DURBAN UNIVERSITY OF TECHNOLOGY
INYUVESI YASETHEKWINI YEZOBUCHWEPHESHE

Faculty of Engineering and the Built Environment

Department of Industrial Engineering

Analysis of the viability of additive manufacturing for rapid tooling: A case study for the plastic industry

Uttam Bhana Pancha

Student Number – 20429731

Submitted in fulfilment of the requirements

of the Master of Engineering degree

April 2022

Supervisor: Dr O A Olanrewaju ________________ **Date:** 30 April 2022

Declaration

I hereby declare that this submission is my own and to the best of my knowledge, it neither contains material previously published nor written by another person, nor material that to a major extent has been accepted for the award of any other degree at Durban University of Technology or any other educational institution. I also declare that the intellectual content of this thesis is a product of my work. Any contribution made to the research by others especially in the use of equipment for sample analysis has been explicitly acknowledged in the dissertation.

____

Uttam Bhana Pancha Student Number – 20429731

30 April 2022

____

Date:

Dedication

This research is dedicated to my family who have been my source of inspiration from the start to finish.

Acknowledgments

I acknowledge and thank my supervisor Dr Oludolapo Olanrewaju, for his support and guidance throughout the course of this study.

Abstract

The current environment of changing market trends that include mass customization, sustainability, environmental impact and localized production drives the manufacturing industry to strive for additive manufacturing because of the versatility of the technology. Injection Moulding Company (IMC) is using traditional manufacturing approaches which compromise its competitiveness resulting in decreased production rate and high operational costs due to lengthy changeover times. The aim of the study was to investigate the viability of additive manufacturing technology for the manufacture of moulds to reduce operational costs. ABC mould demand classification analysis conducted for the top 16 moulds revealed that the moulds for the switch cover ranked highest in terms of the demand of moulds that were fabricated by IMC. The value stream map revealed that there was room for improvement in terms of push to pull and frequent lot transfer, standardising work, reducing cutting time and process scrap, as well as introducing poka yokes and cellular manufacturing, and it was proposed to reduce material movements and setup times. Through the deployment of group technology and rank clustering algorithm, three mould families and three machine cells were derived. As a result, the mould fabrication process was improved by reducing material movements and reducing setup times. Analytic hierarchical process was deployed as criteria for comparison and selection of the best 3D printing technology from among the recent additive manufacturing (AM) technologies that would meet surface finish, dimensional accuracy, cost, and manufacturing lead time requirements. Four AM options included Multilevel Concurrent Printing, MELD technology, Metal Jet 3D printer, and VELO3D. The final results indicated that the VELO3D is better than other additive manufacturing technologies for rapid tooling for the manufacture of moulds. The switch cover mould was then assessed for viability of fabrication through AM. The research proposed a process for evaluation of investment in VELO3D machine. A final decision was made through the comparison of AM technology, VELO3D versus traditional manufacturing capabilities in tool production. The traditional manufacturing was found to be characterised by a huge mould cost which was absent when additive manufacturing technology is adopted. The results

demonstrated that VELO3D outperformed the traditional approach from a cost perspective leading to an 80% overall cost savings from the adoption of AM.

Table of Contents

List of Tables

List of Figures

List of Acronyms

AM	Additive Manufacturing
AHP	Analytic Hierarchical Process
CAD	Computer Aided Design
GT	Group Technology
IMC	Injection Moulding Company
IMM	Injection Moulding Machine
LOM	Laminated Object Manufacturing
MLT	Manufacturing Lead Time
MAM	Metal Additive Manufacturing
OPM	Option Performance Matrix
RT	Rapid Tooling
ROCA	Rank-order Clustering algorithm
RVV	Relative Value Vector
SLS	Selective Laser Sintering
VDI	Verein Deutscher Ingenieure

CHAPTER 1 : INTRODUCTION

1.1 Introduction

Despite the fact that excessive usage of plastics generates terrific amounts of plastics waste, globally, the plastic industry is one of the industries that is growing fast, ranked as one of the limited billion dollar businesses of the world (Singh *et al.* 2021). Most of the plastic products, produced through injection moulding have transitioned from being considered as a cheap alternative for metal and glass to the material of choice, providing significant cost savings and unique properties. Many product development teams face challenges in undertaking successful design of plastic products due to inherent financial risks that characterise the process (Whlean and Sheahan 2019). The reason is that a mould must be custom-designed and manufactured for every part to be produced and the process of designing and manufacturing a mould along with the production of the first plastic part can have a lengthy lead time of up to 6 months (Pereira et al., 2019). The current technology-driven marketplace requires new products in order for a company to survive, hence, innovative firms use product development to create entirely new markets or increase demand through innovative product design. The development of Rapid Tooling (RT) technologies that are based on Additive Manufacturing (AM) for quick manufacturing of dies and tooling inserts directly from Computer Aided Design (CAD) data has demonstrated potential to revitalise firms that operate in the plastics industry (Irons 2020).

The case study injection moulding company (IMC) has a vertically integrated strategic structure whereby it owns the bulk of the supply chain for its products or services. IMC also specialises as a custom manufacturer of die castings for industrial applications and precision mould manufacturing services to other firms. The services that are offered by IMC span from design and material assistance, tool design and fabrication, injection moulding, to metrology and packaging.

1.2 Background to the Study

Manufacturing may be traced back to the 19th century's Industrial Revolution when raw materials were transformed into completed commodities. Whereas earlier, handmade goods dominated the market, this period signalled the transition from human labour to machines and defined production procedures (Mantoux 2013). Steam engine development, accompanied by an early modern industrial age in which business began to use machines in their manufacturing processes led to the coining of the term "machining". The current environment of changing market trends that include mass customization, sustainability, environmental impact and localized production drives the manufacturing industry to strive for additive manufacturing because of the versatility of the technology (Francis 2018). Using computer numerical control, technology has made it easier to produce tooling for near net shape manufacturing processes directly from a CAD software. Since the 1980’s when the first patents were issued for stereolithography, additive manufacturing or three-dimensional printing technology has advanced rapidly (Deshmane *et al.* 2021).

Initially 3D printing was mostly seen as a tool for artists and crafters to produce new and innovative designs. Labelled as the next-generation manufacturing technology. The technology has since moved to the point where numerous new additive manufacturing processes have been developed based on the physical state of raw materials and the manner in which the material is fused (Joshi and Sheikh 2015). Rapid tooling is described as the fast production of parts or tools such as mould inserts for traditional manufacturing such as investment and vacuum casting (Equbal, Sood and Shamim 2015). 3D printing has great potential to add value to the players in the plastic industry in South Africa through reduction of manufacturing cost and manufacturing lead time.

Vertical integration at IMC is fundamentally considered as vital since it gives the organisation some robust degree of control over its operations, having increased market control, and an ability to offer lower prices. Considering the disruption caused by the coronavirus pandemic, vertical integration for IMC conveys a possible advantage over its competitors since independence from suppliers in the value chain enables control over costs. Additionally, during the Covid 19 pandemic, there is substantial unpredictability that characterise relying on third party suppliers. Vertical integration increases process efficiency, and this promotes greater time efficiency and shorter lead times. However, technology is changing, yet the case study IMC was using traditional manufacturing approaches which compromised its competitiveness resulting in uncompetitive production rate and high operational costs due to lengthy changeover times.

1.3 Research Problem

All moulding processes, be it plastic injection moulding, aluminium die casting or compression moulding share some common characteristics (Chen *et al.* 2014). The complex shape of the component to be produced must be machined into two halves of the mould. In the case of multi cavity mould, the shape of the component has to be machined many times and “runners” have to be machined to each of the cavities. Machining for die or mould making requires a highly skilled workforce to perform a time consuming job often at very high costs (Stolt, André and Elgh 2018). The second concern for toolmakers is the provision of heat removal. In the moulding process molten material is injected into the mould, taking the shape of the mould, as it cools and hardens it is ejected from the mould, with the cooling period being the longest (Fu and Ma 2019). The cooling time is dependent on the design of the cooling channel system that is used to remove heat from the mould.

As a vertically integrated organisation, IMC is currently facing challenges in providing rapid response with on-hand expertise for evolving project needs, guaranteeing the quality of the product through its full life cycle, and overseeing production that would translate to shorter lead times and on-demand delivery. The key concern for the case study organisation is lengthy production lead time for the mould and die manufacture and this becomes a problem since clients expect quick product delivery. Additionally, product lifecycles have become shorter, and production includes smaller lots sizes in the global village. Hence, a novel rapid tooling process should be adopted to manufacture a limited number of tools at a reduced cost and time to avoid costly investment in conventional steel tooling for production. It is against the backdrop of these challenges that the aim of the study is to explore the viability of additive manufacturing technology for the manufacture of moulds to increase the production rate and reduce operational costs for the case study organisation that is facing operational challenges.

