquartile range (IQR), 0.9175. Which means that the middle 50% of the maturity spread only has a variability of 0.9175.

Table 35. Process Effectiveness Capability Maturity ranking framework for Machining

Level	Focus	Process Capability Area	Result
5 Process Optimizing	Continuous Process Improvement	**4, 5, 6, 7, 8**	-
4 Process Quantitatively Managed	Process Quantitatively Managed	**1, 2, 3, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44**	
3 Process Defined	Process Standardization		
2 Process Managed	Basic Process Management	-	-
1 Process Initiated	Process is informal and Adhoc	No Process Area	

Table 36. Machining Effectiveness TMA Statistical Results

Variable	Total Count	Percent	Mean	StDev	Variance	Sum	Minimum	Q1
MPEffec. Maturity	44	100	3.9468	0.2372	0.0563	173.6600	3.3300	4.0000

Variable	Median	Q3	Maximum	Range
MPEffec. Maturity	4.0000	4.0000	4.3300	1.0000

Figure 68. The normal probability test plot of CNC MPEffec. maturity data on Minitab.

Figure 69. Histogram of CNC MPEffec. maturity

Figure 70. Boxplot of CNC MPEffec. Maturity.

Figure 71. A double Boxplot for a set of LPBFPEffec. maturity and CNC MPEffec. maturity data.

Method

μ_1: population mean of LPBFPEffec. Maturity
μ_2: population mean of MPEffec. Maturity
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Table 37. Descriptive Statistics of HMT

Sample	N	Mean	StDev	SE Mean
LPBFPEffec. Maturity	44	3.636	0.431	0.065
MPEffec. Maturity	44	3.947	0.237	0.036

Estimation for Difference

Difference	95% CI for Difference
-0.3105	(-0.4584, 0.1625)

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
-4.19	66	0.000

In summary, figure 68 as shown in the results for Anderson-Darling (AD), the probability value; P-Value is less than Alpha value, 0.05. This means strong evidence against the null hypothesis (H_0). Also, the data do not follow a normal distribution and H_0 is rejected. Thus, the test is statistically significant. Where figure 70 is showing the data spread. Thus, in table 36 above, the Minimum (mini) maturity level (ML), 1st Quartile (Q1), the Median, 3rd Quartile (Q3), and the Maximum (max) ML, with spread, Range of 1.0000, and the interquartile range (IQR), 0.0000. Which means that the middle 50% of the maturity spread has no data variability. Finally, the double boxplot representation of figure 71 means that the LPBFPEffec. maturity with the bigger box shows that data is less concentrated in the area, therefore, has more variability than the CNC MPEffec. maturity. Thus, comparing their individual data spread, the equal Range shows that both have equal or the same spread out. Also, on their Interquartile Range (IQR), the LPBFPEffec. data has far more variability than the CNC MPEffec. with zero variability.

Thus, from the statistical analysis results of the two technologies under assessment, the crisp maturity levels, and the percentage maturity of the two manufacturing processes are the two cluster means as in the Table 38 below.

Table 38. Effectiveness TMA Results

Process Effectiveness Maturity Level			
LPBF		***Machining***	
ML	%tage	ML	%tage
3.64	72.8	3.95	79

Therefore, if both classical or crisp maturity levels are as obtained, then there is a need to also determine the degree or the extent of truth in it or how true is it. This leads to the introduction of membership functions.

4.5.3.4 *Determining the Membership Functions of the Results*

To find the membership functions of the results, a set of maturity subsets are established with some related descriptors, to determine the membership functions of the subsets as in the figures 72, 73, 74 and 75 below. Defining the membership functions for each set of the inputs and output descriptors, a triangular membership function is applied in the three fuzzy subsets. The LPBF process (Input 1) subset descriptors; Not Well (NW), Not Quite Well (NQW), Well (W), Not Very Well (NVW), Very Well (VW). The Machining process (Input 2) subset descriptors; Not Dependable (ND), Not Quite Dependable (NQD), Dependable (D), Not Highly Dependable (NHD), Highly Dependable (HD). The Hybrid manufacturing Output subset descriptors: Initial (IN), Managed (MAN), Defined (DEF), Quantitatively Managed (QMAN), Optimizing (OPTIM). Where equation of the straight line is used to determine the membership functions for all the descriptors and their corresponding membership values as follows.

$\frac{y_2-y_1}{x_2-x_1} = \frac{y-y_1}{x-x_1}$ ----------(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 72. Elements of PEffec. TMA of Input 1 universe of discuss

Therefore, in determining the membership function (μ) for (NW), with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

$20\mu = 20 – x$

$\mu = 20 – x/20$

Therefore, $\mu NW = 20 –x/20$ [0,20]

For the membership function (μ) for NQW, involves two cases.

Range from [0,20] and range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x$

$\mu = x/20$

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, $\mu NQW = x/20$ [0,20], $40 – x/20$ [20,40]

For the membership function (μ) for W, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 20$

$\mu = x - 20/20$

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 60$

$\mu = 60 – x/20$

Therefore, $\mu W = x - 20/20$ [20,40], $60 – x/20$ [40,60]

For the membership function (μ) for NVW, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

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

For the membership function (μ) for VW, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 60$

$\mu = x - 60/20$

Therefore, μVW = x - 60/20 [60,80]

Summarily, we have.

- μNW = 20 –x/20 [0,20]
- μNQW = x/20 [0,20], 40 – x/20 [20,40]
- μW = x - 20/20 [20,40], 60 – x/20 [40,60]
- μNVW = x - 40/20 [40,60], 80 – x/20 [60,80]

- μVW = x - 60/20 [60,80]

Input (2)

Figure 73. Elements of PEffect. TMA of Input 2 universe of discuss.

For the membership functions of the Input (2) fuzzy subset, the same equation of straight line is applied.

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

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

Therefore, in determining the membership function (μ) for ND, with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

20μ = 20 – x

μ = 20 – x/20

Therefore, μND = 20 –x/20 [0,20]

For the membership function (μ) for NQD, involves two cases.

Range from [0,20] and Range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x$

$\mu = x/20$

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, μNQD = x/20 [0,20], 40 – x/20 [20,40]

For the membership function (μ) for D, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 20$

$\mu = x - 20/20$

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 60$

$\mu = 60 – x/20$

Therefore, $\mu D = x - 20/20$ [20,40], $60 – x/20$ [40,60]

For the membership function (μ) for NHD, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

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

For the membership function (μ) for HD, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 60$

$\mu = x - 60/20$

Therefore, μHD = x - 60/20 [60,80]

Accordingly, the membership functions of Input (2) are as determined and summarized below.

- μND = 20 –x/20 [0,20]
- μNQD = x/20 [0,20], 40 – x/20 [20,40]
- μD = x - 20/20 [20,40], 60 – x/20 [40,60]
- μNHD = x - 40/20 [40,60], 80 – x/20 [60,80]
- μHD = 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).

It implies that when the maturity of the Input (1) is = 72.8%, then, the membership function (μ) from the graph will be at the 72.8% of 80 (Universe of discourse).

Therefore, 72.8/100 x 80 = 58.24 ≈ 58.3

Thus, it falls between the range [40,60] as illustrated above

On the same hand, if the maturity of the Input (2) is 79%,

Then, the membership function (μ) from the graph will be at 79% of 80 (Universe of discourse) as thus,

79/100 x 80 = 63.2

Thus, falls between the range [60,80] as illustrated above.

Therefore, striking out the rest in Input (1), it implies that,

- μW = 60 – x/20 [40,60], where x = 58.3
- μNVW = x - 40/20 [40,60], where x = 58.3

On the same hand, striking the rest in Input (2)

- μNHD = 80 – x/20 [60,80] where x = 63.2
- μHD= x - 60/20 [60,80] where x = 63.2

Therefore, the membership functions of Input (1); W and NVW will be as stated below.

μW = 60 – x/20 = 60 – 58.3/20 = 0.09

μW = 0.09

Then,

μNVW = x - 40/20 = 58.3 – 40/20 = 0.92

μNVW = 0.92

Whereas the membership functions of Input (2); NHD and HD are as well

μNHD = 80 – x/20 = 80 – 63.2/20 = 0.84

μNHD = 0.84

Then,

μHD = x - 60/20 = 63.2 – 60/20 = 0.2

µHD = 0.2

Therefore,

Input 1 → 72.8% of 80 = 58.3

Also,

Input 2 → 79% of 80 = 63.2

Figure 74. Membership values graph of PEffec. TMA 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 39 below.

Table 39. Four-rule base TMA of the HMT Inputs

Rule 1	Input (1) W (0.09)	Input (2) NHD (0.84)
Rule 2	Input (1) W (0.09)	Input (2) HD (0.2)
Rule 3	Input (1) NVW (0.92)	Input (2) NHD (0.84)
Rule 4	Input (1) NVW (0.92)	Input (2) HD (0.2)

Output

Figure 75. Membership functions graph of Effec. TMA Output

For the membership functions of the Output fuzzy subset, the same equation of straight line is applied.

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

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

Therefore, in determining the membership function (μ) for Initial (IN), with a range [0,20]

$y_1 = 1$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 0$

Substituting in equation (i)

20μ = 20 – x

μ = 20 – x/20

Therefore, μIN = 20 –x/20 [0,20]

For the membership function (μ) for MAN, involves two cases.

Range from [0,20] and Range from [20,40]

Therefore, for the range [0,20],

$y_1 = 0$, and $x_1 = 0$

$x_2 = 20$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x$

$\mu = x/20$

For the range [20,40],

$y_1 = 1$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 40$

$\mu = 40 – x/20$

Therefore, $\mu MAN = x/20$ [0,20], $40 – x/20$ [20,40]

For the membership function (μ) for DEF, also involves two cases.

Range from [20,40] and Range from [40,60]

Therefore, for the range [20,40],

$y_1 = 0$, and $x_1 = 20$

$x_2 = 40$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 20$

$\mu = x - 20/20$

For the range [40,60],

$y_1 = 1$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 60$

$\mu = 60 – x/20$

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

For the membership function (μ) for QMAN, also involves two cases.

Range from [40,60] and Range from [60,80]

Therefore, for the range [40,60],

$y_1 = 0$, and $x_1 = 40$

$x_2 = 60$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 40$

$\mu = x - 40/20$

For the range [60,80],

$y_1 = 1$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 0$

Thus, substituting in equation (i)

$20\mu = - x + 80$

$\mu = 80 – x/20$

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

For the membership function (μ) for OPTIM, with range from [60,80]

$y_1 = 0$, and $x_1 = 60$

$x_2 = 80$, and $y_2 = 1$

Thus, substituting in equation (i)

$20\mu = x - 60$

$\mu = x - 60/20$

Therefore, μOPTIM = x - 60/20 [60,80]

Summarily, we have.

- 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]

4.5.3.5 *Process Effectiveness Professional and Expert Inferences*

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 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: NW, NQW, W, NVW, VW

The Input (2) subset descriptors: ND, NQD, D, NHD, HD

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

Thus, with the metal additive hybrid manufacturing professional and expert knowledge of the compatibility and complementarity of the two processes inputs, a rule base system is developed and applied as in the

table 40 below. The system enables one of the entrusted Design and Process 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.

Table 40. Fuzzy inference rules TMA of HMT Output

Input 1/2	**NW**	**NQW**	**W**	**NVW**	**VW**	Output
ND	IN	IN	MAN	MAN	MAN	**IN**
NQD	IN	IN	MAN	MAN	MAN	**MAN**
D	IN	MAN	DEF	DEF	QMAN	**DEF**
NHD	IN	MAN	DEF	QMAN	QMAN	**QMAN**
HD	IN	MAN	QMAN	QMAN	OPTIM	**OPTIM**

However, the membership functions of Input (1) are within the range of W and NVW, while the membership functions of Input (2) are within the range of NHD and HD

Therefore, fuzzification and evaluation of the rules imply.

Rule 1: If the Input (1) is W, and the Input (2) is NHD, then the Output, which is the hybrid Inputs (1) and (2) effectiveness maturity is Defined (DEF).

Rule 2: If the Input (1) is NVW, and the Input (2) is NHD, then the Output, which is the hybrid Inputs (1) and (2) effectiveness maturity is Quantitatively Managed (QMAN).

Rule 3: If the Input (1) is W, and the Input (2) is HD, then the Output, which is the hybrid Inputs (1) and (2) effectiveness maturity is Quantitatively Managed (QMAN).

Rule 4: If the Input (1) is NVW, and the Input (2) is HD, then the Output, which is the hybrid Inputs (1) and (2) effectiveness maturity is Quantitatively Managed (QMAN).

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

Figure 76. Graphical technique of inference of PEffec. TMA Output

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 maturity value of the hybrid process Inputs Output value, a centroid method is applied as in the figure 77. below, and finally defuzzifying the value (Z*).

Therefore, applying the Centroid Defuzzification method.

Figure 77. Deffuzzification of PEffec. TMA Output result

Thus, 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

Therefore, **<u>ab</u>** implies,

$y_1 = 0$, $x_1 = 20$

$y_2 = 0.09$, $x_2 = 22$

Then, $2y = 0.09x – 1.8$

$y = 0.09x – 1.8/2$ [20,22]

<u>bc</u> implies,

$y_1 = 0.09$, $x_1 = 22$

$y_2 = 0.09$, $x_2 = 40$

$18y = 1.62$

$y = 0.09$ [22,40]

<u>cd</u> implies,

$y_1 = 0.09$, $x_1 = 40$

$y_2 = 0.84$, $x_2 = 55$

$15y = 0.75x – 28.65$

$y = 0.75x – 28.65/15$ [40,55]

<u>de</u> implies,

$y_1 = 0.84$, $x_1 = 55$

$y_2 = 0.84$, $x_2 = 65$

$10y = 8.4$

$y = 0.84$ [55,65]

<u>ef</u> implies,

$y_1 = 0.84$, $x_1 = 65$

$y_2 = 0$, $x_2 = 80$

15y = -0.84x + 67.2

y = -0.84x + 67.2/15 [65,80]

4.5.3.6 *Process Effectiveness Defuzzification of the fuzzy Set Inference Output Result*

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

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

Appendix 34 shows the engineering mathematical calculations and result for the complex system geometries. Hence the technological maturity for PEffec. is the result of the defuzzification of the shaded portion of the graphical figure 77.

4.5.3.7 *Process Effectiveness Maturity Assessment Results Simulations in Fuzzy Logic System*

Figure 78. The Rule Viewer Output format in a fuzzy logic system toolbox in MATLAB.

Figure 79. The Surface Viewer Output format in fuzzy logic system toolbox in MATLAB.