1.4 Research Aim and Objectives

The study is aimed to assess the viability of additive manufacturing for rapid tooling. The objectives of this study are:

- To establish the current operations and processes that characterise the IMC;
- To investigate the usage of group technology and rank-order clustering algorithm as mechanisms to aid the reduction of manufacturing lead time for the traditional mould making process
- To establish the best suitable additive manufacturing technology for rapid tooling for the manufacture of moulds.
- To determine the viability of 3D printed rapid tools for injection moulding.

1.5 Research Questions

The study is aimed to assess the viability of additive manufacturing for rapid tooling. The research questions for this study are:

- What is current operating scenario that characterise IMC?
- Can the moulds be grouped into families?
- Which is the suitable additive manufacturing technique for rapid tooling for the manufacture of moulds for injection moulding, and what criteria can be used for comparison and selection of the best 3D printing technologies?;

- What are the operational and financial indicators for decision analysis to determine viability of 3D printed rapid tools for injection moulding?

1.6 Significance of Study

The results of this study will add to the body of knowledge significantly for those organizations in the plastic sector that are striving to revitalize their processes and embrace 3D printing to produce new and innovative designs. It is also anticipated that the study will result in substantial cost savings and better sustainability of the case study organisation, thereby saving jobs that would have been lost if the company wound up due to poor performance.

1.7 Research Scope and Limitations

The boundaries or scope for the study was established with the view to establish what could be accomplished. The study was limited to the casting services and custom precision mould manufacturing services through the fabrication of injection moulding tools. Several constraints limited the options in conducting the study, and for instance, identification of candidate parts and potential machines was severely constrained by the bounding box of the AM machine. Additionally, the AM technologies were bound by the surface finish, dimensional accuracy, cost and manufacturing lead time requirements.

1.8 Research assumptions

It is worth noting that this study would rely on individual case context, however, it is assumed that AM is presently the most viable technology for small – to - medium series part production, with products of specialised materials or products that involve a high degree of design complexity, from which waste reduction would drive savings. Additionally, although some options may be able to benefit from the 3D printing technologies in their present form, other possibilities will continue to be more economically viable than others up until the technology changes for the better.

1.9 Research Methods

Methods for Objective 1

A current state analysis was used to identify and evaluate a firm's current processes. ABC mould demand classification analysis was conducted for the top moulds on demand for IMC. A value stream map was developed to provide a detailed visualisation of all steps that characterised the injection moulding process.

Methods for Objective 2

The research approach embraced Group Technology (GT) philosophy and Rank-order Clustering algorithm. A comparative analysis was done between the traditional die making and adopting 3D printing technologies which will be configured using the Rank-order Clustering algorithm**.**

Methods for Objective 3

Analytic Hierarchical Process (AHP) was used as decision making technique for comparison and selection of the best 3D printing technologies that would meet the part characteristics, which are surface finish, dimensional accuracy, cost and manufacturing lead time.

Methods for Objective 4

The research embraces proposing a process for evaluation of investment in 3D equipment and production of moulds between AM and conventional manufacturing technologies using financial and operational key performance indicators.

1.10 Structure of dissertation

This study will be composed of six chapters. The structure of the dissertation covers the following:

- Chapter 1 covers the background, problem statement, aims and objectives, as well as rationale and significance of the study.

- Chapter 2 embraces a critical review of relevant literature on additive manufacturing and rapid tooling. Conventional machining techniques for mould and die manufacturing as well as additive manufacturing are covered in this chapter.

- Chapter 3 covers the background for the case study organisation that is in the plastic sector. The focus is on establishing current process state and then identify areas for improvement.

- Chapter 4 covers the methodology that was embraced to determine the viability of 3D printed moulds and the most suitable additive manufacturing technology for rapid tooling for the manufacturing of moulds to increase the production rate and reduce operational costs.

- Chapter 5 focuses on the key results that are derived from the research study. Thereafter, a comprehensive discussion of the results ensued.

- Chapter 6 covers conclusions and recommendations on the viability of additive manufacturing for rapid tooling.

1.11 Conclusion

This chapter provided a background for the research, research problem, aim, objectives, and research questions. It was noted that the current technology-driven marketplace needs new products hence, innovative firms should use product development to create entirely new markets through innovative product design. The context of the current environment of changing market trends that include mass customization and localized production has driven the manufacturing industry to strive for additive manufacturing. It was noted from this chapter that the case study organisation was experiencing lengthy production lead time for the die manufacture, yet the clients expected quick product delivery. Hence, it was vital to investigate the viability of a rapid tooling process to reduce cost and time to avoid costly investment in conventional steel tooling for production. The following chapter will embrace a detailed literature review of conventional manufacturing techniques and additive manufacturing.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

Industrial innovation is driven by marketplace competition and the emergence of new technologies, characterised by the strive to decrease production costs and increase product value in this era of Industry 4.0 (Griffin 2017). Three-dimensional printing or additive manufacturing has an inherent potential to revolutionise approach to design and traditional manufacturing techniques. Nevertheless, high investment costs and uncertainties within the processes hinder organisations from developing and implementing the technology. As the technology continues to progress, while several industries in the western world have benefited from additive manufacturing's present state, organisations in South Africa need to evaluate its industrial viability and adoption (Butt 2020). Additive Manufacturing, also known as three-dimensional printing, has had significant impacts in different industry sectors and will continue as the technology evolves. It has become affordable, and efficiencies have improved over time. It has in some instances replaced, the manufacturing systems with its improved version of building components layer by layer using the additive method (Kamran and Saxena 2016). This chapter encapsulates the relevant literature deemed necessary to meet the study's objectives. Conventional manufacturing techniques, as well as metal casting and forming, plastic injection moulding, and other related procedures, are covered in this part. It also embraces additive manufacturing in greater depth and the various materials that have evolved for additive manufacturing are investigated, as well as the opportunities and challenges that have emerged.

2.2 Overview of Conventional Manufacturing

The first objective of the study is to establish the current operations and processes that characterise the IMC with regards to comprehending the manufacturing processes and production systems. The mould-making industry has been evolving, Low and Lee (2008) posited that the challenge that characterize the injection moulding industry is to shorten the mould lead-time while concurrently retaining the desired quality. The customers demand for better quality and speedy lead times if the firm is to maintain a competitive edge over the competitors. On the other hand, Kumar (2016) conducted a study to appreciate the current operating environment of additive and subtractive manufacturing technology in moulding industry to gain an understanding of moulds. The essence of the study was to gain knowledge about machining processes, different components of mould, adjustment of moving components, and appreciating parameters that influence plastic injection moulding. Moulds are basically made from machining and these basic machining processes are classified as turning, drilling, milling and grinding (Liang 2019).

These procedures are called subtractive manufacturing, as opposed to additive used to describe material removal processes whereby hardened cutting tools are used to remove material from a work piece (Liang 2019). Machining is a group of shaping operations that are characterised by the removal of material from a starting billet or workpiece to produce a part of the desired geometry. It is widely used because a variety of materials can be machined to a very high degree of accuracy and with excellent surface finishing.

Other manufacturing processes such as metal casting, plastic injection and blow moulding and metal forming, whilst not purely subtractive in nature are also important manufacturing processes and have to be considered when comparing additive and subtractive manufacturing (Dutta, Babu and Jared 2019). Therefore, in terms of this study they will be termed as conventional manufacturing processes and these processes do characterise IMC.

2.3 Injection Moulding

Injection moulding is also one of the current operations and processes that characterise the IMC. Moulds and dies are tools that are essential for mass production in present-day manufacturing (Poli 2001). This section focuses on injection moulding given that the first objective of the study is to establish the current operating environment that characterise IMC for the plastic industry, specifically in injection moulding. A mould is a hollow block that is filled with a pliable or liquid material such as plastic, ceramic, metal, or glass material, the raw material sets or hardens inside the mould, thereby taking its shape (Silver and McLean 2008). Articulated moulds are characterised by multiple pieces that are assembled to form the complete mould, and then disassembled to release the final casting, are costly, but essential if the casting has complicated overhangs. On the other hand, several different moulds are used in piece-moulding, with each mould creating a segment of a complex object (Gawdzinska *et al.* 2018).

The techniques that are available currently are able to create micron-order precision moulds and dies, contributing to the mass production of products with the same shape and quality in a wide range of areas (Ishizaki, Komarneni and Nanko 2013). The most common mould rubbers are natural latex, polyurethane, epoxy and silicone. There are number of types of moulds and these include injection, blow, matrix, rotational, extrusion, spin and transfer moulding (Vlachopoulos and Strutt 2003).