Figure 80. Figure 80. Surface Viewer: Processes effectiveness maturity for two axes LPBF and HMT MLs only

Figure 81. Surface Viewer: Processes effectiveness maturity for two axes CNC machining and HMT MLs only

In summary, figure 78 above shows a dynamic inference process for the fuzzy process effectiveness 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. Whereas the following figure 79 shows a static three-dimensional graphical mapping of combination of the Inputs 1 and 2, and the Output process effectiveness 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.

4.5.3.8 *Fuzzy Logic Command Line Functions for the AM (LPBF), Machining, and HM Processes Effectiveness Maturity*

```
[System]
Name='processes_effectiveness_maturity'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=4
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='lpbf_am_process'
Range=[0 80]
NumMFs=5
MF1='nw':'trimf',[-20 0 20]
MF2='nqw':'trimf',[0 20 40]
MF3='w':'trimf',[20 40 60]
MF4='nvw':'trimf',[40 60 80]
MF5='vw':'trimf',[60 80 100]

[Input2]
Name='machining_process'
Range=[0 80]
NumMFs=5
MF1='nd':'trimf',[-20 -2.22e-16 20]
MF2='nqd':'trimf',[0 20 40]
MF3='d':'trimf',[20 40 60]
MF4='nhd':'trimf',[40 60 80]
MF5='hd':'trimf',[60 80 100]

[Output1]
Name='hybrid_manufacturing_technology'
Range=[0 80]
NumMFs=5
MF1='initial':'trimf',[-20 0 20]
MF2='managed':'trimf',[0 20 40]
MF3='defined':'trimf',[20 40 60]
MF4='quantitatively_managed':'trimf',[40 60 80]
MF5='optimizing':'trimf',[60 80 100]

[Rules]
3 4, 3 (1) : 1
4 4, 4 (1) : 1
3 5, 4 (1) : 1
4 5, 4 (1) : 1
```

Therefore, by the model implementation results, the percentage (%) process effectiveness maturity of Machining-Additive LPBF hybrid manufacturing technology, implies

$$\frac{\mathbf{57.40}}{\mathbf{80}} \times \mathbf{100} \;=\; \mathbf{71.75}\%$$

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

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

$$\frac{\mathbf{57.3}}{\mathbf{80}} \times \mathbf{100} \;=\; \mathbf{71.63}\%$$

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

4.5.3.9 *Analysis of Processes Effectiveness MLs*

The technological maturity level of the hybrid manufacturing technology with respect to the process effectiveness (PEffec.) is as follows and in the table 41 below.

PBF: the maturity level is 3.63/5 representing 72.5%

Machining: the maturity level is 3.95/5 representing 79%

HMT: the maturity level is 3.58/5 representing 71.63%

The HMT maturity for PEffec. is therefore at 71.63%

Table 41. Processes Effectiveness MLs

Process Effectiveness Maturity Level					
PBF		***Machining***		***HMT***	
ML	*%*	*ML*	*%*	*ML*	*%*
3.63/5	72.5	3.95/5	79	**3.58/5**	**71.63**

4.6 Assessment of Metal Additive Hybrid Manufacturing Technology Model Results and Discussions

The SDTMAM was executed under the quantified parametric values of the independent variables, process product quality, process efficiency, and process effectiveness. All through the experts' survey, determination of the membership functions of the survey results, through the graphical technique inference for the hybrid inputs and output results, through the engineering mathematical defuzzification process for the hybrid output result, and finally the simulation of the individual HM Process results as thus.

4.6.1 Integrated TMA Results for the CNC Machining-PBF Additive HMT

Table 42 below represents the manually calculated technological maturity level results of the machining-PBF additive hybrid manufacturing process for process product quality, process efficiency, and the process effectiveness in the CMMI model profile and maturity percentage rankings as shown below.

Table 42. Integrated PQ, PE, and PEffec. TMA of CNC Machining-LPBF Additive HMT Results

HM Processes Capability Performance Maturity Assessment Implementation Results																	
Process Product Quality Maturity Level						**Process Efficiency Maturity Level**						**Process Effectiveness Maturity Level**					
LPBF		***Machining***		***HMT***		***LPBF***		***Machining***		***HMT***		***LPBF***		***Machining***		***HMT***	
ML	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*
3.16/5	63.2	3.94/5	78.8	**3.2/5**	**62.91**	3.42/5	68.5	3.71/5	74.2	**3.4/5**	**67.77**	3.64/5	72.8	3.95/5	79	**3.6/5**	**71.75**

4.6.2 Integrated TMA Results of the CNC Machining-PBF Additive HMT Simulation Results Applying Fuzzy Logic Toolbox in MATLAB

Table 43 below represents the simulated results of the technological maturity level results of the machining-PBF additive hybrid manufacturing process, using the fuzzy logic system toolbox in the MATLAB for process product quality, process efficiency, and the process effectiveness in the CMMI model profile and maturity percentage rankings as shown below.

Table 43. Integrated TMA Simulation Results

HM Processes Capability Performance Maturity Assessment Simulation Results																	
Process Product Quality Maturity Level						**Process Efficiency Maturity Level**						**Process Effectiveness Maturity Level**					
LPBF		***Machining***		***HMT***		***LPBF***		***Machining***		***HMT***		***LPBF***		***Machining***		***HMT***	
ML	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*	*ML*	*%tage*
3.19/5	63.75	4.0/5	80	**3.18/5**	**63.5**	3.44/5	68.75	3.75/5	75	**3.39/5**	**67.75**	3.63/5	72.5	3.95/5	79	**3.58/5**	**71.63**

4.6.3 Integrated Experts' Survey Results Vagueness for the HM Processes Capability Performance Maturity Assessment

The table 44 below is showing the difference between the experts' survey technological maturity levels results and the engineering technological maturity levels results or the simulated technological maturity level results of the machining-PBF additive hybrid manufacturing process for process product quality, process efficiency, and the process effectiveness in the CMMI model profile and maturity percentage rankings as shown below. The difference is the representation of the level of vagueness or bias in human decisions in the process. These, I think are all considerably good based on human factors.

Table 44. Integrated Experts' Survey Results Vagueness

The Vagueness of Experts Survey Results of the HM Processes Capability Performance Maturity Assessment																	
Process Product Quality Maturity Level						**Process Efficiency Maturity Level**						**Process Effectiveness Maturity Level**					
LPBF		***Machining***		***HMT***		***LPBF***		***Machining***		***HMT***		***LPBF***		***Machining***		***HMT***	
ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage	ML	%tage
0.03	0.55	0.06	1.2	0.02	0.59	0.02	0.25	0.04	0.8	0.09	0.02	0.01	0.3	0	0	0.02	0.12

4.6.4 Aggregate Performance Capability Maturity of PBF-CNC Machining HMT

Table 45 below represents the metal hybrid manufacturing technological maturity level, which is the average of the aggregated process product quality, process efficiency, and the process effectiveness CMMI maturity levels and the percentage maturity rankings of the machining-PBF additive hybrid manufacturing technology.

Table 45. Aggregate Performance Capability Maturity Results

Aggregate Performance Capability Maturity of LPBF-Machining HMT					
LPBF		***Machining***		***HMT***	
ML	%tage	ML	%tage	ML	%tage
3.42	68.33	3.9	78	3.39	67.63

CHAPTER 5

TECHNOLOGICAL MATURITY COMPATIBILITY MODEL TEST

5.1 Implementation of Processes Maturity Compatibilities Tests for Hybrid Manufacturing Technology that Integrates Metal Additive Manufacturing Processes

5.1.1 *Processes Maturity Compatibilities for Product Quality*

Figure 82. The output of the compatibility test model of hybrid manufacturing processes of fuzzy sets input (1) and input (2) by graphical technique of inference.

5.1.1.1 *Processes Union (U) of HMT Product Quality MLs*

Figure 83. Implementation of the union of the fuzzy Input (1) and Input (2) sets model

The union of the two fuzzy sets in the universe of discourse (X) Є [0,…80] is defined as follows;

$\mu_{Input\ (1) \cup Input\ (2)}(x) = \max[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (ii)

Figure 84. The Output of the union (U)

5.1.1.2 *Processes Complementarity of HMT Product Quality MLs*

The Output of the Complement of the Fuzzy Input (1) and Input (2) sets:

(iv) Independently defined as the fuzzy set Input (1) complement in the universe of discourse (X) Є [0,80] whose membership function is defined as follows;

$\mu_{Input\ (1)\ complement}(x) = [1 - \mu_{Input\ (1)}(x)]\ \forall_x \in X$ ---------- Eqn. (iii)

and;

$\mu_{Input\ (2)\ complement}(x) = [1 - \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (iv)

The complement of a fuzzy set should contain all elements along with their membership values from the universe of discourse (X)

(v) Applying the DE Morgan's Law of union for fuzzy sets Input (1) and Input (2) with the universe of discourse (X) Є [0,…80], the complement of the union of the fuzzy sets Input (1) and Input (2) implies that,

Input (1)∪Input (2) complt = Input (1)complt∩Input (2) complt

Where the membership function values of, Input (1)∪Input (2) complt, and the Input (1)complt∩Input (2) complt, are defined as,

$\text{Input (1)}\cup\text{Input (2) complt} = 1 - \max[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ------- Eqn. (v)

and;

$\text{Input (1)complt}\cap\text{Input (2) complt} = \min[\mu_{Input\ (1)\ complt}(x), \mu_{Input\ (2)\ complt}(x)]\ \forall_x \in X$

---------- Eqn. (vi)

And;

Figure 85. First outputs of the complement of the fuzzy Input (1) and Input (2) sets

(vi) Also, going by the DE Morgan's law of intersection, it implies that, for fuzzy Input (1) and Input (2) sets with the universe of discourse (X) Є [0,…80], the complement of Input (1) and Input (2) intersection, ie;

[(Input (1)∩Input (2))complt] = Input (1)compltuInput (2)complt

Thus, the membership function values of,

[(Input (1)∩Input (2))complt] and Input (1)compltuInput (2)complt, are defined as;

[(Input (1)∩Input (2))complt] = 1 – min[$\mu_{Input\ (1)}(x)$,$\mu_{Input\ (2)}(x)$] $\forall_x$ Є X

---------- Eqn. (vii)

and;

Input (1)compltuInput (2)complt = max[$\mu_{Input\ (1)\ complt}(x)$, $\mu_{Input\ (2)\ complt}(x)$] $\forall_x \in X$ ---------- Eqn. (viii)

And;

Figure 86. Second output of the complement of the fuzzy Input (1) and Input (2) sets

5.1.1.3 *Processes Difference (|) of HMT Product Quality MLs*

C. The Output of the Difference between the Fuzzy Input (1) and Input (2) sets, with the membership function values $\mu_{Input\ (1)}(x)$ and $\mu_{Input\ (2)}(x)$ respectively in the universe of discourse (X) Є [0,…80] will imply;

$\mu_{Input\ (1)|Input\ (2)}(x) = \min[\mu_{Input\ (1)}(x), \mu_{Input\ (2)\ complt}(x)]\ \forall_x \in X$ ---------- Eqn. (ix)

Figure 87. Output of the difference between the fuzzy Input (1) and Input (2) sets

D. The Output of the Deference between the Fuzzy Input (2) and Input (1) sets, with the membership function values $\mu_{Input\ (2)}(x)$ and $\mu_{Input\ (1)}(x)$ respectively in the universe of discourse (X) Є [0,…80] will imply;

$\mu_{Input\ (2)|Input\ (1)}(x) = \min[\mu_{Input\ (2)}(x), \mu_{Input\ (1)\ complt}(x)]\ \forall_x \in X$ ---------- Eqn. (x)

Figure 88. Output of the difference between the fuzzy Input (1) and Input (2) sets

5.1.1.4 *Processes Intersection (∩) or Interface of HMT Product Quality MLs*

E. The Output of the Intersection of the Fuzzy Input (1) and Input (2) sets represents all elements for which the corresponding membership values can be computed by;

$\mu_{Input\ (1) \cap Input\ (2)}(x) = \min[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (xi)

Figure 89. Output of the intersection of the fuzzy Input (1) and Input (2) sets

5.1.2 Processes Maturity Compatibilities for Efficiency

Figure 90. The output of the compatibility test model of hybrid manufacturing processes of fuzzy sets input (1) and Input (2) by graphical technique of inference brought forward.

5.1.2.1 *Processes Union (U) of HMT Efficiency MLs*

Figure 91. Implementation of the union of the fuzzy Input (1) and Input (2) sets model

The Output of the Union of the Fuzzy Input (1) and Input (2) sets:

The union of the two fuzzy sets in the universe of discourse (X) Є [0,…80] is defined as follows;

$\mu_{Input\ (1) \cup Input\ (2)}(x) = \max[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (ii)

Figure 92. The Output of the union (U)

5.1.2.2 *Processes Complementarity of HMT Efficiency MLs*

The Output of the Complement of the Fuzzy Input (1) and Input (2) sets:

(vii) Independently defined as the fuzzy set Input (1) complement in the universe of discourse (X) Є [0,…80] whose membership function is defined as follows;

$\mu_{Input\ (1)\ complement}(x) = [1 - \mu_{Input\ (1)}(x)]\ \forall_x \in X$ ---------- Eqn. (iii)

and;

$\mu_{Input\ (2)\ complement}(x) = [1 - \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (iv)

The complement of a fuzzy set should contain all elements along with their membership values from the universe of discourse (X)

(viii) Applying the DE Morgan's Law of union for fuzzy sets Input (1) and Input (2) with the universe of discourse (X) Є [0,…80], the complement of the union of the fuzzy sets Input (1) and Input (2) implies that,

Input (1)∪Input (2) complt = Input (1)complt∩Input (2) complt

Where the membership function values of, Input (1)∪Input (2) complt, and the Input (1)complt∩Input (2) complt, are defined as,

Input (1)∪Input (2) complt = 1 – max[$\mu_{Input\ (1)}(x)$,$\mu_{Input\ (2)}(x)$] $\forall_x$ Є X ------- Eqn. (v)

and;

Input (1)complt∩Input (2) complt = min[$\mu_{Input\ (1)\ complt}(x)$, $\mu_{Input\ (2)\ complt}(x)$] $\forall_x$ Є X

---------- Eqn. (vi)

And;

Figure 93. First outputs of the complement of the fuzzy Input (1) and Input (2) sets

(ix) Also, going by the DE Morgan's law of intersection, it implies that, for fuzzy Input (1) and Input (2) sets with the universe of discourse (X) Є [0,…80], the complement of Input (1) and Input (2) intersection, ie;

[(Input (1)∩Input (2))complt] = Input (1)compltuInput (2)complt

Thus, the membership function values of,

[(Input (1)∩Input (2))complt] and Input (1)compltuInput (2)complt, are defined as;

[(Input (1)∩Input (2))complt] = 1 – min[$\mu_{Input\ (1)}(x)$,$\mu_{Input\ (2)}(x)$] $\forall_x$ Є X

---------- Eqn. (vii)

and;

Input (1)compltuInput (2)complt = max[$\mu_{Input\ (1)\ complt}(x)$, $\mu_{Input\ (2)\ complt}(x)$] $\forall_x$ Є X ---------- Eqn. (viii)

And;

Figure 94. Second outputs of the complement of the fuzzy Input (1) and Input (2) sets

5.1.2.3 *Processes Difference (|) of HMT Efficiency MLs*

F. The Output of the Difference between the Fuzzy Input (1) and Input (2) sets, with the membership function values $\mu_{Input\ (1)}(x)$ and $\mu_{Input\ (2)}(x)$ respectively in the universe of discourse (X) Є [0,…80] will imply;

$\mu_{Input\ (1)|Input\ (2)}(x) = \min[\mu_{Input\ (1)}(x), \mu_{Input\ (2)\ complt}(x)]\ \forall_x \in X$ ---------- Eqn. (ix)

Figure 95. Output of the difference between the fuzzy Input (1) and Input (2) sets

G. The Output of the Difference between the Fuzzy Input (2) and Input (1) sets, with the membership function values $\mu_{Input\ (2)}(x)$ and $\mu_{Input\ (1)}(x)$ respectively in the universe of discourse (X) Є [0,…80] will imply;

$\mu_{Input\ (2)|Input\ (1)}(x) = \min[\mu_{Input\ (2)}(x), \mu_{Input\ (1)\ complt}(x)]\ \forall_x \in X$ ---------- Eqn. (x)

Figure 96. Output of the difference between the fuzzy Input (2) and Input (1) sets

5.1.2.4 *Processes Intersection (∩) or Interface of HMT Efficiency MLs*

H. The Output of the Intersection of the Fuzzy Input (1) and Input (2) sets represents all elements for which the corresponding membership values can be computed by;

$\mu_{Input\ (1) \cap Input\ (2)}(x) = \min[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (xi)

Figure 97. Output of the intersection of the fuzzy Input (1) and Input (2) sets

5.1.3 Processes Maturity Compatibilities for Effectiveness

Figure 98. Output of the compatibility test model of hybrid manufacturing processes of fuzzy sets Input (1) and Input (2) by graphical technique of inference brought forward.