The injection moulding process is cyclical and is characterised by plasticising and an injection, wherein the plastic is injected into a mould through a heated cylinder (Singh and Verma 2017). As shown in Figure 2.1, a hopper is used to feed the raw materials into the injection moulding machine. The raw material is fed into the screw channel by a rotating screw and is melted due to frictional heat that is generated by rotating the screw, and additionally, heat is transferred by conduction from the heater bands. The pressure builds when the screw moves forward, and thereafter, the screw moves backwards to fill the front end of the screw barrel with molten material. the plasticising stage is accomplished when the barrel is filled with the desired volume of the molten and the screw rotation stops (Fernandes *et al.* 2014).

The injection phase is characterised by four key steps, which are filling, packing, cooling, and ejection. During the filling phase, the unfilled mould is sealed by a clamp unit and the screw is moved forward. In the next step, mould filling is accomplished, and the screw moves with a small displacement or is held in the forward position to maintain pressure, while the material cools down. The cavity pressure is reduced during the cooling phase, and the part cools down and solidifies. Lastly, following adequate cooling, the part becomes stiff, and the mould opens, ejects the part, closes again and the cycle restarts (Singh and Verma 2017).

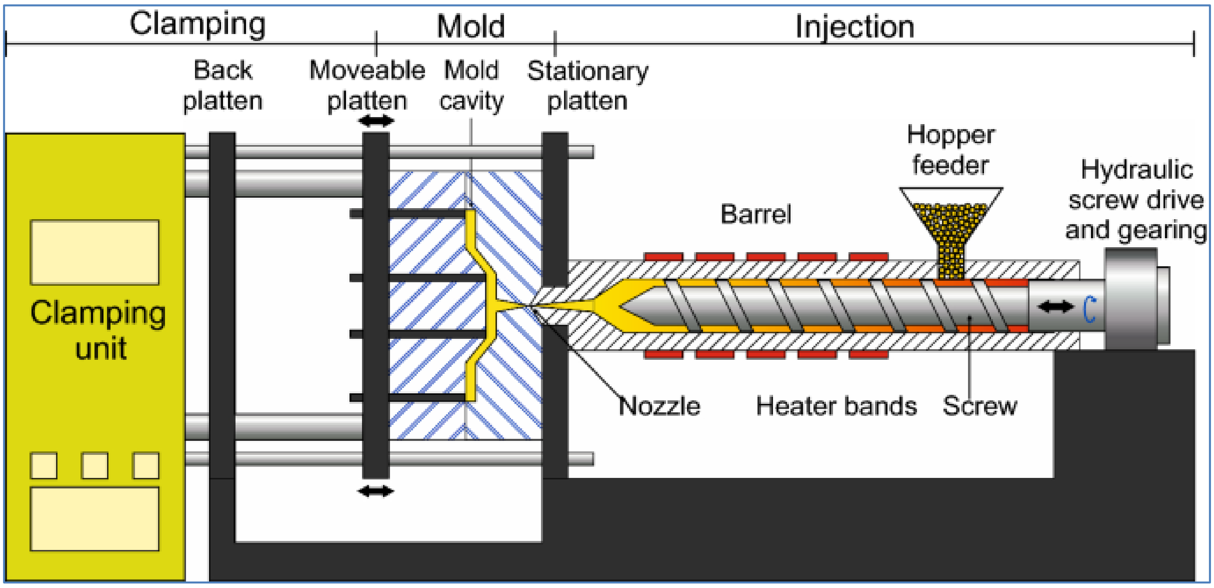

Figure 2.1: Injection moulding process

2.4 Tool and Die Manufacturing

IMC is also involved in tool and die manufacturing. A die is a tool that is used to shape sheet metal and other metal forms and the two basic types are cutting dies are used to cut the material and forming dies that change the appearance of the blank without removing any stock (Astakhov 2018). The proliferation of machining centres had simplified the die making process easier. However, die manufacturing is still regarded a high-skill job since there is need for techniques and skills that embrace the entire process, including the selection of materials and machining methods, computer aided design (CAD), and performing minute machining that cannot be done through automated procedures (Stewart and Kelley 2020). Since product lifecycles have become shorter and production includes smaller lots sizes in the global village, shorter turnarounds for die delivery are requested nowadays (Culkin and Simmons 2018).

Today, further innovations in die manufacturing technology are imperative, and the emergence of 3D printers is expected to drastically change the manner by which these dies are fabricated (Ruiz-Morales *et al.* 2017).

It is crucial to comprehend the kind of material that can be used to fabricate dies and moulds since that would influence the additive manufacturing technology that can be used as an alternative to the conventional fabrication technologies. The materials used for dies are generally hard and demanding when cutting and these include ceramics, tool steels with carbon or chromium content, high-speed steels, die steels, and cemented carbides (Qudeiri *et al.* 2020). For this reason, dies are normally cut using machining centres or other NC machining tools, and for added precision, the products generally go through subsequent processes such as grinding. Furthermore, non-traditional machining techniques such as electrical discharge machining are used to produce complex three-dimensional dies with even greater precision (Ranjan, Kar and Patowari 2020).

On the other hand, direct tooling using AM technologies would generally use metal-based laser melting to manufacture moulds and mould inserts using materials such as cobalt, steel, chromium, titanium, and alloy blends (Nagahanumaiah et al., 2008).

2.5 Overview of Additive Manufacturing Technologies

The third objective of this study is to establish the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds. Additive manufacturing processes build layers in different ways, some processes use heat from electron beams or lasers to sinter or melt plastic or metallic powders together (Prakash, Nancharaih and Rao 2018). Other processes use inkjet printing heads to precisely spray the solvent or binder onto powdered polymers or ceramics. On the other hand Whlean and Sheahan (2019) posited that AM could provide benefits in various ways in manufacturing and tooling by producing the complex geometries and customization that would be difficult to fabricate using traditional manufacturing methods.

According to Altaf *et al.* (2018), one of the key bottlenecking processes in the overall metal injection moulding process is mould making. Despite the fact that machined metal moulds are robust and appropriate when part demand is in high volumes. This is due to the intrinsic demand for time, labour effort, and material, and the machining process is cost intensive, skill intensive and time consuming. On the other hand, in applications where part demand is low and design change is regular, and part demand is customized, once the demand is fulfilled, the mould would become unusable (Parry, Best and Banks 2020). Rapid tooling (RT) is described as use of additive manufacturing process for fabricating moulds, patterns, inserts or auxiliary mould components (Gao *et al.* 2021). RT techniques can be direct or indirect, for instance, the creation of moulds or inserts for injection moulding is direct, while the fabrication of sacrificial patterns for castings is indirect RT (Afonso *et al.* 2019).

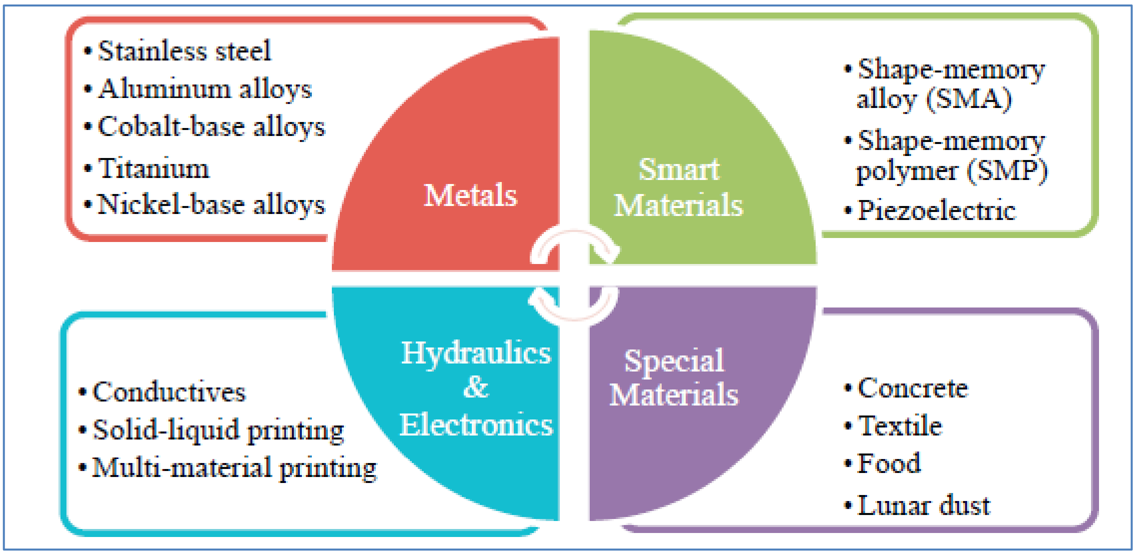

Figure 2.2: Current research materials for additive manufacturing
Source: Dilberoglu *et al.* (2017)

Dilberoglu *et al.* (2017) posited that material science is fundamental for comprehending the developments in additive manufacturing technologies. The researchers have intense attention in developing novel materials that are appropriate for AM applications. Figure 2.2 shows some specific materials that have attracted more attention of industry and the properties of these prospective materials would possibly to be improved in the era of Industry 4.0.

The recent developments in AM technology gave rise to more dynamic research on Metal additive manufacturing (MAM). A lot of metallic components can be fabricated by additive manufacturing techniques using titanium, stainless steel, aluminum and other metals. Additionally, it is anticipated that manufacturing will in future navigate the industry in the direction of combined utilization of these processes. The new era of hybrid manufacturing is becoming popular and it offers the practice of subtractive methods accompanied by additive methods to produce better products with improved fatigue strength and surface quality (Dilberoglu *et al.* 2017). Given that the objective is to determine the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds, it is vital to comprehend the different types of AM technologies available on the market. The following section details of AM technologies and these include vat polymerization; powder bed fusion; material extrusion; material jetting; binder jetting; sheet lamination; and directed energy deposition.

2.5.1 Vat polymerization

Vat polymerization is the first of the additive manufacturing process to be developed and stereolithography (SLA) uses a layer-by-layer manufacturing through photo-polymerisation by using an ultraviolet (UV) laser (Irons 2020). Figure 2.3 shows a schematic for vat polymerization that uses a vat of liquid photosensitive resin to build a component layer by layer. A UV light is used to cure the resin on the build platform which descends after each layer. The resin is cured when a light is beamed onto the surface of the liquid resin. As the resin is heated by the laser, it cures and becomes hardened. The thickness of the layer and resolution is dependent upon the equipment that is being utilised. A platform is constructed to anchor the product that is being fabricated and support any overhanging structures, unlike powder or plastic filament based systems (Wong and Hernandez 2012).

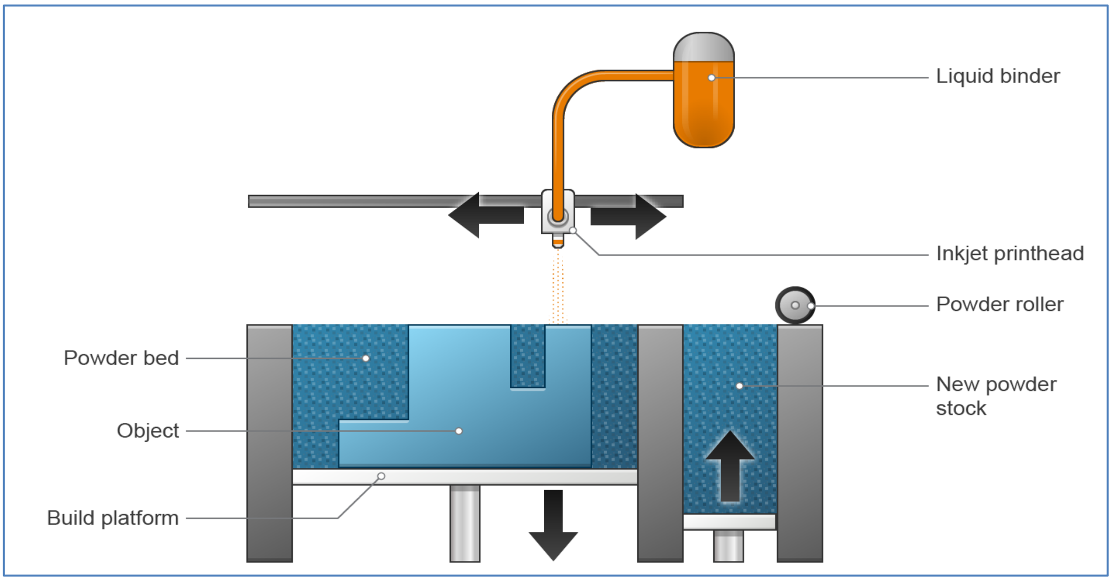

Figure 2.3: Schematic for vat polymerization
Source: Irons (2020)

2.5.2 Powder Bed Fusion

There are numerous variations of powder based fusion, which are differentiated by the type of material used and the heat source used (Wong and Hernandez 2012). The variants are selective laser melting, selective laser sintering (SLS), direct metal laser sintering, and electron beam melting. All powder bed fusion processes are characterised by the spreading of the powders over layers of material. A reservoir or hopper would provide fresh supply of material and there are numerous methods for spreading the powder, such as rollers or blades. Layers are added and a platform lowers the model according to some prescribed layer thickness.

Direct metal laser sintering melts and fuses layers of metallic powders together using a computer-controlled laser beam. Despite the use of the term "sintering," being use full melting occurs. Electron beam melting is similar method to selective laser melting, but as opposed to using a laser, it employs an electron gun. As an electron beam is employed, the build chamber operates in a vacuum rather than an inert environment. Minguella-Canela *et al.* (2020) conducted a study on redesign of cooling inserts produced through selective laser melting for high production steel moulds and benchmarked the results with similar industrial AM approaches. The results revealed a decrease in the cooling times of the mould to up to 8%, while the same conformation properties were maintained, thereby leading to crucial time savings and reduction in production costs. Selective laser sintering processes would generally sinter powdered polymer materials such as ceramics and nylon. Selective laser melting would completely melt the powder instead of sintering the material. The selective laser melting process is employed to metal powders such as aluminium and titanium alloys and stainless steels. An inert atmosphere is required in the build chamber to prevent oxidation.

2.5.3 Material Extrusion

Fused Deposition modelling is a process by which thermoplastic wire filament is melted and extruded through an electrically heated print head (Shi, Peng and Wei 2014). As shown in Figure 2.4, in fused deposition modelling, a continuous plastic filament of thermoplastic polymer is employed to print layers of material. The material is pushed through a heater element and drawn out through the nozzle and is then deposited layer onto layer on the build platform.

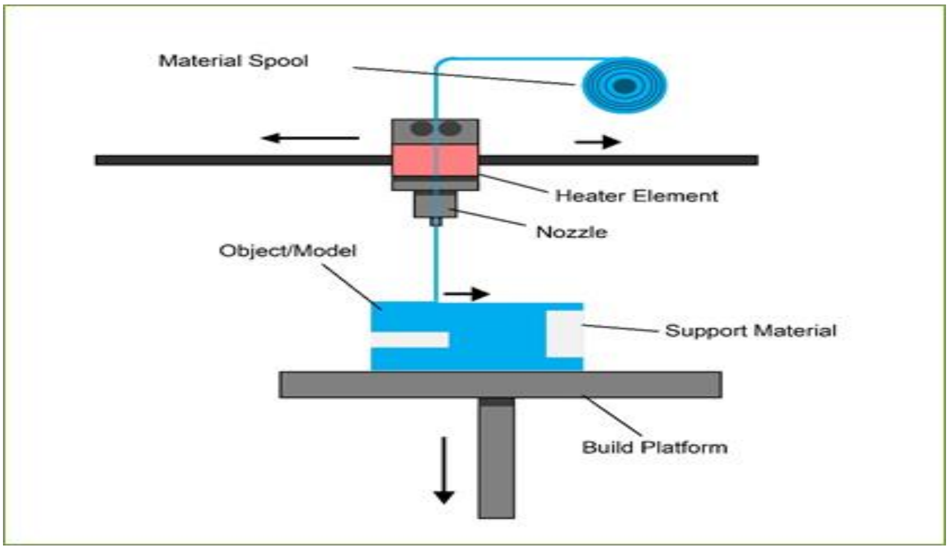

Figure 2.4: Fused deposition modelling
Source: Shi, Peng and Wei (2014)

The nozzle can traverse in horizontal plane and a platform moves up and down vertically after each new layer is deposited. One of the main differences between fusion deposition modelling and other additive manufacturing processes is that in this process the material feed is under unchanging pressure and in an uninterrupted stream. The pressure should be retained at a steady and constant speed to ensure accurate results. The plasticity of the filament is a crucial parameter for this approach and enables the filaments to bond during printing and then to solidify at ambient temperature conditions.

2.5.4 Material Jetting

Material jetting is a process whereby material is streamed onto a build platform using either a continuous or drop on demand approach to create 3D objects (Varotsis 2019). The material is jetted from a nozzle and deposited onto the build platform or surface where solidification occurs, with the model constructed layer-by-layer.