5.1.3.1 *Processes Union (U) of HMT Effectiveness MLs*

Figure 99. Implementation of the union of the fuzzy Input (1) and Input (2) sets model

The Output of the Union of the Fuzzy Input (1) and Input (2) sets:

The union of the two fuzzy sets in the universe of discourse (X) ∈ [0,…80] is defined as follows;

$\mu_{Input\ (1) \cup Input\ (2)}(x) = \max[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (ii)

Figure 100. The Output of the union (U)

5.1.3.2 *Processes Complementarity of HMT Effectiveness MLs*

The Output of the Complement of the Fuzzy Input (1) and Input (2) sets:

(x) Independently defined as the fuzzy set Input (1) complement in the universe of discourse (X) Є [0,…80] whose membership function is defined as follows;

$\mu_{Input\ (1)\ complement}(x) = [1 - \mu_{Input\ (1)}(x)]\ \forall_x \in X$ ---------- Eqn. (iii)

and;

$\mu_{Input\ (2)\ complement}(x) = [1 - \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (iv)

The complement of a fuzzy set should contain all elements along with their membership values from the universe of discourse (X)

(xi) Applying the DE Morgan's Law of union for fuzzy sets Input (1) and Input (2) with the universe of discourse (X) Є [0,…80], the complement of the union of the fuzzy sets Input (1) and Input (2) implies that,

Input (1)∪Input (2) complt = Input (1)complt∩Input (2) complt

Where the membership function values of, Input (1)∪Input (2) complt, and the Input (1)complt∩Input (2) complt, are defined as,

Input (1)∪Input (2) complt = $1 - \max[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ------- Eqn. (v)

and;

Input (1)complt∩Input (2) complt = min[$\mu_{Input\ (1)\ complt}(x)$, $\mu_{Input\ (2)\ complt}(x)$] $\forall_x \in X$

---------- Eqn. (vi)

And;

Figure 101. First outputs of the complement of the fuzzy Input (1) and Input (2) sets

(xii) Also, going by the DE Morgan's law of intersection, it implies that, for fuzzy Input (1) and Input (2) sets with the universe of discourse (X) ∈ [0,…80], the complement of Input (1) and Input (2) intersection, ie;

[(Input (1)∩Input (2))complt] = Input (1)compltuInput (2)complt

Thus, the membership function values of,

[(Input (1)∩Input (2))complt] and Input (1)compltuInput (2)complt, are defined as;

[(Input (1)∩Input (2))complt] = 1 – min[$\mu_{Input\ (1)}(x)$,$\mu_{Input\ (2)}(x)$] $\forall_x \in X$

---------- Eqn. (vii)

and;

Input (1)compltuInput (2)complt = max[$\mu_{Input\ (1)\ complt}(x)$, $\mu_{Input\ (2)\ complt}(x)$] $\forall_x \in X$ ---------- Eqn. (viii)

And;

Figure 102. Second output of the complement of the fuzzy Input (1) and Input (2) sets

5.1.3.3 *Processes Difference (|) of HMT Effectiveness MLs*

I. The Output of the Deference between the Fuzzy Input (1) and Input (2) sets, with the membership function values $\mu_{Input\ (1)}(x)$ and $\mu_{Input\ (2)}(x)$ respectively in the universe of discourse (X) $\in$ [0,…80] will imply;

$\mu_{Input\ (1)|Input\ (2)}(x) = \min[\mu_{Input\ (1)}(x), \mu_{Input\ (2)\ complt}(x)]$ $\forall_x \in X$ ---------- Eqn. (ix)

Figure 103. Output of the difference between the fuzzy Input (1) and Input (2) sets

J. The Output of the Deference between the Fuzzy Input (2) and Input (1) sets, with the membership function values $\mu_{Input\ (2)}(x)$ and $\mu_{Input\ (1)}(x)$ respectively in the universe of discourse (X) Є [0,…80] will imply;

$\mu_{Input\ (2)|Input\ (1)}(x) = \min[\mu_{Input\ (2)}(x), \mu_{Input\ (1)\ complt}(x)]\ \forall_x \in X$ ---------- Eqn. (x)

Figure 104. Output of the difference between the fuzzy Input (2) and Input (1) sets

5.1.3.4 *Processes Intersection (∩) or Interface of HMT Effectiveness MLs*

K. The Output of the Intersection of the Fuzzy Input (1) and Input (2) sets represents all elements for which the corresponding membership values can be computed by;

$\mu_{Input\ (1) \cap Input\ (2)}(x) = \min[\mu_{Input\ (1)}(x), \mu_{Input\ (2)}(x)]\ \forall_x \in X$ ---------- Eqn. (xi)

Figure 105. Output of the intersection of the fuzzy Input (1) and Input (2) sets

5.2 Experience and Experimental Observation of the New Generic Technological Maturity Assessment and Compatibility Test Models

5.2.1 Prospective and Extended Areas of Application of the Models

The generic TMA model harbours components that potentially through experience and experimental observation are capable of accommodating, and used to

1. Monitor and assess performance of manufacturing systems and processes for improvement and stability.
2. Calculate or determination of the efficiency of hybrid manufacturing technology by quantifying the output and inputs variables of compatible units.
3. Technological maturity assessment of a manufacturing technology that integrates more than two manufacturing processes. Example, machining, LPBF, and DED or any other.
4. Effect material and process selection
5. Implement quality control.
6. The effects of angular positions of simultaneous additively manufactured metal components. Given positions and angles; vertical, 22.5°, 45°, 22.5°', and horizontal.
7. Xray and project spectrum/spectra process Inputs and Outputs parametric variables requirements for research and experiments
8. Implement product and manufacturing process design.
9. Express some scientific relations for engineers.
10. Predict outcomes of activities or events through artificial intelligence, probability principle and theory

Thus,

Figure 106. Manufacturing technology parametric variables monitoring and control model screen

5.2.2 Relationships among the designed and implemented models

From the graphical technique of inference maturity level results and that of the processes maturity compatibility tests carried out in this research, it is observed that the maturity levels of the processes product quality, processes efficiency, and the processes effectiveness for the hybrid manufacturing processes have some relationships and similarities with all the processes compatibility test results both graphically and in mathematical calculations.

Thus,

1. The PPQ maturity level of Machining – LPBF hybrid manufacturing process = (A) The Difference between the Input (1) and Input (2) output = (B) The Intersection between the Input (1) and (2) output, But (C) Equal and Opposite the Difference between the Input (2) and Input (1) output

2. The PE maturity level of Machining – LPBF hybrid manufacturing process = (A) The Intersection between the Input (1) and Input (2) output ≠ (B) The Difference between Input (1) and Input (2) output, But (C) Equal and Opposite the Difference between Input (2) and Input (1) output

3. The PEffec. Maturity level of Machining – LPBF hybrid manufacturing process = (A) The Difference between Input (1) and Input (2) output = (B) The Intersection between Input (1) and Input (2) output, But (C) Equal and Opposite the Difference between Input (2) and Input (1) output.

CHAPTER 6

RESULTS, DISCUSSION AND RESEARCH FINDINGS

6.1 Experts' Survey for the PBF and CNC Machining Processes Product Quality Capability Maturity

In addition to the experts' survey statistical results for the PBF process product quality capability maturity level ranking on the Table 13, it is seen that 7 out of the 26 numbers of research survey statements of the questionnaire as coded with their serial numbers, made it to the 4th stratum of the CMMI maturity profile. While the remaining 19 PBF 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. Thus, the representation shows that in the current performance capability maturity status of the PBF manufacturing process and products, attention is needed with respect to each of the research statements to find out what is required to be done to ensure a continuous and sustainable movement of those on the 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. The findings and analyses are as presented in the tables 13 and 14, and the graphic figures 29, 30 and 31 above.

Also, as seen in table 15 of the process product quality capability maturity ranking framework for CNC machining, it is seen that 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 CMM 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. Thus, the representation shows that in the current process product quality performance capability maturity status of the machining process and products, attention is also needed with respect to each of the research survey statements to find out what is required to be done to ensure a continuous and sustainable movement of those on the 3rd stratum into the 4th

stratum. The same thing will be expected of those on the 4th stratum to move into the 5th stratum, while those already on the maturity level 5 go through and maintain continuous optimization process. The findings and analyses are as presented in the tables 15 and 16, and the graphic figures 32, 33 and 34 above.

6.2 Experts' Survey for the PBF and CNC Machining Processes Efficiency Capability Maturity

Again, looking at the experts' survey statistical results for the process efficiency capability maturity level ranking profile for the PBF on the Table 23, it is seen that 18 out of the 34 numbers of research survey statements of the questionnaire as coded with numbers, made it to the 4th stratum of the CMMI maturity profile. 16 made it to the 4th stratum, while none is found on the 5th and the 2nd strata. Where the 1st stratum of the CMMI maturity profile has no process area, which as well means that it did not come into assessment, hence overqualified for maturity level 1. Thus, the representation shows that in the current efficiency performance capability maturity status of the PBF process and products, attention is needed with respect to each of the research survey statements to find out what is required to be done to ensure a continuous and sustainable movement of those on the 4th stratum into the 5th stratum, and those on the 3rd stratum to move into the 4th stratum. Like this it continues, while those new on the maturity level 5 go through and maintain continuous optimization process at the same time. The findings and analyses are as presented in the Tables 23 and 24, and the graphic figures 47, 48 and 49 above.

For the experts' survey statistical results for the process efficiency capability maturity level ranking profile for the CNC machining on the Table 25, it is seen that it is just only 1 out of the 34 numbers of research survey statements of the questionnaire as coded with numbers, made it to the 5th stratum of the CMMI maturity profile. 27 made it to the 4th stratum, while just 6 are found on the 3rd stratum. There is none on the 2nd strata, where the 1st stratum of the CMMI maturity profile has no process area, which as well means that it did not come into assessment, hence overqualified also for maturity level 1. Thus, the representation

shows that in the current efficiency performance capability maturity status of the machining process and products, attention is needed with respect to each of the research survey statements to find out what is required to be done positively to ensure a continuous and sustainable movement of those on the 4th stratum into the 5th stratum, and those on the 3rd stratum to move into the 4th stratum. Like this it continues as the one on the maturity level 5 go through and maintain continuous optimization process at the same time. The findings and analyses are as presented in the tables 25 and 26, and the graphic figures 50, 51 and 52 above.

6.3 Experts' survey for the PBF and CNC Machining Processes Effectiveness Capability Maturity

Now, on the experts' survey statistical results for the process effectiveness capability maturity level scaling profile for the PBF on the table 33, it shows that 33 out of the total 44 numbers of research survey statements of the questionnaire as coded with numbers, made it to the 4th stratum of the CMMI maturity profile. 11 made it to the 3rd stratum, while none is found on the 5th and the 2nd strata. Where the 1st stratum of the CMMI maturity profile has no process area, which as well means that it did not come into assessment, hence overqualified for maturity level 1. Thus, the representation shows that in the current effectiveness performance capability maturity status of the PBF process and products, attention is needed with respect to each of the research survey statements to find out what is required to be done to ensure a continuous and sustainable movement of those on the 4th stratum into the 5th stratum, and those on the 3rd stratum to move into the 4th stratum. Like this it continues, while those new on the maturity Level 5 go through and maintain continuous optimization process at the same time. The findings and analyses are as presented in the tables 33 and 34, and the graphic figures 65, 66 and 67 above.

Finally, for the experts' survey statistical results for the process effectiveness capability maturity level ranking profile for the CNC machining on the table 35, it is also observed that only 5 out of the 44 numbers of research survey statements of the questionnaire as coded with numbers, made it to the 5th stratum of the

CMMI maturity profile. 39 made it to the 4th stratum. There is none on the 3rd, and the 2nd strata, where the 1st stratum of the CMMI maturity profile has no process area, which implies that it did not come into the assessment, hence overqualified also for maturity level 1. Thus, the representation shows that in the current effectiveness performance capability maturity status of the machining process and products, attention is needed with respect to each of the research survey statements to find out what is required to be done differently to ensure a continuous and sustainable movement of those on the 4th stratum into the 5th stratum. This continues as those on the maturity level 5 go through and maintain continuous optimization process at the same time. The findings and analyses are as presented in the tables 35 and 36, and the graphic figures 68, 69 and 70 above.

The numbers under the Process Capability Area column of the tables 13, 15, 23, 25, 33, 35, are the serial numbers of the research statement or propositions of the questionnaires. Thus, because of space and aesthetics, they are coded same to represent instead.

From the statistical results of the questionnaire survey result based on the arrangement of the questionable research statements along the CMMI processes capability maturity scale or profile, the aspects of the processes that requires more attention are known for the necessary actions. Take the result to the design, process, manufacturing, and cost engineers of the industry, they will know what to do. In fact, it is expected under effective management that expert review of both the achievements and areas of concern of the processes in hybrid solution will continue until all the maturity conditions are reasonably satisfied. Hence, it involves continuous examination of the system independently for more improvement and optimization as they are all not on the same degree of maturity to be on any maturity level.

Moreover, it is good to know that the questionnaire was developed and designed based on the state and literature review as at the year 2020. While the experts survey was carried out at the same time. Hence, a lot of positive efforts must have gone in or happened in the industry since then. It was observed that the

same sets of questionnaires used for the assessment of maturity can also be used or adapted for process improvement purposes, hence very fluidic and generic.

6.4 Engineering Mathematical Calculations Results

Since the process effectiveness maturity is higher than the process product quality and the process efficiency, it suggests that the personnel experience and expertise in design, material, and operation are required to achieve greater product quality and efficiency.

The closeness, similarity, and consistency of the results, despite the system length and complexity of engineering mathematical application of integral equations in the appendices 18, 26 and 34, and no bias. Hence the conciseness and the technological maturity assessment results consistencies of the various implemented results show the validity. It was very carefully implemented as would be required, which show repeatability and reproducibility of the model. Also, show that though the three process capability areas are all within the maturity level 4, but of various levels.

The improvement of machine effectiveness should have a corresponding positive effect on the output, then the efficiency. However, process can be very effective, and offers qualified products, all other things being equal and assured. Otherwise, it can as well yield substandard products, and of low or inefficient system when taken for granted.

From the results, the present machine operational effectiveness capability performance, reliability, and availability has improved more than its product quality and its overall efficiency which again has improved more than the product quality. So, considering the maturity paths of hybrid manufacturing technology and monitoring, maturity and improvement starts with the machine effectiveness, output, or product quality,

then machine efficiency. Therefore, if machine is got right, the product is good, and the efficiency is high, what then is the common equalization factor among the three variables? I think the personnel.

Now, since the main areas of concern in metal additive hybrid manufacturing is in the nature of the output, the result shows that the technology can be mature, and at the same time the product quality still below standard, because of other possible factors. But it will be better that the technology effectiveness remains the highest while other causative factors and variables are investigated.

The closeness of the technological capability maturity of the three capability areas of the hybrid manufacturing process is evidence that they are the same and are expected to be developing at equal pace. Thus, they are for the common objective, and are being given continuous and relatively equal industry attention.

The maturity levels of the independent processes are higher than those for and in hybrid manufacturing process. Also, the results of the machining process is below the 80% maturity benchmark [26]. All is due to the hybrid factors, bye-products, the nature of workpiece and products of complex geometry. Meanwhile, the maturity level of the subtractive process is still maintaining the highest rank with about 10% above the hybrid manufacturing results, which rank third with about 1% below that of the additive manufacturing process that the results rank average of 68% on the CMMI maturity profile. This is because products of complex geometries were involved. This means that all things being equal here, the intricacy or the complexity of products affects the quality of the final hybrid manufactured part. Which implies that the less the complexity the more part quality, all things been equal. Although the subtractive manufacturing technology in HM process results rank below its achievement as an independent process, followed by the hybrid manufacturing process, which signifies its advantages, while the comes third, which shows that it is the one or process being complemented. Also, results are true representation of information in the outside

domain. It was also found that the application of the fuzzy logic in the design of the questionnaire did reduce the vagueness of the experts' survey results to the insignificant levels.

6.5 The Rigors of the Processes Technological Maturity Assessment Results

To x-ray the rigorous process from the first principle, reference is made on the extent, the stages and how researcher arrived at their various processes' maturity level. For example, in any practical laboratory experiment, a single result outcome can be reported and presented. Also, series, sets, or group of results or outcomes can be reported or presented as a single result outcome too by way of the mean or median values by striking a balance once among the various series, sets, or groups results or outcomes. Again, Pierre et al [26] directly applied the mean values of their experts' survey statistical results each for manufacturing processes (P1) and (P2) as their maturity levels. But in the semi-direct technological maturity assessment model (SDTMAM), it went further ahead to a secondary stage of looking for their membership functions values. Then, the fuzzy values had to defuzzify the results to get the final crisp MLs, hence the results were still having some vague architecture. Thus, it is seen that balance was struck as necessary, and majorly in three places to arrive at an exert unbiased results. That shows a continuous iterative process.

6.6 Aggregated Technological Maturity Levels of a PBF-CNC Machining HMT

From the results in the table 45. above, the aggregate maturity levels of the PBF- CNC Machining HMT is 3.39 of 5/67.63% respectively. However, it is seen that,

The laser-based powder bed fusion additive manufacturing process has the second to the last maturity level at 3.42 of 5/68.33%, while the machining has the highest maturity level at 3.9 of 5/78%. Although both were assessed based on the hybrid manufacturing condition or factors, and not as a separate or independent individual process.

Notwithstanding, the HMT maturity level is the lowest, there is hope as it is not that bad, hence not the end. The post process technology attention is expected to perform the magic. This shows that there is still a need

for a post processing activity. Also, there is a need for a little improvement effort on the machining process under HMT effectiveness to maturity level (ML)4, which is 80%. Thus, it is expected that whatever effort input on the machining process must have a corresponding or resultant reflection on the HMT output. Therefore, at this point now, it seems that the onus lies on the capability of machining process in the post machining activity and requirement for metal components or products of complex geometry. I think, this has created another challenge for the machining process and researchers, once the PBF and HM Processes are able to reach the ML considering the main purpose of the invention.

It was discovered that the maturity level of hybrid manufacturing technology is equal to the outcome of the intersection of the two technologies maturity levels but needs proof with calculated values.

6.7 Size of Models and Source of Error

To reduce the rigor of a very long mathematical calculations which is prone to mistakes and errors in the fuzzy process, the number of membership functions of the Inputs and the Output subsets can be reduced to three. Whereas the experts' survey questionnaire response options can also be reduced to three, such as Yes, No and Other, which should be in percentage (%). Or Low, Medium, High response options. Yet, it still boils down to the researcher, the research aims and objectives, and tools employed. It is not that a serious problem.

6.8 Diversity, Fluidity and Adaptive Characteristics of Models

The generic technological maturity assessment model designed is observed to be fluidic in nature, hence the application on the process product quality, process efficiency and the process effectiveness show a lot of changes and differences in structures and nomenclatures as peculiarly demands by each variable. Thus, cannot be termed a repeat job even as they are not even the same going by their mathematical or theoretical relationships.

Meanwhile, if it is impossible for a single or the same machine to either consecutively or successively produce batches of metallic components, ceramic components, and plastic components in a row, then the generic semi-direct technological maturity assessment model developed, designed, and implemented in this research is not the same for the process product quality, efficiency, and effectiveness technological maturity assessment of the hybrid manufacturing technology that integrates metal additive manufacturing process. Hence, all basically require different ideology, different parameters, different personnel, different knowledge and experience, different materials, different machine component, different environment, different process, different approach, different expertise, and professional survey participants, which affect, change or adapt the original model.

6.9 Vague Decision Situation

The vagueness of the professionals and experts survey was determined by the difference between each defuzzified maturity value and the fuzzy experts expert survey statistical maturity value. Where the level of insignificance and negligibility is attributed to introduction of fuzzy logic theory at every level of the procedure.

6.10 Precautionary Measures

To further checkmate the chances or situation of bias in the questionnaire planning and administration system, and results, sure was made that the participating experts and professionals do not know the intended use or the actual purpose of the questionnaire exercise, neither the data nor their responses. With this approach, the possible sentimental influences are eliminated from the entire process.

6.11 Limitations

It will be good to know that first unlike the other or similar research, this research is not sponsored. Secondly, it is a private individual student's research with some limited social, political, and business opportunities. For instance, also unlike in the case of others who were able to organize, pulled out or mobilized experts in the manufacturing domain together to be able to identify and determine the processes maturity indicators (PMI) that will drive their research through brainstorming and Delphi-type workshops as a group. Where in this case, there was no such or near opportunity by the university, hence every attempt for inhouse or internal collaboration and corroboration was denied that I took it at some point as maybe PhD research norms. The same thing happened during quest for training on the SEI's CMM software as required. It was never considered even for discussion, that the research virtually remained a sole research effort. Some efforts were made to organize such privately off campus but was dashed by the COVID-19 Pandemic Lockdown and restrictions regime. Thus, slowed down the pace of the research as the process performance indicators applied were solely identified from publications and reading.

Although it may be understandable, hence CMM and CMMI maturity model as a business and management model, thereby needed to be guided and secured jealously by the owners or first investors from probable or potential competitors. Similarly, the same thing to some additive and hybrid manufacturing technology professionals and experts who hoard AM information and materials from certain individuals, being secretive, fearful and exercising some form of monopoly and control to prevent early acquisition and technology transfer or participation by Africa at this stage.

Thirdly, the questionnaire administration targeted but could not capture or reach the professional actors and experts in the industry uppermost echelon due to lack of required resources including connections to be able to get there. Unlike with others funded by international bodies and industry. When the desirable is not available, the available becomes desirable. Therefore, it is advised that the questionnaire be re-

administered at the industry top echelons for a more reliable and competitive performance capability maturity level results, and the responses collected, then sent for processing and reporting back. So, if the semi-direct technological maturity assessment model (SDTMAM) questionnaire can be sponsored to be administered at that high level of technology responsibility in collaboration with the University of Birmingham, MIT, Manufacturing Technology Centre (MTC), Research and Development (R&D), Research Institutes, and data is collected, then the SDTMAM will continue to process the technology current and more authentic maturity level of the CNC machining-PBF Hybrid Manufacturing Technology. This further industrial research I think, can be carried out under the postdoctoral research programme of the University of Birmingham.

Notwithstanding, in the research plan included an arrangement for industrial visits to some key institutions whose resources and activities in the course of this project dominated and drove the inspirations, hope and aspirations of the researcher. They include the Software Engineering Institute (SEI) at the Carnegie Mellon University, Pittsburgh, Pennsylvania, United States of America purposely for their CMM and CMMI maturity assessment models. As well, the two Japanese major and largest machine tools companies of the world, namely Yamazaki Mazak Corporation at the Mazak UK Ltd., Worcester, England and DMG MORI Company Ltd. at DMG MORI UK Ltd., Coventry, England purposely for their industrial revolutionary exploits in the additive and hybrid manufacturing technologies. However, only a visit to Mazak came to fruition during the period, but on a different arrangement by the University of Birmingham Mechanical Engineering students industrial visit led by my Supervisor early 2019, before the COVID-19 pandemic and its consequential lockdown later set in. It was a landmark experience, being lectured and introduced to the company history, business and goals, later taken round the entire production line, products and showroom. Although the other two intended visits were not physically accomplished at the time, but there is still hope for our future relationship in the academic and industrial research, and production services having gone this far.

Nevertheless, maturity assessment of complex systems like in manufacturing technology can never be carried out totally or wholesomely because the project depends on researchers' areas of interest and focus, guided by the aim and objective of the assessment which position and define the parametric variables, research architecture and the direction.

CHAPTER 7

CONCLUSION, CONTRIBUTION TO KNOWLEDGE, RECOMMENDATIONS AND FUTURE WORK

7.1 Summary

Guided by the aim and methodology of the research, the planned, developed and designed generic model for technological maturity assessment of hybrid manufacturing technologies commenced with the proper definition of the subject and process areas. Then, determination of process variable and parameters, and their capability performance indices, which formed the source of target research data. Also, guided by the objectives of the research which looked and determined the maturity of the hybrid manufacturing technology first from the proposed process capability areas (PCAs). They include the process products quality, production economy (customers), system effectiveness or ruggedness, and the process efficiency, for more research information and data requirement for process and product improvement. The CMMI model maturity profile only was adopted and characterized for all the three PCAs. Research interface model (tool), a fuzzy logic-based questionnaire was developed and designed each for the product quality, efficiency, and effectiveness technological maturity assessment of the manufacturing technologies.

Experts' technological maturity assessment survey for the three PCAs of the manufacturing technologies were planned for administration among the target and reachable respondent audience of quality and manufacturing engineers, production and cost engineers, design and process engineers respectively. These were targeted within a scope of three industry areas of academia, industrial and technology research institutes. Engineering statistical model was introduced for processing and analysing the results of each survey area. All the survey propositions which also represent the process performance indicators and invariably, the present state process or technology state or maturity will be ranked on the referenced CMMI maturity profile. However, since the mean values maturity results will still be in fuzzy form, hence each fuzzy

process technological maturity value will be 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 solution, the Inference System and graphing model will be used with the contribution of experts in a particular area 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, efficiency and the effectiveness maturity levels of a hybrid manufacturing technology that integrates metal subtractive (CNC machining) and additive (PBF) manufacturing technologies with very impressive results shown in the tables 42, 43, 44 and 45. Thus, considering the procedure, the consistency of results, and reality, technological maturity of any manufacturing technology, process and management system can be assessed by the generic semi-direct methodology model.

7.1.1 Testing the SDTMAM Processes Research Parametric Variables Utilized in a Word Cloud System

Having met research objectives, it just struck, and an idea came that word clouds each to be represented in a common shape, be formed on each set of process capability areas parametric variables and performance indices for each of the processes as in the appendices 5, 6, 7, 8 and 9. Then, on that of the metal hybrid manufacturing process, and compare the resultant word clouds formed afterwards. Thus, Figures 107, 108, 109, and 110 below show tests and results in aircraft shape expressing the sensitivity or intelligence of the variables, parameters, and capability performance indicators all equal and constant, utilized in the generic technological maturity assessment of the metal additive hybrid manufacturing technology in a word cloud system. The difference in the results is clear when tested on the individual processes, when the performance indices are still inactive state, and when the PIs are defined and active in hybrid manufacturing solution. Hence, the quality of products complete fit of sharpest edges as shown is best under hybrid manufacturing condition. This is a form of simple illustration of artificial intelligence and its capability. Hence, any product

of hybrid manufacturing technology or process is expected to always come out a novel phenotype, and better than the result of each of the parent processes under hybrid platform.

Figure 107. LPBF additive manufacturing process parameters and performance indices of appendices 5, 6, 7, 8 and 9, word cloud test result

Figure 108. CNC machining process parameters and performance indices of appendices 5, 6, 7, 8 and 9, word cloud test result

Figure 109. CNC machining-LPBF hybrid manufacturing process parameters and performance indices of appendices 5, 6, 7, 8 and 9, word cloud test result

Figure 110. CNC machining-LPBF hybrid manufacturing process parameters and performance indices of appendices 5, 6, 7, 8 and 9, word cloud test result

7.2 Contributions to Knowledge

Based on the development, design, implementation, and testing of the generic model for technological maturity assessment of HM technology that integrates machining and metal additive manufacturing processes, the research has been able make significant contributions to the field of HM and manufacturing engineering in general. Some of the key contributions are discussed below.