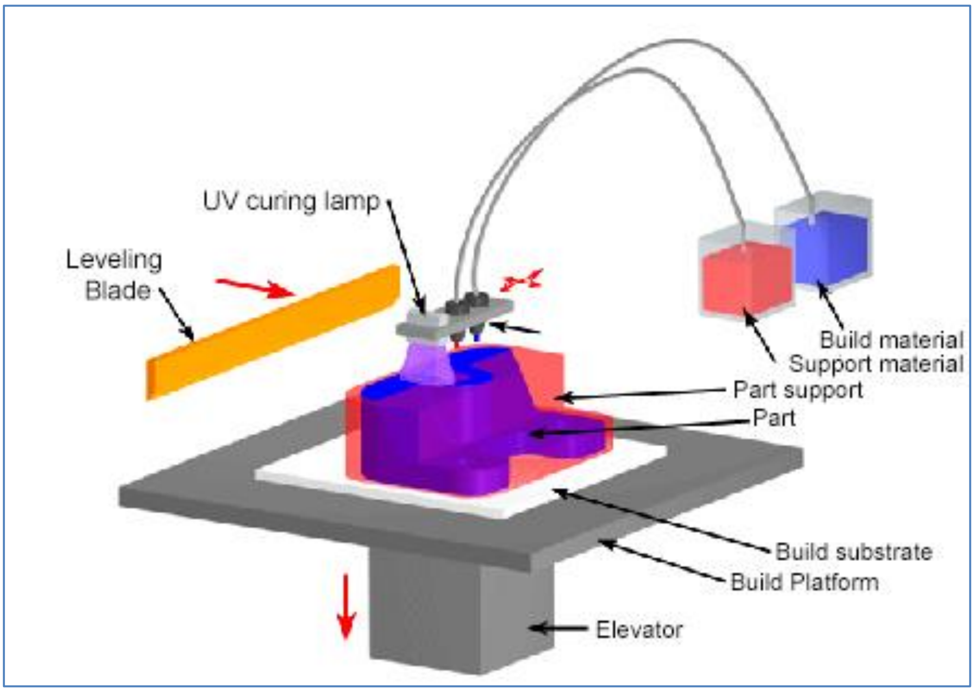

Figure 2.5: Schematic for material jetting process
Source: Varotsis (2019)

Figure 2.5 shows a diagram for process of material jetting, and the material jetting machines vary in their methods of directing how the material is deposited as well as in terms of complexity. Due to their ability to form drops and viscosity, polymers and waxes are appropriate and commonly used materials for material jetting.

Kaweesa et al. (2017) investigated the material jetted specimens to ascertain the effect of functionally graded materials on fatigue life. The results demonstrated the adverse effects of gradient transitions in a material on fatigue life in addition to the qualitative material properties of true against discrete material gradient. Yuan *et al.* (2020) developed a novel framework for printing a photogrammetry-based oil painting 3D model using the ultraviolet inks jetting system with a variable layer thickness. Basing on contour tracking, a height-rendering image of the oil painting model was generated, which was additionally split into segments and pasted to the equivalent slicing layers to regulate an inclusive printing sequence of colouring layers and white layers. The results demonstrated that photogrammetric models of oil paintings could be printed brilliantly by UV-curable colour polymers.

2.5.5 Binder jetting

The binder jetting process uses two materials, which is a powder-based material and a binder that glues the particles of base material to form a product layer by layer, without using heat (Ziaee and Crane 2019). Figure 2.6 shows a diagram for binder jetting process where a print head traverses horizontally and deposits interchanging layers of the build and binding materials. The product being printed is dropped by a distance equal to the prescribed layer thickness as the build platform descends after the build of each layer.

The material characteristics for the products from binder jetting are generally unsuitable for structural parts due to the technique of bonding (Lv *et al.* 2019). Additional post processing can add significant time to the overall process despite the relatively faster speed of fabrication. The object being printed is self-supported within the powder bed, just like other powder-based manufacturing methods.

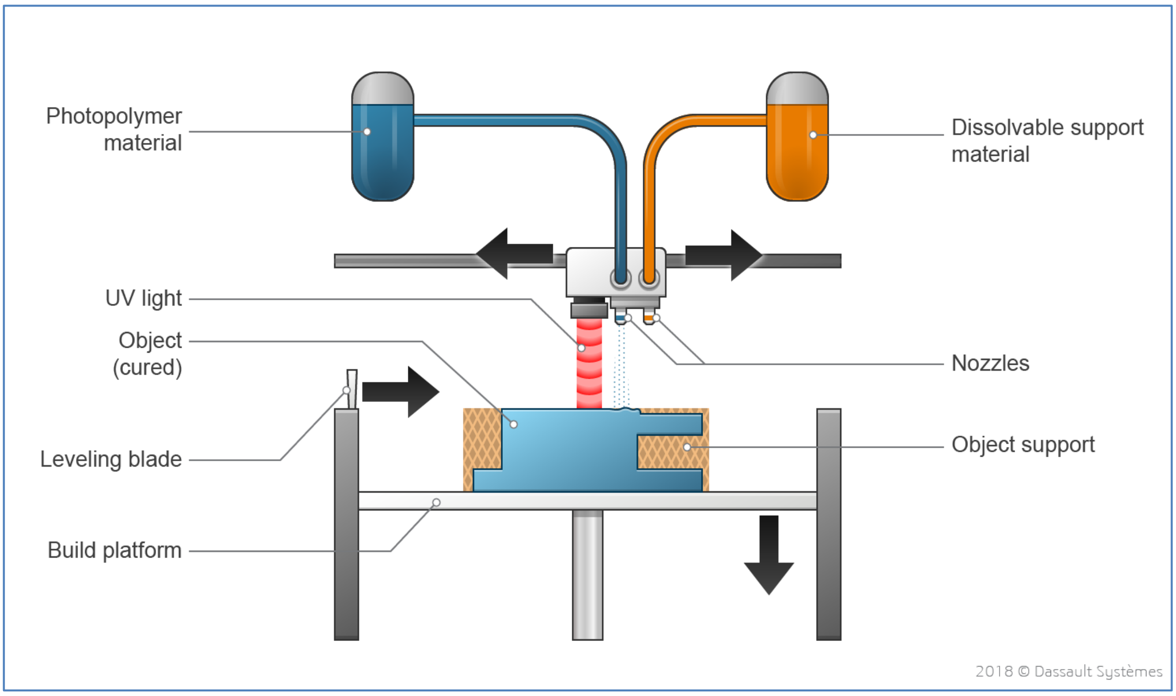

Figure 2.6: Schematic for binder jetting process
Source: Ziaee and Crane (2019)

Using a hybrid approach that embraced binder jetting 3D printing of Ti–6Al–4V followed by pressure-less ex situ infiltration with Al, Yadav *et al.* (2020) demonstrated the ability to construct dense titanium aluminides-based products. Microstructure characterisation and phase analysis were undertaken by scanning electron microscopy equipped with X-ray diffraction and energy dispersive spectroscopy. Zhang *et al.* (2021) investigated the use of binder jetting technique in 3D printing of silk powder and the printed green samples were analysed to determine the resolution, printing performance, mechanical strength, and porosity. The high compressive modulus of the printed parts was found to be comparable to ceramic-printed parts and thus a strong infusing and immersion post-crosslinking approach was used to improve the water stability of the products, making the printed parts appropriate for load-bearing bio-medical applications.

2.5.6 Sheet Lamination

Sheet lamination processes include laminated object manufacturing (LOM) and ultrasonic additive manufacturing that use sheets of paper or metal ribbons, which are bound together using adhesive materials or through ultrasonic welding (Lee et al., 2017). Ultrasonic additive manufacturing would require additional CNC machining and it is crucial to remove the unbound metal from the welding process. With LOM, cross hatching approach is used during the printing process to enable easier removal the 3D printed product.

Gibson *et al.* (2021a) posited that sheet lamination has not been very successful on the marketplace despite the notion that it was one of the earliest commercialised additive manufacturing techniques. Sheet material, however, is quite easy to handle and is one of the cheapest materials available. Through the use of a robotic cell to execute sheet manipulation and handling, Bhatt *et al.* (2019) presented an addition to the sheet LOM process. The approach enabled inclusion of prefabricated components between the layers and the use of multi-material layers. An algorithmic groundwork was developed to simplify automatic generation of robotic instructions, and identification of the applicable process constraints related to accuracy, speed, and strength.

2.6 Group Technology

The second objectives of this study is to investigate the usage of group technology and rank-order clustering algorithm as mechanisms to aid the reduction of manufacturing lead time for the traditional mould making process. Group technology (GT) is a philosophy whereby similar parts are identified and grouped together and was adopted to take advantage of their similarities during production (Ernawati et al., 2020). Sousa et al. (2010) posited that group technology can be exploited to performing similar activities together, thereby avoiding wastage of time on the changes for switching from one activity to another unrelated activity. On the other hand, Huang and Li (2010) proposed a hybrid approach of Group technology and case-based reasoning to design injection mould embracing the notion that the structure of plastic parts is extremely complex and diverse.

Abdelhadi (2018) used the concept of group technology, and that resulted in grouping of machines according to the effect of failure based on the criteria specified by the decision makers. Accordingly, the benefits facilitated the process of maintenance execution through the ordering of spare parts leading to maintenance cost minimisation. To improve the utilisation of machines as well as productivity of additive manufacturing processes under the context of multiple parts production, Zhang and Bernard (2014) proposed the concept of group technology. Based on the GT, a modified group technology for AM under multiple parts manufacturing context is presented. A set of key attributes affecting the additive manufacturing production cost, time, quality and work preparation were identified to represent the parts for grouping and similarity analysis was conducted through the adoption of Grey Clustering method.