1. I have developed, designed, and delivered a new and generic technological maturity assessment model for hybrid manufacturing technologies.

2. I have used the model to determine the maturity level of metal additive HMT in terms of PPQ at QMML, PE at QMML, PEffec. at QMML and integrated ML also at quantitatively managed ML which is a novel contribution to the field.
3. I have generated the process capability areas performance indices for the HMT, in the areas of PPQ, PE, and PEffec. which further researchers could utilise.
4. I have extended the semi-direct technological maturity assessment model from the basic statistical process and analysis methodology to an iterative and more precise and conclusive model.
5. I have demonstrated 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.
6. I have been able to substantiate and quantify technological maturity in terms of the technology product quality, the technology efficiency, and the technology effectiveness of the processes, which is the first of its kind.
7. I have developed, designed, and generated a set of fluidic fuzzy questionnaires each for process product quality, process efficiency and process effectiveness maturity assessment of hybrid manufacturing technology.
8. I have generated a questionnaire statement bank for manufacturing technological assessment in the areas of PPQ, PE, and PEffec.
9. I have applied fuzzy logic which has enabled a more precise and realistic maturity survey, monitoring and assessment, which further researchers embarking on similar study will find as a useful tool.
10. Set theory is applicable to the maturity assessment results, especially in the maturity or compatibility assessment of the technologies in hybrid manufacturing process.
11. The vagueness of each of the experts' survey results as shown can be determined from the maturity assessment result.

12. A proof is established based on the graphical technique inference for the inputs and output, that the maturity level of hybrid manufacturing technology is the intersection or interface of the two technologies or processes maturity levels.

7.3 Conclusion

In conclusion therefore, the methodology for maturity assessment of hybrid manufacturing technology was designed. The model was successfully illustrated and implemented on the CNC machining-LPBF hybrid manufacturing process, and the results were simulated with impressive and consistent outcomes as follows and shown in table 46 below.

The HMT maturity for PPQ is therefore at 63.5%

The HMT maturity for PE is therefore at 67.75%

The HMT maturity for PEffec. is therefore at 71.63%

The overall maturity level of the HMT for the PPQ, PE and PEffec. is 3.39 which is 67.63%.

This technology is therefore at the 'quantitively managed' maturity level.

Table 46. Aggregate PCM ML of the Machining-PBF HMT

Aggregate Performance Capability Maturity of PBF-Machining HMT					
PBF		***Machining***		***HMT***	
ML	%tage	ML	%tage	ML	%tage
3.42	68.33	3.9	78	3.39	67.63

Moreover, it is a generic model in the sense that it takes only provisions and definition of any choice technology maturity data, the variables, and the parameters of the capability area, and the performance indices. Thus, a raw maturity survey results to run the capability maturity assessment model for any

manufacturing technology as with the case of the product quality, efficiency, and effectiveness technological maturity assessment of the metal additive hybrid manufacturing technology.

Also, it is a generic model because it has proved its flexibility and capacity that it can be adopted or adapted and used to plan and execute a technological maturity assessment of a single manufacturing technology, a hybrid manufacturing technology, and any other technology that integrates more than two manufacturing processes.

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 not able to apply it in every other domain. Hence, you will always need corroboration or collaboration with the experts in that field.

Thus, the current study is therefore a smart pioneer or foundational research which will open doors for further research in the manufacturing technologies with the help of digital technology and artificial intelligence, data, and software engineering.

7.4 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, hence

1. A computer programme to run the new designed generic technological maturity assessment model and the algorithm for hybrid manufacturing technology be written

2. Determine the compatibility of the hybrid manufacturing processes

3. Conventional laboratory qualitative method should be conducted for parametric PPQ technological maturity assessment research data collection

4. Study should also be carried out on the technological maturity assessment of polymers or plastics, and ceramics additive hybrid manufacturing technologies.

5. A larger sample size should be utilised in the next data collection. It positively influences the statistical properties such as the precision of estimates and the power of the study to draw conclusion.

6. Conduct Technological Maturity Assessment in terms of Certification, Qualification and Standardization in Additive and Hybrid Manufacturing Technology (HMT)

7. Continuous interrogation and review of the process capability performance areas, characteristics, propositional statements, and questionnaire design for maturity assessment of HMT

8. For more reliability and confidence of research, sure must be made that complementary structured interviews, internet- or intranet- mediated questionnaires are administered directly to the industry quality and manufacturing engineers for process product quality, the production and cost engineers, for the process efficiency, also the design and process engineers, for the process effectiveness

9. Consider applying, and combining other fuzzy membership functions such as the Gaussians

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APPENDICES

Appendix 1

The pictures of some Additive and Hybrid Manufacturing Machines by Mazak, from Yamazaki Mazak UK Ltd.

Appendix 2

The pictures of some industry application and examples of Additively hybrid Manufactured metal components by Yamazaki Mazak UK Ltd.

Some pictures of Mazak's aerospace industry application and examples

Some high efficiency machining demanding difficult to cut materials
medical industry equipment and prothetics application and examples

Artificial Knee

Artificial heart valve component

Knee joint

Spine plate

Knee-joint prosthetic

Some pictures of Mazak's automotive industry application and examples

Engine cylinder block

Automotive component

Machine model

Engine crankshaft

Some pictures of Mazak's industrial application and examples

Coating as sealing purpose

Near net shape

Repair/modification

Coating with metallurgical bond/Fine modeling

Some Pictures of Mazak's construction and power industry Application and examples

Large Component machining by quil

Gear skiving

Smooth gear milling

A piston pump part endmill machining

Appendix 3

The pictures of some Additive and Hybrid Manufacturing Machines by DMG MORI

Lasertec 12 SLM Powder Bed

Lasertec 125, DED Hybrid

Lasertec 30 Dual SLM Powder Bed

Lasertec 3000 DED Hybrid

Lasertec 65 DED Powder Nozzle

Lasertec 65 DED Hybrid

Lasertec 6600 DED Hybrid

Appendix 4

The pictures of some industry application and examples of Powder Bed Additively Hybrid Manufactured metal components by DMG MORI

Heat Exchanger, for Aerospace Industry

Blade, for Aerospace Industry

Palatal Plate, for Medical Industry

Tooth Crowns, for Medical Industry

Sensor Elements, for Medical Industry

Robo2Go Head, for Engineering Industry

Powder Nozzle Body, for Engineering Industry

Tube with Inner Cooling, for Engineering Industry

Distribution Tube, for Engineering Industry

Insert, for Plant Engineering Industry

Laminar Flow Reverser,
for Plant Engineering Industry

Wheel Carrier, for Automotive Industry

Functional Parts, for Automotive Industry

PKD Milling Head, for Tooling Industry

Appendix 5

The Subtractive (CNC machining) and Metal Additive Manufacturing Processes 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

Appendix 6

The Hybrid CNC Machining-LPBF Additive Manufacturing Parametric Interface

S/No	**The Hybrid Machining-LPBF Additive 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		

Appendix 7

Process Product Quality Performance Indices

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

Appendix 8

Process Efficiency Performance Indices

S/No.	***Process Efficiency Performance Indices***
1	Fulfilment of a full implementation of hybrid machines in terms of process planning
2	Space management
3	Number of personnel or operator requirement
4	Investment capital rating and requirement
5	Cost of final part reduction
6	Material efficiency target of 97%
7	Material movement inside factory
8	Material waste reduction
9	Attainment of standard methodology or process planning in hybrid machines
10	Involving software tool solution in design, process planning, and part inspection
11	Designers and engineer's mindset status
12	Process or technology attainment of its commercial values
13	Financial risk associated with the process
14	Machine downtime
15	Process becoming off the shelve technology
16	Cost of maintenance of machine
17	Cost of human, services, and material resources
18	Process Commercial value
19	Process flexibility
20	A good number of equipment manufacturers or suppliers
21	Low capital investment
22	Reduction in production cycle
23	Product availability and affordability
24	Process Industrial demand
25	Commercialized process or technology
26	Process financial risk assessment
27	Development of new application areas for the process
28	Process Automation
29	Process impact study or analysis
30	Quantitative production run or work product
31	Process attainment of current and future business need
32	Increased profit margin
33	Process throughput yield
34	Level of control and monitoring systems

Appendix 9

Process Effectiveness Performance Indices

S/No.	***Process Effectiveness Performance Indices***
1	Vibration during machining
2	Seamless switching between additive and machining operations during manufacturing
3	Ecological footprint analysis
4	Use of cutting fluid and the effects or influence
5	Establishing the material deposition rate relationship between machine feed rate, volume of the substrate, and the geometry of the region where the material is being deposited, the surface finish etc
6	Safety issues of powder handling and laser operation
7	Generated residues or remnants handling
8	Powder recovery, recycling, or reusability
9	Maintaining a constant processing velocity during the DED process
10	Melt pool width size and temperature monitoring, and control
11	Control of microstructure of a deposited material
12	Detect deviation from set parametric values of process such as layer size and thickness
13	Look ahead monitoring system in place
14	Maintaining the gap between the nuzzle and the substrate or preceding layer
15	Experimentally obtained databases to correlate process parameters
16	Power blowing and laser cleaning prior to additive process
17	Enough research, publication, and discussions about the process
18	Existence of operational procedure and standard
19	Compatibility with the standard data handling software
20	Ability to convert data files to specific data formats
21	Documentation in data management system
22	Provisions or accommodation for new materials and application
23	Availability of well-defined parameters
24	Training programmes
25	A unified or universal procedure
26	Adequate teaching and learning in the universities and colleges
27	Review or auditing mechanism or procedure for quality management purposes
28	Process laboratory or industrial application

29	Determination of the effects of individual process parameters on the performance
30	Defined and calculated process characteristics
31	Study and understanding the source of measurement error or process uncertainty
32	Application of specific implementation of process
33	Defined aim and objective of process improvement and optimization
34	Continuous process performance improvement through scientific research and innovations
35	New applicable materials findings in the process
36	Operators' skill and knowledge-based process performance and capabilities
37	Process attainment of potential values
38	Process yield analysis
39	Process measurement system
40	Known effects of process parameters on product characteristics
41	Process precise but inaccurate results due to system error
42	Relationship between process modelling or simulation and the actual performance
43	Accuracy of the process model simulation with respect to the actual performance
44	Availability of accepted and accurate process analytical model for simulation

Appendix 10

A cover Letter sample for research questionnaire administered to the one hundred recipients [109].

University of Birmingham
Edgbaston
Birmingham
B15 2TT
United Kingdom

Mr X
Address:

3rd July 2020

Dear Mr X,

Hybrid Metal Manufacturing Technologies Questionnaire (Your views on maturity state of individual and integrated machining-PBF processes)

This questionnaire is part of a research project to understand experts' views about state - of - the - art hybrid metal manufacturing technologies. Your responses are important in enabling me to obtain as full an understanding as possible of this subject.

The questionnaire should take you about fifteen minutes to complete. Please, answer the questions in the provisions made. If you wish to add further comments, please feel free to do so. All your responses will be treated in the strictest of confidence and only aggregated data will be available to the thesis. All the questionnaires will be shredded once the data have been extracted. A summary of the results will be published. You will notice that you are not asked to include your name and address anywhere in the questionnaire.

The findings from your questionnaire and others will be used as the main data set for my thesis for my PhD course in Mechanical Engineering at the University of Birmingham.

I hope you will find completing the questionnaire interesting. Please return the completed questionnaire to me, Eberechukwu Dim by 10th October 2020 through the above email address. If you have any queries or would like further information, please feel free to contact me on

Thank you for your help.

Mr Eberechukwu Dim

Appendix 11

LPBF AMT Performance Product Quality Maturity Questionnaire and Data Matrix of the 1St, 2Nd, and 3Rd Groups of Respondents

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

2nd Respondent						3rd Respondent				
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*		*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
			X					X		
		X						X		
		X						X		
		X						X		
			X						X	
		X						X		
		X						X		
		X						X		
			X					X		
		X						X		
		X						X		
		X						X		
		X						X		
		X						X		
		X						X		
			X						X	
			X						X	
			X						X	
		X						X		
		X						X		
		X						X		
		X						X		
		X						X		
		X						X		
			X						X	
		19	**7**					**21**	**5**	

Appendix 12

LPBF AMT Product Quality Survey Data Collection

LPBF AMT PQ Survey Data Collation							
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*	Average	ML	Process Area PI No.
		1	2		**3.67**	4	1
		3			**3**	3	2
		3			**3**	3	3
		3			**3**	3	4
			3		**4**	4	5
		3			**3**	3	6
		3			**3**	3	7
		3			**3**	3	8
		1	2		**3.67**	4	9
		3			**3**	3	10
		3			**3**	3	11
		3			**3**	3	12
		3			**3**	3	13
	1	2			**2.67**	3	14
	1	2			**2.67**	3	15
		3			**3**	3	16
			3		**4**	4	17
			3		**4**	4	18
	1		2		**3.33**	4	19
	1	2			**2.67**	3	20
		3			**3**	3	21
		3			**3**	3	22
	1	2			**2.67**	3	23
	1	2			**2.67**	3	24
		3			**3**	3	25
			3		**4**	4	26
	6	**54**	**18**				

LPBF PQ Capability Maturity		
S/No	PA & PI	ML
1		5
2	1, 5, 9, 17, 18, 19, 26	4
3	11, 12, 13, 14, 15, 16, 20	3
4		2
5		1

Appendix 13

LPBF Product Quality Capability Maturity

LPBF PQ Capability Maturity		
S/No	PA & PI	ML
1		5
2	1, 5, 9, 17, 18, 19, 26	4
3	2, 3, 4, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 20, 21, 22, 23, 24, 25	3
4		2
5		1

Appendix 14

Machining AMT Performance Product Quality Maturity Questionnaire and Data Matrix of the 1St, 2Nd, and 3Rd Groups of Respondents

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

	2nd Respondent						3rd Respondent			
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*		*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
			X						X	
		X						X		
		X							X	
			X							X
			X						X	
			X						X	
			X							X
			X							X
		X						X		
			X							X
		X						X		
			X							X
			X						X	
			X						X	
		X						X		
			X							X
			X						X	
			X						X	
			X						X	
		X						X		
			X					X		
			X						X	
			X						X	
			X						X	
		X						X		
			X							X
		7	**19**					**7**	**12**	**7**

Appendix 15

Machining Product Quality Survey Data Collection

Machining PQ Survey Data Collation							
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*	Average	ML	Process Area PI No.
			3		**4**	4	1
		3			**3**	3	2
		1	2		**3.67**	4	3
			1	2	**4.67**	5	4
			2	1	**4.33**	5	5
			2	1	**4.33**	5	6
			1	2	**4.67**	5	7
			1	2	**4.67**	5	8
		3			**3**	3	9
			2	1	**4.33**	5	10
		3			**3**	3	11
			2	1	**4.33**	5	12
			3		**4**	4	13
			3		**4**	4	14
		3			**3**	3	15
			2	1	**4.33**	5	16
			3		**4**	4	17
			3		**4**	4	18
		1	2		**3.67**	4	19
		3			**3**	3	20
		1	2		**3.67**	4	21
			3		**4**	4	22
			2	1	**4.33**	5	23
			2	1	**4.33**	5	24
		2	1		**3.33**	4	25
			1	2	**4.67**	5	26
		20	**43**	**15**			

Machining PQ Capability Maturity		
S/No	PA & PI	ML
1	6, 7, 8, 10, 12, 16, 23, 2	5
2	13, 14, 17, 18, 19, 21, 2	4
3	2, 9, 11, 15, 20	3
4		2
5		1

Appendix 16

Machining Product Quality Capability Maturity

Machining PQ Capability Maturity		
S/No	PA & PI	ML
1	4, 5, 6, 7, 8, 10, 12, 16, 23, 24, 26	5
2	1, 3, 13, 14, 17, 18, 19, 21, 22, 25	4
3	2, 9, 11, 15, 20	3
4		2
5		1

Appendix 17

LPBF and Machining Processes Product Quality Frequency Distributions

Processes Product Quality Frequency Distributions			
LPBF			
Serial No	Maturity Levels	%tage Ratings	Frequency (f)
1	Initial	0 - 19	
2	Managed	20 - 39	6
3	Defined	40 - 59	54
4	Quantitatively managed	60 - 79	18
5	Optimizing	80 - 99	
Machining			
Serial No	Maturity Levels	%tage Ratings	Frequency (f)
1	Initial	0 - 19	
2	Managed	20 - 39	
3	Defined	40 - 59	20
4	Quantitatively managed	60 - 79	43
5	Optimizing	80 - 99	15

Appendix 18

Engineering mathematical manual calculation based on the Centroid Defuzzification for the PPQ HMT maturity level.