2.7 Rank-order Clustering Algorithm

The Rank-order Clustering Algorithm (ROCA) was introduced by King (1980) and is used in cell manufacturing systems to optimise a manufacturing process based on key independent variables with weights and reorganisation of machine-product data. The binary weights are computed from a machine part matrix and the cells are formed so that each cell would have approximately the same work load (Amruthnath and Gupta 2016).

Danilovic and Ilic (2019) posited that the problems related to cell formation in manufacturing systems are complex NP-hard problems and developed a novel hybrid algorithm for manufacturing cell formation. The goal of the algorithm was to use the specificities of the input instances to narrow down the feasible set for the cell formation problem and derive a more efficient algorithm characterised by higher efficiency and efficacy. The results demonstrated a robust hybrid algorithm that can solve complex cell formation problems and multi-criteria optimisation problems.

On the other hand Jahan and Souri (2020) used multi-attribute decision-making algorithm for cell formation based on similarity in parts design to create a cellular model. An improved algorithm with ROCA and row and column masking methods was proposed and the superiority of the improved algorithm was realised when the results were compared to the previous methods using the productivity index.

The current study considered the applicability of the ROCA in comparative analysis of traditional die manufacturing for injection moulding and adopting 3D printing technologies which were configured using the Rank-order Clustering algorithm. The essence of the study would be to develop a sustainable business case that reduces operational costs or increase the production rate in the manufacture of moulds.

2.8 Analytic Hierarchical Process

The Analytic Hierarchy Process (AHP) is a technique that is used to organise and analyse complex decisions by using maths and psychology (Saaty 2008). AHP provides a balanced framework for decision making by quantifying criteria and alternative options and relating those elements to the ultimate goal. AHP is characterised by three elements which include the problem being solved or ultimate goal, the possible solutions called alternatives, and the criteria that is used to judge the alternatives (Albayrak and Erensal 2004). The importance of criteria is compared through pair-wise comparisons and AHP converts these evaluations into figures for all of the possible criteria and this quantifying capability differentiates AHP from other decision making methods (Vargas and IPMA-B 2010).

Kengpol and O'brien (2001) conducted a study on developing a decision support tool that was used to select advanced technology for achieving rapid product development. It was noted that the challenge for a firm was on how to maintain a technically advanced and competitive product as well as reducing the design, development and manufacturing time consistent with the demands from the market environment. A decision support tool was outlined to ascertain the viability of investing in time compression technologies to attain swift product development. A unique data structure was proposed to monitor the effectiveness of a decision was proposed, and a decision model that consolidated qualitative and quantitative variables through the use of the AHP was developed.

Using the analytic hierarchy process, Nyembwe (2012) used a case study to comprehend the applicability and selection of additive manufacturing process for a casting application. The objective of the study was to select a suitable AM process between the Z-cast process and direct croning process. Of which the selected better process would be used to produce sand moulds for the casting of dies and metallic tools.

To analyse criteria weights for 3D printer selection-related factors, Khamhong et al. (2019) used a fuzzy analytic hierarchy process. The factors concerning 3D printer characteristics, 3D printed product, and material properties were considered in the evaluation and the results demonstrated that product factor was the most essential factor for both types of decision makers, followed by material, and printer, respectively.

It is worth noting that there are other several decision making techniques such as affinity diagrams, heuristic methods, and linear programming. Affinity diagrams are more suitable for brainstorming and mind mapping while heuristic methods, though they may generate desirable results, they are not accurate (Martí and Reinelt, 2022). Hence, this study adopted AHP for Multiple criteria decision analysis due to the complex nature of the decisions that had to be made regarding the selection of the suitable 3D printing technologies that would meet the part characteristics, which are surface finish, dimensional accuracy, cost and manufacturing lead time.

2.9 Cost Estimation in Conventional Die Manufacturing

The third objective of this study is determining the viability of 3D printed rapid tools for injection moulding. Hence, it is vital to comprehend cost estimation in conventional die manufacturing and compare it against additive manufacturing. The estimation of cost of part manufacturing is a critical and vital undertaking for industrial firms since it feeds into price evaluation which aids an organization’s competitiveness in the marketplace

(Bouaziz et al., 2006). Cost estimation is a preliminary activity that is accomplished during design and requires a classification of material and manufacturing process cost items as well as for the definition of a cost model (Favi et al., 2017). The specific knowledge of the firm is critical for cost estimation and a proper manufacturing cost estimation, as well as process planning and production planning issues should be embraced in cost estimation, with process planning requiring the generation and the selection of the sequence of operations, machining processes, as well as machining parameters.

The cost estimation is an activity carried out at different stages of the product-process design, for instance, conceptual based on a semi-analytic approach, Bouaziz, Younes and Zghal (2006) presented a cost estimation system of manufacturing dies that used a semi-analytic approach based on the principle of the analogic and analytic approaches. The principle had recourse to the analogic approach for searching analogies between machined shapes prior to grouping them into complex machining features. The system generated a process to be used for each feature parameter as a sample, and subsequently, a machining time model. Using the analytic approach in the second stage, the cutting time was established from the finishing operation surface or by removal rates of metal units for rough operation or by both production approaches.

Favi et al. (2017) proposed an analytical cost estimation model for high pressure die casting based on knowledge formalisation and cost estimation algorithms. The cost model considered the raw material, the transformation process, accessory operations and the setup operations. The proposed model linked the analytical algorithms and the geometrical features of the product under development and the results demonstrated a positive relationship between cost items and geometrical features.

With open-die forging technology, Campi *et al.* (2020) proposed an analytical model for cost estimation in the design of axisymmetric components. The model is based on the analysis of geometrical features that are provided during the design stage and a detailed cost breakdown with regards to the raw material and all the subsequent operations. The model also enables product cost estimation, connecting cost items to geometrical features to perform design-to-cost actions that are focused on reducing manufacturing cost. Campi *et al.* (2020) proposed an open die forging cost model that was characterised by machine cost; equipment cost; material cost; labor cost; energy cost and consumable cost. The cost model was tested on eight cylindrical parts, for instance, shafts and discs with different materials shapes, and dimensions.

On the other hand, Ganorkar et al. (2019) posited that time-driven activity-based costing (TDABC) system has gained significance and provided a procedure that enables organisations to implement TDABC using an operation sequence technique to improve profitability and productivity. The time required to perform an activity and the unit cost of supplying capacity are the two parameters that were required for TDABC. An operation sequence technique was used to estimate the time required for each activity. Ganorkar et al. (2019) thereafter formulated the time equations and determined the practical capacity of activities and the approach provided the cost analysis and capacity analysis together with hierarchical decomposition.

2.10 Cost Estimation in Additive Manufacturing

The cost estimation of the product plays a substantial role in the evaluation of the viability of additive manufacturing technology. Cost estimation is directly linked to business performance and represents the basis for development of the key decision variable of additive manufacturing, which is the product cost (Busachi *et al.* 2017). The key cost factors in additive manufacturing systems are build time, machine utilization, material cost and machine investment costs, which include issues pertaining to housing, using, and maintaining the system. This includes machine purchase, energy costs and associated labor costs to operate the system. The understanding of material costs in additive manufacturing can be of significance in making key decisions regarding the adoption of the technology by organisations. While maintaining the necessary performance, additive manufacturing permits products to be produced using less material. However, the price of materials for additive manufacturing can often surpass the price materials for traditional manufacturing (Thomas and Gilbert 2014).

Atzeni *et al.* (2010) showed that the additive manufacturing material was nearly ten times more expensive than material for traditional manufacturing after selecting a metal part made from aluminium alloys for traditional manufacturing and additive manufacturing using selective laser sintering. Other research on metal parts confirms that material costs are a major cost driver for additive manufacturing technology (Frazier 2014). However, increasing the adoption of additive manufacturing may result in a reduction in raw material cost through economies of scale, thereby propagating further implementation of additive manufacturing.

Using injection moulding and comparing it to the additive manufacturing process of selective laser sintering, Atzeni *et al.* (2010) compared the costs of fabricating a lamp holder using two different machines. The results demonstrated that the major costs are machine cost per part, and the material cost per part for additive manufacturing.

In addition to material costs, machine cost is one of the most significant costs that characterise additive manufacturing. While the trends in 3D printer machine costs are largely following a downward path, huge differences remain between the costs for metal-based systems and polymer-based systems (Thomas 2017). The average selling price of additive manufacturing systems has been strongly influenced by the incredible growth in sales of low-cost, polymer-based systems. Build envelope and envelope utilization can also significantly influence the costs that characterise additive manufacturing. The size of the build envelope influences the size of products that can be built, which means there might be need to enlarge the build envelope in order to build some products using additive manufacturing technologies (Gibson 2017). Additionally, the build envelope is related to the utilisation of the total amount of build capacity.

As highlighted by Baumers *et al.* (2013), build time is a substantial element in estimating the cost of additive manufacturing and several software packages are available for the estimation of build time. According to Chan et al. (2018), there are two approaches to estimating build time and these are parametric analysis and detailed analysis. Parametric analysis uses information on process time and characteristics such as layer thickness while detailed analysis uses knowledge about the inner mechanisms of a system.

Energy consumption is also a vital factor in considering the cost of additive manufacturing compared to other manufacturing methods, especially with regards to examining the life-cycle costs (Peng *et al.* 2018). Liu *et al.* (2018) provided a comprehensive review on the energy consumption of metal parts in additive manufacturing. It was noted that at process level, the energy flow distribution in an additive manufacturing system is critical while the energy beam is the most energy consuming subunit for a metal additive manufacturing machine at the machine level. The energy density presented by process parameters was found to have a pronounced impact on the mechanical properties, microstructure, thermal history, and defect types.

Telenko and Seepersad (2012) used selective laser sintering and compared the results with injection moulding to examine the energy consumption in the production of nylon parts. The results demonstrated that although SLS used considerably more energy than injection moulding during part fabrication and the energy consumed per part for SLS remains relatively constant as long as builds are packed efficiently while the energy consumed per part for injection moulding decreased with the number of parts fabricated. The crossover production volume, at which injection moulding and SLS consumed equivalent amounts of energy per part was found to range from 50 to 300 representative parts, dependent upon the choice of mould plate material. According to Thomas (2017), labour tends to contribute a small portion of the additive manufacturing cost. Labour would include activities such as refilling the raw material and removing the finished product among other things. It is worth noting that additional labour is built into the other costs such as the machine and material cost, as these items also require labour to produce.

However, looking back into history, there are two major contributions to additive manufacturing cost modelling that received significant attention in additive manufacturing and these are the work by Hopkinson and Dicknes (2003) and Ruffo, Tuck and Hague (2007). Hopkinson and Dicknes (2003) calculated the cost of additive manufactured parts basing on the average cost per part and three additional assumptions. These additional assumptions were that the system was assumed to produce a single type of part for one year, utilising maximum volumes.

On the other hand, Ruffo et al. (2007) calculated the cost of additive manufactured parts using an activity based cost model, where each cost is associated with a specific task or activity. The total cost of a build was computed is the sum of raw material and indirect costs, with the raw material costs computed as the price of material multiplied by its mass in kilograms. The indirect costs were computed as the total build time multiplied by indirect cost rate.

For additive manufacturing in cyber-manufacturing, Chan et al. (2018) proposed a novel framework for data-driven cost estimation where the similarities of three-dimensional geometry of parts and printing processes were established through the identification of the relevant features. To predict the additive manufacturing cost based on historical data, machine learning algorithms for dynamic clustering, least absolute selection and shrinkage operator (LASSO) and elastic net regressions were applied to feature vectors. The cost estimation framework commenced with the generation of a G-code from the submitted STL file. LASSO and elastic net (EN) regression models were used for prediction in each cluster and developed for large volume of data with several input variables to solve regression problems for big data analytics, where the input variables can be highly dependent on each other (Chan, Lu and Wang 2018).

2.11 Research Gap

It was noted from the literature review that the use of AHP as criteria for comparison and selection of the best 3D printing technologies that would meet the part characteristics is rather scanty. Additionally, the additive manufacturing technologies are evolving at a larger pace in this current fourth Industrial Revolution environment. Cost estimation of production parts made from additive manufactured is typically conducted to drive data collection (Chan, Lu and Wang 2018). Many researchers have discussed business cases for 3D printing and provided associated cost models, but these mathematical models comprised of material costs, machine costs, energy costs, production units, and build times. However, there is need to provide more accurate insight into reality by incorporating the additional costs involved which are not conventionally factored into the prior costing models.

2.12 Conclusion

The chapter has given a general overview of several manufacturing processes and technology. The traditional manufacturing techniques, plastic injection moulding, as well as tool and die manufacturing were covered in this section. It also embraced the various additive manufacturing in greater depth, current research materials for additive manufacturing, and key technologies for future intelligent manufacturing MAM and hybrid production methods. It was also noted that the analytic hierarchy process and group technology can be used to comprehend the applicability and selection of additive manufacturing process. Furthermore, it was vital to comprehend the literature on cost estimation in conventional die manufacturing and compare it against additive manufacturing. The estimation of cost of part manufacturing was noted as critical for industrial firms since it feeds into price evaluation which aids an organisation's competitiveness in the marketplace. The next chapter covers the methodology that was embraced to determine viability of 3D printed moulds and the most suitable additive manufacturing technology for rapid tooling for the manufacturing of moulds.

CHAPTER 3 : CASE STUDY BACKGROUND

3.1 Introduction

The previous chapter provided insight on a compressive literature review on conventional machining and manufacturing techniques, tool and die manufacturing and additive manufacturing. The essence of this chapter is to give a bird's eye view of the processes and machines that characterise the case study organisation. Through plant walkthroughs, it focuses on interrogating the facilities and equipment, as well as the current processes that characterise IMC. The facilities and equipment basically focus on designers of moulds, dies, inserts and electrodes, die casting tooling manufacturing, plastic injection mould manufacturing, and injection moulding equipment.

3.2 Die Casting Tooling Manufacturing

IMC offers die casting services and is a custom manufacturer of dies made of high-speed steel, die steel, and cemented carbide for industrial applications, as well as custom injection mould tool making services. Figure 4.1 shows the current layout for the foundry for die casting process which produce high quality aluminium dies for injection moulding at IMC.

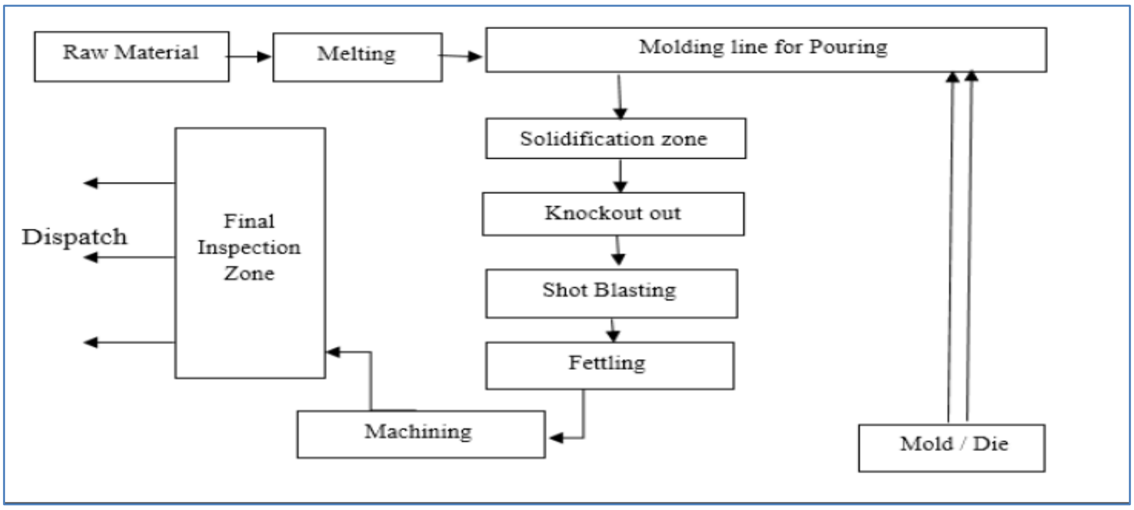

Figure 3.1: Current layout for die-casting foundry

The production runs range from prototype to high volume and short production runs. IMC's full-service capabilities include mould repairs, support and acceptance of existing tooling transfers, and a comprehensive mould management maintenance program.

The raw material is heated to an elevated temperature until it turns to molten metal. The permanent moulds or dies are manually cleaned and sent to the pouring section where the molten metal is poured into dies, filling the mould space by gravity. Once filled, the die is then transferred to the solidification zone where it cools down. Thereafter, the knocking process in which casting is separated from the mould takes place, after which the separated casting is shot blasted. The casting is then heat treated and sent for fettling process where extra protrusions, marks are removed. After fettling, the casting goes for machining to achieve required surface finish and dimensions. Finally, the casting is inspected for quality and dispatched to the warehouse.