Finally, defuzzifying value (Z*) implies introducing a Centroid Defuzzification formula

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

Hence the technological maturity for PPQ is the result of the defuzzification of the shaded portion of the graphical figure 41.

Therefore,

Z* =

$$\frac{\int_{20}^{28}\frac{0.45x-9}{8}*xdx+\int_{28}^{48}0.45*xdx+\int_{48}^{52}\frac{0.1x-3}{4}*xdx+\int_{52}^{68}0.55*xdx+\int_{68}^{80}\frac{-0.55x+44}{12}*xdx}{\int_{20}^{28}\frac{0.45x-9}{8}*dx+\int_{28}^{48}0.45*dx+\int_{48}^{52}\frac{0.1x-3}{4}*dx+\int_{52}^{68}0.55*dx+\int_{68}^{80}\frac{-0.55x+44}{12}*dx}$$

Solving for the value of the numerator:

(i) $\int_{20}^{28}\frac{0.45x-9}{8}*xdx = \frac{1}{8}\int_{20}^{28}(0.45x-9)xdx = \frac{1}{8}\int_{20}^{28}(0.45x^2-9x)dx$

$= \frac{1}{8}\left(\frac{0.45x^3}{3}-\frac{9x^2}{2}+C\,\Big|_{20}^{28}\right) = \frac{0.45x^3}{24}-\frac{9x^2}{16}+C\,\Big|_{20}^{28}$; **when x = 28, and subtracting when x = 20**

= (411.6 – 441) – (150 – 225) = (-29.4) – (-75) = -29.4 + 75

= <u>45.6</u>

(ii) $\int_{28}^{48}0.45*xdx = \int_{28}^{48}(0.45x)dx = \frac{0.45x^2}{2}+C\,\Big|_{28}^{48}$;

when x = 48, and subtracting when x = 28

= (518.4 – 176.4) = <u>342</u>

(iii) $\int_{48}^{52}\frac{0.1x-3}{4}*xdx = \frac{1}{4}\int_{48}^{52}(0.1x-3)xdx = \frac{1}{4}\int_{48}^{52}(0.1x^2-3x)dx$

$= \frac{1}{4}\left(\frac{0.1x^3}{3}-\frac{3x^2}{2}+C\,\Big|_{48}^{52}\right) = \frac{0.1x^3}{12}-\frac{3x^2}{8}+C\,\Big|_{48}^{52}$;

when x = 52, and subtracting when x = 48

= (1171.73 – 1014) – (921.6 – 864) = (157.73) – (57.6) = <u>100.13</u>

(iv) $\int_{52}^{68}0.55*xdx = \int_{52}^{68}(0.55x)dx = \frac{0.55x^2}{2}+C\,\Big|_{52}^{68}$;

when x = 68, and subtracting when x = 52

= (1271.6 – 743.6) = <u>528</u>

(v) $\int_{68}^{80}\frac{-0.55x+44}{12}*xdx = \frac{1}{12}\int_{68}^{80}(-0.55x^2+44x)dx = \frac{1}{12}\left(\frac{-0.55x^3}{3}+\frac{44x^2}{2}+C\,\Big|_{68}^{80}\right)$

$= \frac{-0.55x^3}{36}+\frac{44x^2}{24}+C\,\Big|_{68}^{80}$;

when x = 80, and subtracting when x = 68

= (-7822.22 + 11733.33) – (-4803.82 + 8477.33) = 3911.11 – 3673.51 = <u>237.6</u>

Now, for the denominator:

(i) $\int_{20}^{28} \frac{0.45x-9}{8} * dx = \frac{1}{8}\int_{20}^{28}(0.45x-9)dx = \frac{1}{8}\left(\frac{0.45x^2}{2} - 9x + C\,\Big|_{20}^{28}\right)$

= $\frac{0.45x^2}{16} - \frac{9x}{8} + C\,\Big|_{20}^{28}$; when x = 28, and subtracting when x = 20

= (22.05 – 31.5) – (11.25 – 22.5) = (-9.45) – (-11.25) = -9.45 + 11.25 = <u>1.8</u>

(ii) $\int_{28}^{48} 0.45 * dx = 0.45x + C\,\Big|_{28}^{48}$;

when x = 48, and subtracting when x = 28

= 21.6 – 12.6 = <u>9</u>

(iii) $\int_{48}^{52} \frac{0.1x-3}{4} * dx = \frac{1}{4}\int_{48}^{52}(0.1x-3)dx = \frac{1}{4}\int_{48}^{52}\left(\frac{0.1x^2}{2} - 3x\right)dx$

= $\frac{1}{4}\left(\frac{0.1x^2}{2} - \frac{3x}{1} + C\,\Big|_{48}^{52}\right) = \frac{0.1x^2}{8} - \frac{3x}{4} + C\,\Big|_{48}^{52}$;

when x = 52, and subtracting when x = 48

= (33.8 – 39) – (28.8 – 36) = (-5.2) – (-7.2) = -5.2 + 7.2 = <u>2</u>

(iv) $\int_{52}^{68} 0.55 * dx = 0.55x + C\,\Big|_{52}^{68}$;

when x = 68, and subtracting when x = 52

= 37.4 – 28.6 = <u>8.8</u>

(v) $\int_{68}^{80} \frac{-0.55x+44}{12} * dx = \frac{1}{12}\int_{68}^{80}(-0.55x+44)dx = \frac{1}{12}\left(\frac{-0.55x^2}{2} + 44x + C\,\Big|_{68}^{80}\right)$

$$= \frac{-0.55x^2}{24} + \frac{44x}{12} + C \Big|_{68}^{80};$$

when x = 80, and subtracting when x = 68

= (-146.67 + 293.33) – (-105.97 + 249.33) = 146.66 – 143.36 = <u>3.3</u>

Thus,

$$\boldsymbol{Z^*} = \frac{\sum(45.6 + 342 + 100.13 + 528 + 237.6)}{\sum(1.8 + 9 + 2 + 8.8 + 3.3)} = \frac{1253.33}{24.9} = 50.33$$

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

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

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 (%) process product quality maturity of Machining-Additive LPBF hybrid manufacturing technology, implies

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

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

Appendix 19

LPBF AMT Performance Efficiency Maturity Questionnaire and Data Matrix of the 1St, 2Nd, and 3Rd Groups of Respondents

LPBF AMT Performance Efficiency Maturity Questionnaire and Data Matrix (1st Respondent)						
S/No	***Questionnaire Statements/Proposition***	***Not True***	***Not Quite True***	***Fairly True***	***True.***	***Very True***
1	Full implementation of manufacturing in terms of process planning has been fulfilled			X		
2	Process operational space requirement has been minimized				X	
3	The number of personnel or operator requirement has reduced				X	
4	The investment capital rating and requirements has reasonably dwindled			X		
5	There are proven means of achieving a substantial reduction in the cost of final part				X	
6	The material efficiency target of 97% has been attained, in terms of reduction in energy demand, reducing the emissions and other environmental impacts of the industry			X		
7	There is enough investment in the approaches that optimise material management		X			
8	There are practices established to minimize the generation of waste in the manufacturing process				X	
9	There is a standard methodology for process planning in manufacturing			X		
10	There is a software tool solution in design, process planning and part inspection in the technology			X		
11	Engineers and designers mindsets have been focused on the priority area of product quality or customers based				X	
12	The process has been able to deliver or attained business values			X		
13	There are no potential financial risks associated with investing in the process			X		
14	There is a system in place to minimize down time			X		
15	The process has become off the shelve technology			X		
16	The cost of maintenance is at minimal			X		
17	There are now reductions in the cost of human and material resources			X		
18	There are systems available to enhance the performance of the manufacturing facilities				X	
19	The manufacturing process is coping with the growing product varieties				X	
20	The number of original equipment manufacturers (OEM) has gone more than 50			X		
21	The technology now require a low capital investment			X		
22	There is a recorded time reduction in production cycle			X		
23	The process manufactured products are readily available and affordable			X		
24	The industrial demand for the process is getting higher				X	
25	The process of introducing the technology and products into the general market has been successful			X		
26	There exists a financial risk assessment system for potential investors				X	
27	There are new application areas developed for the process				X	
28	The process make use of largely or mostly automatic equipment				X	
29	There is a systematic instrument to determine and evaluate the potential effects of an interruption to critical manufacturing operations as a result of fluctuation or failure of resources; power, energy etc				X	
30	The process quantitative production run or workproduct target has been attained			X		
31	The business need of the manufacturing process has been identified and well understood				X	
32	The measure of the process profitability has been satisfactory				X	
33	The number of the process manufactured product defect free unit or pieces is optimized			X		
34	Complex qeometric parts now produced without much human intervention				X	
			1	**18**	**15**	

	2nd Respondent						3rd Respondent			
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*		*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
		X						X		
			X						X	
			X						X	
		X						X		
			X						X	
		X						X		
		X						X		
			X						X	
		X						X		
		X							X	
			X						X	
		X							X	
		X						X		
			X						X	
		X						X		
X									X	
		X						X		
			X						X	
			X						X	
		X						X		
		X						X		
		X						X		
		X						X		
		X						X		
		X						X		
		X						X		
			X						X	
			X						X	
			X						X	
		X						X		
			X						X	
			X						X	
		X						X		
			X						X	
1		**19**	**14**					**17**	**17**	

Appendix 20

LPBF AMT Process Efficiency Survey Data Collection

LPBF AMT PE Survey Data Collation							
Not True	***Not Quite True***	***Fairly True***	***True.***	***Very True***	**Average**	**ML**	**Process Area PI No.**
		3			**3**	3	1
			3		**4**	4	2
			3		**4**	4	3
		3			**3**	3	4
			3		**4**	4	5
		3			**3**	3	6
	1	2			**2.67**	3	7
			3		**4**	4	8
		3			**3**	3	9
		2	1		**3.33**	4	10
			3		**4**	4	11
		2	1		**3.33**	4	12
		3			**3**	3	13
		1	2		**3.67**	4	14
		3			**3**	3	15
1		1	1		**2.67**	3	16
		3			**3**	3	17
			3		**4**	4	18
			3		**4**	4	19
		3			**3**	3	20
		3			**3**	3	21
		3			**3**	3	22
		3			**3**	3	23
		2	1		**3.33**	4	24
		3			**3**	3	25
		2	1		**3.33**	4	26
			3		**4**	4	27
			3		**4**	4	28
			3		**4**	4	29
		3			**3**	3	30
			3		**4**	4	31
			3		**4**	4	32
		3			**3**	3	33
			3		**4**	4	34
1	**1**	**54**	**46**				

LPBF PE Capability Maturity		
S/No	**PA & PI**	**ML**
1		**5**
2	**2, 14, 18, 19, 24, 26, 27**	**4**
3	**3, 15, 16, 17, 20, 21, 22,**	**3**
4		**2**
5		**1**

Appendix 21

LPBF Process Efficiency Capability Maturity

LPBF PE Capability Maturity		
S/No	PA & PI	ML
1		5
2	2, 3, 5, 8, 10, 11, 12, 14, 18, 19, 24, 26, 27, 28, 29, 31, 32, 34	4
3	1, 4, 6, 7, 9, 13, 15, 16, 17, 20, 21, 22, 23, 25, 30, 33	3
4		2
5		1

Appendix 22

Machining AMT Performance Efficiency Maturity Questionnaire and Data Matrix of the 1St, 2Nd, and 3Rd Groups of Respondents

Machining Performance Efficiency Maturity Questionnaire and Data Matrix (1st Respondent)						
S/No	***Questionnaire Statements/Proposition***	***Not True***	***Not Quite True***	***Fairly True***	***True.***	***Very True***
1	Full implementation of manufacturing in terms of process planning has been fulfilled					X
2	Process operational space requirement has been minimized					X
3	The number of personnel or operator requirement has reduced					X
4	The investment capital rating and requirements has reasonably dwindled				X	
5	There are proven means of achieving a substantial reduction in the cost of final part				X	
6	The material efficiency target of 97% has been attained, in terms of reduction in energy demand, reducing the emissions and other environmental impacts of the industry				X	
7	There is enough investment in the approaches that optimise material management			X		
8	There are practices established to minimize the generation of waste in the manufacturing process				X	
9	There is a standard methodology for process planning in manufacturing				X	
10	There is a software tool solution in design, process planning and part inspection in the technology				X	
11	Engineers and designers mindsets have been focused on the priority area of product quality or customers based				X	
12	The process has been able to deliver or attained business values				X	
13	There are no potential financial risks associated with investing in the process			X		
14	There is a system in place to minimize down time				X	
15	The process has become off the shelve technology				X	
16	The cost of maintenance is at minimal				X	
17	There are now reductions in the cost of human and material resources				X	
18	There are systems available to enhance the performance of the manufacturing facilities				X	
19	The manufacturing process is coping with the growing product varieties			X		
20	The number of original equipment manufacturers (OEM) has gone more than 50				X	
21	The technology now require a low capital investment				X	
22	There is a recorded time reduction in production cycle				X	
23	The process manufactured products are readily available and affordable				X	
24	The industrial demand for the process is getting higher				X	
25	The process of introducing the technology and products into the general market has been successful				X	
26	There exists a financial risk assessment system for potential investors				X	
27	There are new application areas developed for the process				X	
28	The process make use of largely or mostly automatic equipment				X	
29	There is a systematic instrument to determine and evaluate the potential effects of an interruption to critical manufacturing operations as a result of fluctuation or failure of resources; power, energy etc				X	
30	The process quantitative production run or workproduct target has been attained				X	
31	The business need of the manufacturing process has been identified and well understood				X	
32	The measure of the process profitability has been satisfactory				X	
33	The number of the process manufactured product defect free unit or pieces is optimized				X	
34	Complex qeometric parts now produced without much human intervention			X		
				4	**27**	**3**

	2nd Respondent						3rd Respondent			
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*		*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
			X						X	
			X						X	
			X						X	
		X						X		
		X						X		
			X						X	
			X						X	
		X						X		
			X						X	
			X						X	
			X						X	
			X						X	
		X						X		
			X						X	
			X						X	
X								X		
		X							X	
			X						X	
		X						X		
			X						X	
X								X		
			X						X	
X									X	
			X						X	
			X						X	
		X							X	
			X					X		
		X							X	
			X						X	
			X						X	
			X						X	
			X						X	
		X						X		
3		**9**	**22**					**9**	**25**	

Appendix 23

Machining Process Efficiency Survey Data Collection

Machining PE Survey Data Collation							
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*	Average	ML	Process Area PI No.
			2	1	**4.33**	5	1
			3		**4**	4	2
			3		**4**	4	3
		2	1		**3.33**	4	4
		2	1		**3.33**	4	5
			3		**4**	4	6
		1	2		**3.67**	4	7
		2	1		**3.33**	4	8
			3		**4**	4	9
			3		**4**	4	10
			3		**4**	4	11
			3		**4**	4	12
		3			**3**	3	13
			3		**4**	4	14
			3		**4**	4	15
1		1	1		**2.67**	3	16
		1	2		**3.67**	4	17
			3		**4**	4	18
		3			**3**	3	19
			3		**4**	4	20
1		1	1		**2.67**	3	21
			3		**4**	4	22
1			2		**3**	3	23
			3		**4**	4	24
			3		**4**	4	25
		1	2		**3.67**	4	26
		1	2		**3.67**	4	27
		1	2		**3.67**	4	28
			3		**4**	4	29
			3		**4**	4	30
			3		**4**	4	31
			3		**4**	4	32
			3		**4**	4	33
		3			**3**	3	34
3		**22**	**76**	**1**			

Machining PE Capability Maturity		
S/No	PA & PI	ML
1	1	5
2	4, 15, 17, 18, 20, 22, 24,	4
3	13, 16, 19, 21, 23, 34	3
4		2
5		1

Appendix 24

Machining Process Efficiency Capability Maturity

Machining PE Capability Maturity		
S/No	PA & PI	ML
1	1	5
2	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 17, 18, 20, 22, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33	4
3	13, 16, 19, 21, 23, 34	3
4		2
5		1

Appendix 25

LPBF and Machining Processes Efficiency Frequency Distributions

Processes Efficiency Frequency Distributions			
LPBF			
Serial No	Maturity Levels	%tage Ratings	Frequency (f)
1	Initial	0 - 19	1
2	Managed	20 - 39	1
3	Defined	40 - 59	54
4	Quantitatively managed	60 - 79	46
5	Optimizing	80 - 99	
Machining			
Serial No	Maturity Levels	%tage Ratings	Frequency (f)
1	Initial	0 - 19	3
2	Managed	20 - 39	
3	Defined	40 - 59	22
4	Quantitatively managed	60 - 79	76
5	Optimizing	80 - 99	1

Appendix 26

Engineering mathematical manual calculation based on the Centroid Defuzzification for the PE HMT maturity level.

Finally, defuzzifying value (Z*) implies introducing a Centroid Defuzzification formula

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

Hence the technological maturity for PE is the result of the defuzzification of the shaded portion of the graphical figure 59.

Therefore,

Z* =

$$\frac{\int_0^{20}(0) * xdx + \int_{20}^{25}\frac{0.25x-5}{5} * xdx + \int_{25}^{45} 0.25 * xdx + \int_{45}^{55}\frac{0.5x-20}{10} * xdx + \int_{55}^{65} 0.75 * xdx + \int_{65}^{80}\frac{-0.75x+60}{15} * xdx}{\int_0^{20}(0) * dx + \int_{20}^{25}\frac{0.25x-5}{5} * dx + \int_{25}^{45} 0.25 * dx + \int_{45}^{55}\frac{0.5x-20}{10} * dx + \int_{55}^{65} 0.75 * dx + \int_{65}^{80}\frac{-0.75x+60}{15} * dx}$$

Solving for the value of the numerator:

(i) $\int_0^{20}(0) * xdx = 0$

(ii) $\int_{20}^{25}\frac{0.25x-5}{5} * xdx = \frac{1}{5}\int_{20}^{25}(0.25x^2 - 5x)dx = \frac{1}{5}\int_{20}^{25}\frac{0.25x^3}{3} - \frac{5x^2}{2}$

= $\frac{0.25x^3}{15} - \frac{5x^2}{10} + C \Big|_{20}^{25}$ **; when x = 25, and subtracting when x = 20**

= (260.42 – 312.5) – (133.33 – 200) = (-52.08) – (-66.67) = -52.08 + 66.67

= $\underline{14.59}$

(iii) $\int_{25}^{45} 0.25 * xdx = \int_{20}^{25}(0.25x)dx = \frac{0.25x^2}{2} + C \Big|_{25}^{45}$ **;**
when x = 45, and subtracting when x = 25

= (253.13 – 78.13) = <u>175.01</u>

(iv) $\int_{45}^{55} \frac{0.5x-20}{10} * xdx = \frac{1}{10}\int_{45}^{55}(0.5x-20)dx = \frac{1}{10}\int_{45}^{55}(0.5x^2-20x)dx$

$= \frac{1}{10}\left(\frac{0.25x^3}{3} - \frac{5x^2}{2} + C\,|_{45}^{55}\right) = \frac{0.25x^3}{30} - \frac{5x^2}{20} + C\,|_{45}^{55}$;

when x = 55, and subtracting when x = 45

= (2772.92 – 3025) – (1518.75 – 2025) = (-252.08) – (-506.25) = -252.08 + 506.25

= $\underline{254.17}$

(v) $\int_{55}^{65} 0.75 * xdx = \int_{55}^{65}(0.75x)dx = \frac{0.75x^2}{2} + C\,|_{55}^{65}$;
when x = 65, and subtracting when x = 55

= (1584.38 – 1134.38) = 449.995 = <u>450</u>

(vi) $\int_{65}^{80} \frac{-0.75x+60}{15} * xdx = \frac{1}{15}\int_{65}^{80}(-0.75x^2+60x)dx = \frac{1}{15}\left(\frac{-0.75x^3}{3} + \frac{60x^2}{2} + C\,|_{65}^{80}\right)$

$= \frac{-0.75x^3}{45} + \frac{5x^2}{30} + C\,|_{65}^{80}$;

when x = 80, and subtracting when x = 65

= (-8533.33 + 12800) – (-4577.08 + 8450) = (4266.67) – (3872.92) = <u>393.75</u>

Now, for the denominator:

(i) $\int_{0}^{20}(0)\,dx = 0$

(ii) $\int_{20}^{25} \frac{0.25x-5}{5} * dx = \frac{1}{5}\int_{20}^{25}(0.25x-5)dx = \frac{1}{5}\int_{20}^{25} \frac{0.25x^2}{2} - \frac{5x}{1}$

$= \frac{0.25x^2}{10} - \frac{5x}{5} + C\,|_{20}^{25}$; when x = 25, and subtracting when x = 20

= (15.63 – 25) – (10 – 20) = (-9.37) – (-10) = -9.37 + 10

= $\underline{0.63}$

(iii) $\int_{25}^{45} 0.25 * dx \quad = \quad 0.25x + C \,|\, \begin{matrix} 45 \\ 25 \end{matrix}$

when x = 45, and subtracting when x = 25

= (11.25 – 6.25) = <u>5</u>

(iv) $\int_{45}^{55} \frac{0.5x-20}{10} * dx \quad = \quad \frac{1}{10} \int_{45}^{55} (0.5x - 20) dx \quad = \quad \frac{1}{10}\left(\frac{0.5x^2}{2} - \frac{20x}{1} + C \,|\, \begin{matrix} 55 \\ 45 \end{matrix}\right)$

$= \quad \frac{0.5x^2}{20} - \frac{20x}{10} + C \,|\, \begin{matrix} 55 \\ 45 \end{matrix};$

when x = 55, and subtracting when x = 45

= (75.63 – 110) – (50.63 – 90) = (-34.37) – (-39.37) = -34.37 + 39.37

= <u>5</u>

(v) $\int_{55}^{65} 0.75 * dx \quad = \quad 0.75x + C \,|\, \begin{matrix} 65 \\ 55 \end{matrix}$

when x = 65, and subtracting when x = 55

= (48.75 – 41.25) = <u>7.5</u>

(vi) $\int_{65}^{80} \frac{-0.75x + 60}{15} * dx \quad = \quad \frac{1}{15} \int_{65}^{80} (-0.75x + 60) dx \quad = \quad \frac{1}{15}\left(\frac{-0.75x^2}{2} + 60x + C \,|\, \begin{matrix} 80 \\ 65 \end{matrix}\right)$

$= \quad \frac{-0.75x^2}{30} + \frac{60x}{15} + C \,|\, \begin{matrix} 80 \\ 65 \end{matrix};$

when x = 80, and subtracting when x = 65

= (-160 + 320) – (-105.63 + 260) = 160 – 154.37 = <u>5.63</u>

Thus,

$$Z^* \quad = \quad \frac{\sum(0 + 14.59 + 175.01 + 254.17 + 450 + 393.75)}{\sum(0 + 0.63 + 5 + 5 + 7.5 + 5.63)} \quad = \quad \frac{1287.52}{23.76} \quad = \quad 54.19$$

Therefore, by the model implementation results, the percentage (%) process efficiency maturity of Machining-Additive LPBF hybrid manufacturing technology, implies

$$\frac{\mathbf{54.19}}{\mathbf{80}} \times \mathbf{100} \;=\; \mathbf{67.77}\%$$

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

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

$$\frac{\mathbf{54.2}}{\mathbf{80}} \times \mathbf{100} \;=\; \mathbf{67.75}\%$$

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

Appendix 27

LPBF AMT Performance Effectiveness Maturity Questionnaire and Data Matrix of the 1St, 2Nd, and 3Rd Groups of Respondents

LPBF AMT Performance Effectiveness Maturity Questionnaire and Data Matrix (1st Respondent)						
S/No	*Questionnaire Statements/Proposition*	*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
1	Vibration tendencies during manufacturing operation are now minimized				X	
2	There is now a seamless switching between processes and materials during manufacturing operation, and without causing defects				X	
3	Environmental impact analysis has been conducted on the process, and it is certified passed.				X	
4	There is a permanent solution to the cutting fluid on the environment raw materials and products			X		
5	The relationship between the manufacturing process, material, product geometry and the surface finish etc has been established			X		
6	The Safety and risk assessment concerns of material handling and processing tool is acceptable				X	
7	There is a universal methodology for managing or handling the process material residues, debris or byproducts				X	
8	The waste material or remains of the process is confirmed recoverable, recyclable and reusable				X	
9	There is a best processing velocity or speed determined for specific manufacturing operation				X	
10	The processing temperature and material properties dynamics monitoring, and control can be carried out remotely				X	
11	There are means of controlling the macro and microstructure of material under manufacturing process				X	
12	Deviation from the set parametric values of process can be detected during manufacturing operation			X		
13	There is a look ahead process monitoring system in place to prevent faulty product or manufacture			X		
14	There is possibility of maintaining a constant gap between the tool and the substrate or workpiece during manufacturing or processing				X	
15	There are experimentally obtained database to correlate process parameters			X		
16	There are provisions for power blowing and cleaning of the build volume or workspace and environment before subsequent manufacturing operation or process				X	
17	There are enough research, publications and discussions about the process and application			X		
18	There are existence of a unified operational procedure and standard for the process			X		
19	The manufacturing technology is compatible with the standard data handling software			X		
20	The technology has the ability to convert data files to specific data format				X	
21	The process database is documented in data management system for research and industrial accesses			X		
22	The technology has provisions or accommodation for new materials and application				X	
23	There are numerical or other measurable parameter or factor that define the process or sets the condition of operation				X	
24	There are training and retraining programmes designed for the personnel				X	
25	There are universal or internationally agreed set of procedures for process operation and safety				X	
26	There are adequate teaching and learning of the process in the universities and colleges			X		
27	There is a regulated auditing mechanism or procedure for quality management in use				X	
28	The process is mature for both laboratory and industrial applications			X		
29	The effects of individual process parameters on the performance are widely known				X	
30	The technology has a well defined or calculated process characteristics				X	
31	There is a study and result for the source of measurement error and process uncertainty				X	
32	There is a specific implementation methodology that turns plan into action in order to accomplish process strategic objectives and goals				X	
33	There are defined aim and objective of process improvement and optimization				X	
34	There is a record of continuos process performance improvement through scientific research and innovations				X	
35	There are new applicable materials findings in the process				X	
36	Operators skill and knowledge contrubute significantly to the process performance and capabilities				X	
37	The process has attained its potential values			X		
38	The process yield has been applied to measure the performance of the process to determine the percentage of the products that pass through compliance check				X	
39	The process measurement system is available				X	
40	There are known effects of process parameters on products characteristics				X	
41	There is a precise process that can give inaccurate results due to system error				X	
42	There are difference between process simulation and the actual physical performance				X	
43	The accuracy of the process model simulation is based on the actual performance				X	
44	There is a universal process analytical model for the process simulation			X		
				13	**31**	

	2nd Respondent						3rd Respondent			
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*		*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
			X						X	
			X					X		
			X						X	
		X						X		
			X						X	
			X						X	
		X						X		
			X						X	
			X						X	
		X							X	
		X							X	
		X						X		
		X						X		
		X							X	
		X						X		
			X						X	
		X						X		
		X						X		
		X						X		
		X						X		
		X						X		
			X						X	
			X						X	
			X						X	
			X						X	
		X						X		
		X						X		
		X						X		
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
		X						X		
			X						X	
			X						X	
			X						X	
			X						X	
		X						X		
			X						X	
		18	**26**					**17**	**27**	

Appendix 28

LPBF AMT Process Effectiveness Survey Data Collection

LPBF AMT PEffec. Survey Data Collation							
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*	Average	ML	Process Area PI No.
			3		**4**	4	1
		1	2		**3.67**	4	2
			3		**4**	4	3
		3			**3**	3	4
		1	2		**3.67**	4	5
			3		**4**	4	6
		2	1		**3.33**	4	7
			3		**4**	4	8
			3		**4**	4	9
		1	2		**3.67**	4	10
		1	2		**3.67**	4	11
		3			**3**	3	12
		3			**3**	3	13
		1	2		**3.67**	4	14
		3			**3**	3	15
			3		**4**	4	16
		3			**3**	3	17
		3			**3**	3	18
		3			**3**	3	19
		2	1		**3.33**	4	20
		3			**3**	3	21
			3		**4**	4	22
			3		**4**	4	23
			3		**4**	4	24
			3		**4**	4	25
		3			**3**	3	26
		2	1		**3.33**	4	27
		3			**3**	3	28
			3		**4**	4	29
			3		**4**	4	30
			3		**4**	4	31
			3		**4**	4	32
			3		**4**	4	33
			3		**4**	4	34
			3		**4**	4	35
			3		**4**	4	36
		3			**3**	3	37
			3		**4**	4	38
			3		**4**	4	39
			3		**4**	4	40
			3		**4**	4	41
			3		**4**	4	42
		2	1		**3.33**	4	43
		2	1		**3.33**	4	44
		48	**83**				

LPBF PEffec. Capability Maturity		
S/No	PA & PI	ML
1		5
2	24, 25, 27, 28, 29, 30, 3	4
3	3, 15, 17, 18, 19, 21, 26,	3
4		2
5		1

Appendix 29

LPBF Process Effectiveness Capability Maturity

LPBF PEffec. Capability Maturity		
S/No	PA & PI	ML
1		5
2	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 14, 16, 20, 22, 23, 24, 25, 27, 29, 30, 31, 32, 33, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44	4
3	4, 12, 13, 15, 17, 18, 19, 21, 26, 28, 37	3
4		2
5		1

Appendix 30

Machining AMT Performance Effectiveness Maturity Questionnaire and Data Matrix of the 1St, 2Nd, and 3Rd Groups of Respondents

Machining Performance Effectiveness Maturity Questionnaire and Data Matrix (1st Respondent)						
S/No	*Questionnaire Statements/Proposition*	*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
1	Vibration tendencies during manufacturing operation are now minimized				X	
2	There is now a seamless switching between processes and materials during manufacturing operation, and without causing defects				X	
3	Environmental impact analysis has been conducted on the process, and it is certified passed.				X	
4	There is a permanent solution to the cutting fluid on the environment raw materials and products					X
5	The relationship between the manufacturing process, material, product geometry and the surface finish etc has been established					X
6	The Safety and risk assessment concerns of material handling and processing tool is acceptable					X
7	There is a universal methodology for managing or handling the process material residues, debris or byproducts					X
8	The waste material or remains of the process is confirmed recoverable, recyclable and reusable					X
9	There is a best processing velocity or speed determined for specific manufacturing operation				X	
10	The processing temperature and material properties dynamics monitoring, and control can be carried out remotely				X	
11	There are means of controlling the macro and microstructure of material under manufacturing process			X		
12	Deviation from the set parametric values of process can be detected during manufacturing operation				X	
13	There is a look ahead process monitoring system in place to prevent faulty product or manufacture				X	
14	There is possibility of maintaining a constant gap between the tool and the substrate or workpiece during manufacturing or processing				X	
15	There are experimentally obtained database to correlate process parameters				X	
16	There are provisions for power blowing and cleaning of the build volume or workspace and environment before subsequent manufacturing operation or process				X	
17	There are enough research, publications and discussions about the process and application				X	
18	There are existence of a unified operational procedure and standard for the process				X	
19	The manufacturing technology is compatible with the standard data handling software				X	
20	The technology has the ability to convert data files to specific data format				X	
21	The process database is documented in data management system for research and industrial accesses				X	
22	The technology has provisions or accommodation for new materials and application				X	
23	There are numerical or other measurable parameter or factor that define the process or sets the condition of operation				X	
24	There are training and retraining programmes designed for the personnel				X	
25	There are universal or internationally agreed set of procedures for process operation and safety				X	
26	There are adequate teaching and learning of the process in the universities and colleges				X	
27	There is a regulated auditing mechanism or procedure for quality management in use				X	
28	The process is mature for both laboratory and industrial applications				X	
29	The effects of individual process parameters on the performance are widely known				X	
30	The technology has a well defined or calculated process characteristics				X	
31	There is a study and result for the source of measurement error and process uncertainty				X	
32	There is a specific implementation methodology that turns plan into action in order to accomplish process strategic objectives and goals				X	
33	There are defined aim and objective of process improvement and optimization				X	
34	There is a record of continuos process performance improvement through scientific research and innovations				X	
35	There are new applicable materials findings in the process				X	
36	Operators skill and knowledge contrubute significantly to the process performance and capabilities				X	
37	The process has attained its potential values				X	
38	The process yield has been applied to measure the performance of the process to determine the percentage of the products that pass through compliance check				X	
39	The process measurement system is available				X	
40	There are known effects of process parameters on products characteristics				X	
41	There is a precise process that can give inaccurate results due to system error				X	
42	There are difference between process simulation and the actual physical performance				X	
43	The accuracy of the process model simulation is based on the actual performance				X	
44	There is a universal process analytical model for the process simulation				X	
				1	**38**	**5**

	2nd Respondent						3rd Respondent			
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*		*Not True*	*Not Quite True*	*Fairly True*	*True.*	*Very True*
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X					X		
			X					X		
			X					X		
		X						X		
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X					X		
			X					X		
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X					X		
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
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			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
			X						X	
		X						X		
		X							X	
		3	**41**					**8**	**36**	

Appendix 31

Machining Process Effectiveness Survey Data Collection

Machining PEffec. Survey Data Collation							
Not True	*Not Quite True*	*Fairly True*	*True.*	*Very True*	Average	ML	Process Area PI No.
			3		**4**	4	1
			3		**4**	4	2
			3		**4**	4	3
			2	1	**4.33**	5	4
			2	1	**4.33**	5	5
			2	1	**4.33**	5	6
			2	1	**4.33**	5	7
			2	1	**4.33**	5	8
			3		**4**	4	9
		1	2		**3.67**	4	10
		2	1		**3.33**	4	11
		1	2		**3.67**	4	12
		2	1		**3.33**	4	13
			3		**4**	4	14
			3		**4**	4	15
			3		**4**	4	16
			3		**4**	4	17
			3		**4**	4	18
			3		**4**	4	19
		1	2		**3.67**	4	20
		1	2		**3.67**	4	21
			3		**4**	4	22
			3		**4**	4	23
			3		**4**	4	24
			3		**4**	4	25
			3		**4**	4	26
			3		**4**	4	27
			3		**4**	4	28
			3		**4**	4	29
			3		**4**	4	30
		1	2		**3.67**	4	31
			3		**4**	4	32
			3		**4**	4	33
			3		**4**	4	34
			3		**4**	4	35
			3		**4**	4	36
			3		**4**	4	37
			3		**4**	4	38
			3		**4**	4	39
			3		**4**	4	40
			3		**4**	4	41
			3		**4**	4	42
		2	1		**3.33**	4	43
		1	2		**3.67**	4	44
		12	**115**	**5**			

Machining PEffec. Capability Maturity		
S/No	PA & PI	ML
1	4, 5, 6, 7, 8	5
2	, 23, 24, 25, 26, 27, 28, 2	4
3		3
4		2
5		1

Appendix 32

Machining Process Effectiveness Capability Maturity

Machining PEffec. Capability Maturity		
S/No	PA & PI	ML
1	4, 5, 6, 7, 8	5
2	1, 2, 3, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44	4
3		3
4		2
5		1

Appendix 33

LPBF and Machining Processes Effectiveness Frequency Distributions

Processes Effectiveness Frequency Distributions			
LPBF			
Serial No	Maturity Levels	%tage Ratings	Frequency (f)
1	Initial	0 - 19	
2	Managed	20 - 39	
3	Defined	40 - 59	48
4	Quantitatively managed	60 - 79	83
5	Optimizing	80 - 99	
Machining			
Serial No	Maturity Levels	%tage Ratings	Frequency (f)
1	Initial	0 - 19	
2	Managed	20 - 39	
3	Defined	40 - 59	12
4	Quantitatively managed	60 - 79	115
5	Optimizing	80 - 99	5

Appendix 34

Engineering mathematical manual calculation based on the Centroid Defuzzification for the PEffec. HMT maturity level.

Finally, defuzzifying value (Z*) implies introducing a Centroid Defuzzification formula.

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

Hence the technological maturity for PEffec. is the result of the defuzzification of the shaded portion of the graphical figure 77.

Therefore,

Z* =

$$\frac{\int_{20}^{22} \frac{0.09x - 1.8}{2} * xdx + \int_{22}^{40} 0.09 * xdx + \int_{40}^{55} \frac{0.75x - 28.65}{15} * xdx + \int_{55}^{65} 0.84 * xdx + \int_{65}^{80} \frac{-0.84x + 67.2}{15} * xdx}{\int_{20}^{22} \frac{0.09x - 1.8}{2} * dx + \int_{22}^{40} 0.09 * dx + \int_{40}^{55} \frac{0.75x - 28.65}{15} * dx + \int_{55}^{65} 0.84 * dx + \int_{65}^{80} \frac{-0.84x + 67.2}{15} * dx}$$

Solving for the value of the numerator:

(i) $\int_{20}^{22} \frac{0.09x - 1.8}{2} * xdx = \frac{1}{2} \int_{20}^{22} (0.09x^2 - 1.8x)dx = \frac{1}{2} \int_{20}^{22} \frac{0.09x^3}{3} - \frac{1.8x^2}{2}$

= $\frac{0.09x^3}{6} - \frac{1.8x^2}{4} + C \Big|_{20}^{22}$ **; when x = 22, and subtracting when x = 20**

= (159.72 – 217.8) – (120 – 180) = (-50.08) – (-60) = -50.08 + 60 = <u>1.92</u>

(ii) $\int_{22}^{40} 0.09 * xdx = \int_{22}^{40} (0.09x)dx = \frac{0.09x^2}{2} + C \Big|_{22}^{40}$ **;**

when x = 40, and subtracting when x = 22

= 72 – 21.78 = <u>50.22</u>

(iii) $\int_{40}^{55} \frac{0.75x-28.65}{15} * xdx \;=\; \frac{1}{15}\int_{40}^{55}(0.75x^2 - 28.65x)dx \;=\; \frac{1}{15}\left(\frac{0.75x^3}{3} - \frac{28.65x^2}{2} + C\,|_{40}^{55}\right)$

$= \frac{0.75x^3}{45} - \frac{28.65x^2}{30} + C\,|_{40}^{55}$;

when x = 55, and subtracting when x = 40

= (2772.92 – 2888.88) – (1066.67 – 1528) = (-115.96) – (-461.33) = -115.96 + 461.33

= <u>345.37</u>

(iv) $\int_{55}^{65} 0.84 * xdx \;=\; \int_{55}^{65}(0.84x)dx \;=\; \frac{0.84x^2}{2} + C\,|_{55}^{65}$;

when x = 65, and subtracting when x = 55

= 1774.5 – 1270.5 = <u>504</u>

(v) $\int_{65}^{80} \frac{-0.84x + 67.2}{15} * xdx \;=\; \frac{1}{15}\int_{65}^{80}(-0.84x^2 + 67.2x)dx \;=\; \frac{1}{15}\left(\frac{-0.84x^3}{3} + \frac{67.2x^2}{2} + C\,|_{65}^{80}\right)$

$= \frac{-0.84x^3}{45} + \frac{67.2x^2}{30} + C\,|_{65}^{80}$;

when x = 80, and subtracting when x = 65

= (-9557.33 + 14336) – (-5126.33 + 9464) = 4778.67 – 4337.67 = <u>441</u>

Now, for the denominator:

(i) $\int_{20}^{22} \frac{0.09x-1.8}{2} * dx \;=\; \frac{1}{2}\int_{20}^{22}(0.09x - 1.8)dx \;=\; \frac{1}{2}\int_{20}^{22} \frac{0.09x^2}{2} - 1.8x$

$= \frac{0.09x^2}{4} - \frac{1.8x}{2} + C\,|_{20}^{22}$; **when x = 22, and subtracting when x = 20**

= (10.89 – 19.8) – (9 – 18) = (-8.91) – (-9) = -8.91 + 9 = <u>0.09</u>

(ii) $\int_{22}^{40} 0.09 * dx \;=\; 0.09x + C\,|_{22}^{40}$;

when x = 40, and subtracting when x = 22

= 3.6 – 1.98 = <u>1.62</u>

(iii) $\int_{40}^{55} \frac{0.75x-28.65}{15} * dx = \frac{1}{15}\int_{40}^{55}(0.75x - 28.65)dx = \frac{1}{15}\left(\frac{0.75x^2}{2} - 28.65x + C\,|_{40}^{55}\right)$

$= \frac{0.75x^2}{30} - \frac{28.65x}{15} + C\,|_{40}^{55};$

when x = 55, and subtracting when x = 40

= (75.63 – 105.05) – (40 – 76.4) = (-29.42) – (-36.4) = -29.42 + 36.4

= <u>6.98</u>

(iv) $\int_{55}^{65} 0.84 * dx = \int_{55}^{65}(0.84)dx = 0.84x + C\,|_{55}^{65};$

when x = 65, and subtracting when x = 55

= 54.6 – 46.2 = <u>8.4</u>

(v) $\int_{65}^{80} \frac{-0.84x + 67.2}{15} * dx = \frac{1}{15}\int_{65}^{80}(-0.84x + 67.2)dx = \frac{1}{15}\left(\frac{-0.84x^2}{2} + 67.2x + C\,|_{65}^{80}\right)$

$= \frac{-0.84x^2}{30} + \frac{67.2x}{15} + C\,|_{65}^{80};$

when x = 80, and subtracting when x = 65

= (-179.2 + 358.4) – (-118.3 + 291.2) = 179.2 – 172.9 = <u>6.3</u>

Thus,

$$Z^* = \frac{\sum(1.92 + 50.22 + 345.37 + 504 + 441)}{\sum(0.09 + 1.62 + 6.98 + 8.4 + 6.3)} = \frac{1342.51}{23.39} = 57.40$$

Therefore, by the model implementation results, the percentage (%) process effectiveness maturity of Machining-Additive LPBF hybrid manufacturing technology, implies

$$\frac{\mathbf{57.40}}{\mathbf{80}} \times \mathbf{100} \;=\; \mathbf{71.75}\%$$

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

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

$$\frac{\mathbf{57.3}}{\mathbf{80}} \times \mathbf{100} \;=\; \mathbf{71.63}\%$$

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