3.3 Plastic Injection Mould Manufacturing

IMC also offers custom precision mould manufacturing services through the fabrication of injection moulding tools according to the demand of tooling specification. The mould design and manufacturing cycle commences with a primary engineering design solution, which is endorsed and approved by a client. The mould is then fabricated and tested to demonstrate its ability to produce conforming moulded parts and then finally delivered to the client. In between, after detailed design, the mould fabrication process is undertaken through a combination of numerically controlled machines, basically through milling, grinding, drilling and electro-discharge machining. The key specifications that are taken into consideration include the client's mould standard, size of machine, material and shrinkage used, injection cycle time, and mould life requirement. Depending on the part size, mould structure complex, accuracy and mould life, the manufacturing period normally ranges from to 15 days to 60 days. Figure 4.2 shows a specimen of the injection moulding manufacturing tooling workshop and process for delivering quality moulds and mould services.

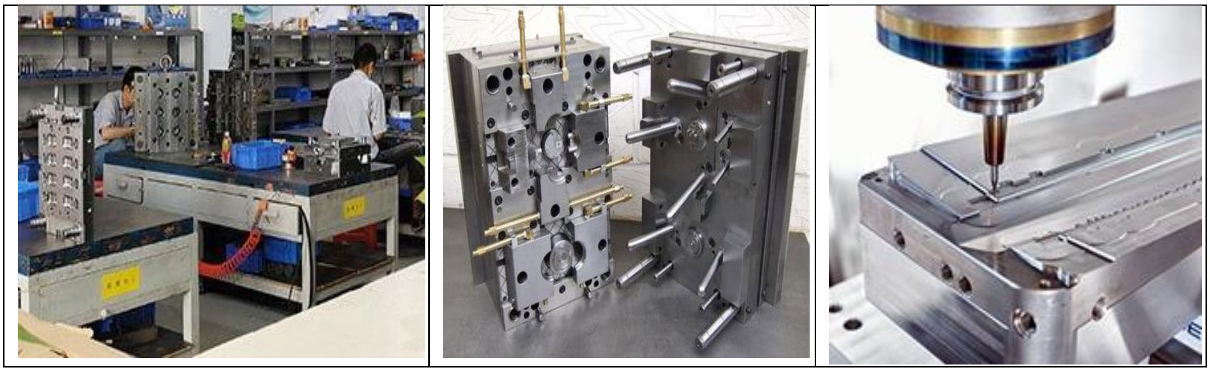

Figure 3.2: Injection moulding manufacturing tooling workshop

The machining zone is composed of CNCs for machining, and these are equipped with the Mouldex 3D CAM programs. Mouldex3D is known as a world leader in plastic injection computer-aided engineering moulding software that is characterized by simulation capabilities for optimizing designs, enhancing manufacturability, and shortening the product time-to-market.

3.4 Non-Traditional Machining in Mould and Die Manufacturing

The non-traditional machining methods employed for the fabrication of moulds and dies at IMC include erosion with penetration, and erosion with dielectric.

Figure 3.3: CNC machine erosion with penetration

Erosion with penetration is accomplished by using copper or a graphite electrode. In this case, the electrode is always at a certain distance away from the work and not in contact with the material.

Figure 4.3 shows the CNC machine erosion with penetration and in this type of erosion, there is a Verein Deutscher Ingenieure (VDI) scale used to measure the roughness values of the final surface finish of the work.

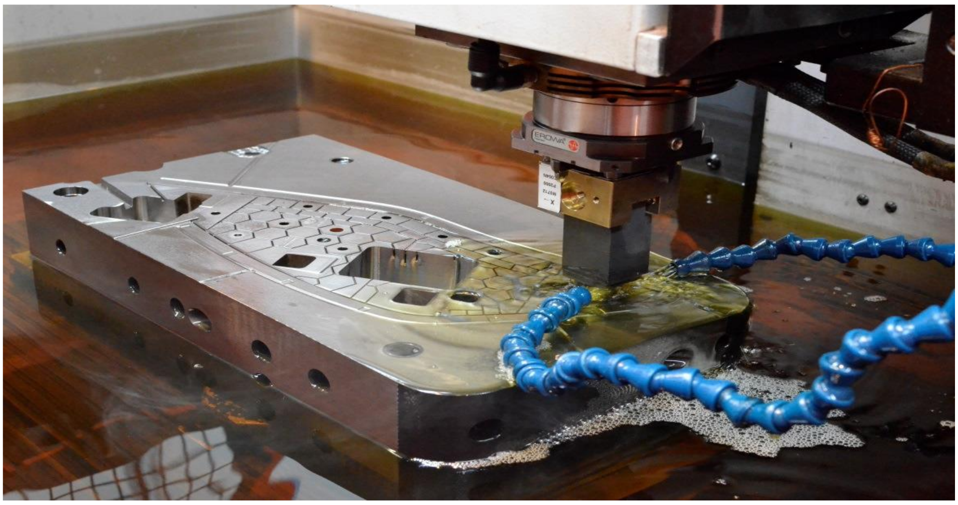

Figure 3.4: CNC machine erosion with ddielectric

Concerning erosion with dielectric, Figure 4.4 shows the CNC machine erosion with dielectric, whereby the work piece is covered by a dielectric liquid. The flushing process is crucial when metals are subjected to this procedure. The dielectric performs the flush away of the eroded bits from the gap between work piece and electrode, or else they may form electrical bridges, which would result in short circuits.

3.5 Injection moulding

IMC boasts injection moulding machines and strives to use less energy and generate less waste from injection moulding without sacrificing quality. Figure 4.5 shows sample injection moulding machines, which is the Dream series and the 3 series connecting rod type injection moulding machine (Culkin and Simmons). The Dream series is a more flexibly modularized design that provides moulding solutions of high precision and speed. It is characterised by a highly efficient servo linear guiding track with less friction, and series single cylinder mono-track low inertia injection unit. The injection volume is less or equal to 7kg with 80MPa low pressure injection and the actual weight of the machine is 540kg.

Like any other traditional injection moulding machines, IMC's injection moulding machines consist of the injection system, mould system, hydraulic system, clamping system and a control system.

Figure 3.5: Dream series D-J series and (3 series) connecting rod type IMM

IMC also excels in the manufacture plastic moulded products to the highest quality and with plastic injection contract moulding, plastic products are made by using the clients' existing mould.

3.6 Surface Finishing Requirements

The current surface finishing requirements from using traditional and non-traditional machining methods are essential, since the understanding thereof will have an influence on the AM technology that may be chosen to replace these prior technologies. There are several surface finish alternatives for injection moulding that would impact the look, feel, texture, and other surface features that characterize the final products. Surface finish is a vital design consideration from both the design engineer's perspective and customer's point of views as it is essential for the mould design since moulded product would emulate even the tiniest flaws in the mould surfaces. Surface finishing in injection moulding is when the mould surface itself is prepared in such a manner that the part comes out finished. This is different from CNC machining or 3D printing surface finishes where surface finishing is accomplished after the part is made, as an extra step. IMC uses VDI 3400 surface finish category commonly known as VDI surface finish mainly processed by the traditional texturing method or electrical discharge machining when mould machining.

3.7 Conclusion

It was noted from the case study background that IMC offers die casting services and custom precision mould manufacturing services through the fabrication of injection moulding tools according to the demand of tooling specification. The key concern for IMC was noted as lengthy production lead time for the mould and die manufacture that affected product delivery. The key specifications that were taken into consideration for IMC include the client’s mould standard, size of machine, material and shrinkage used, injection cycle time, and mould life requirement. It was also noted that the the non-traditional machining methods that were employed for the fabrication of moulds and dies at IMC include erosion with penetration, and erosion with dielectric. IMC was noted as having 15 injection moulding machines and striving to use less energy and generate less waste from injection moulding without sacrificing quality. The current surface finishing requirements from using traditional and non-traditional machining methods were also noted as essential, since the understanding thereof will have an influence on the AM technology that may be chosen to replace these prior technologies. The next chapter focuses on the research methodology that was adopted to assess the viability of additive manufacturing for rapid tooling.

CHAPTER 4 : RESEARCH METHODOLOGY

4.1 Introduction

This chapter focuses on the research methodology, outlining the methods that were adopted for the study. The research framework is outlined to guide the direction of the study. Ethical issues in scientific research area also taken into consideration to ensure credible results. The research methods that were used to accomplish the research objectives were also outlined in this chapter.

4.2 Research Framework

Figure 4.1 shows the research framework that is grounded on a comprehensive literature review. As the availability of data has increased through the use of online resources, interest in using various data libraries to investigate research issues has grown steadily and can be considered as a viable means of performing research. When faced with multi-variable considerations, a multi-dimensional criteria analysis can be used to compare different alternatives and select the best combination (Rezaei 2018). The Analytic Hierarchical Process (AHP) was used as criteria for comparison and selection of the best 3D printing technologies that would meet the part characteristics, which are surface finish, dimensional accuracy, cost and manufacturing lead time (MLT).

Concerning developing a business case for increasing the production rate and reduce operational costs for the manufacture of moulds, Group technology philosophy in which similar parts are identified and grouped together was adopted to take advantage of their similarities during production.

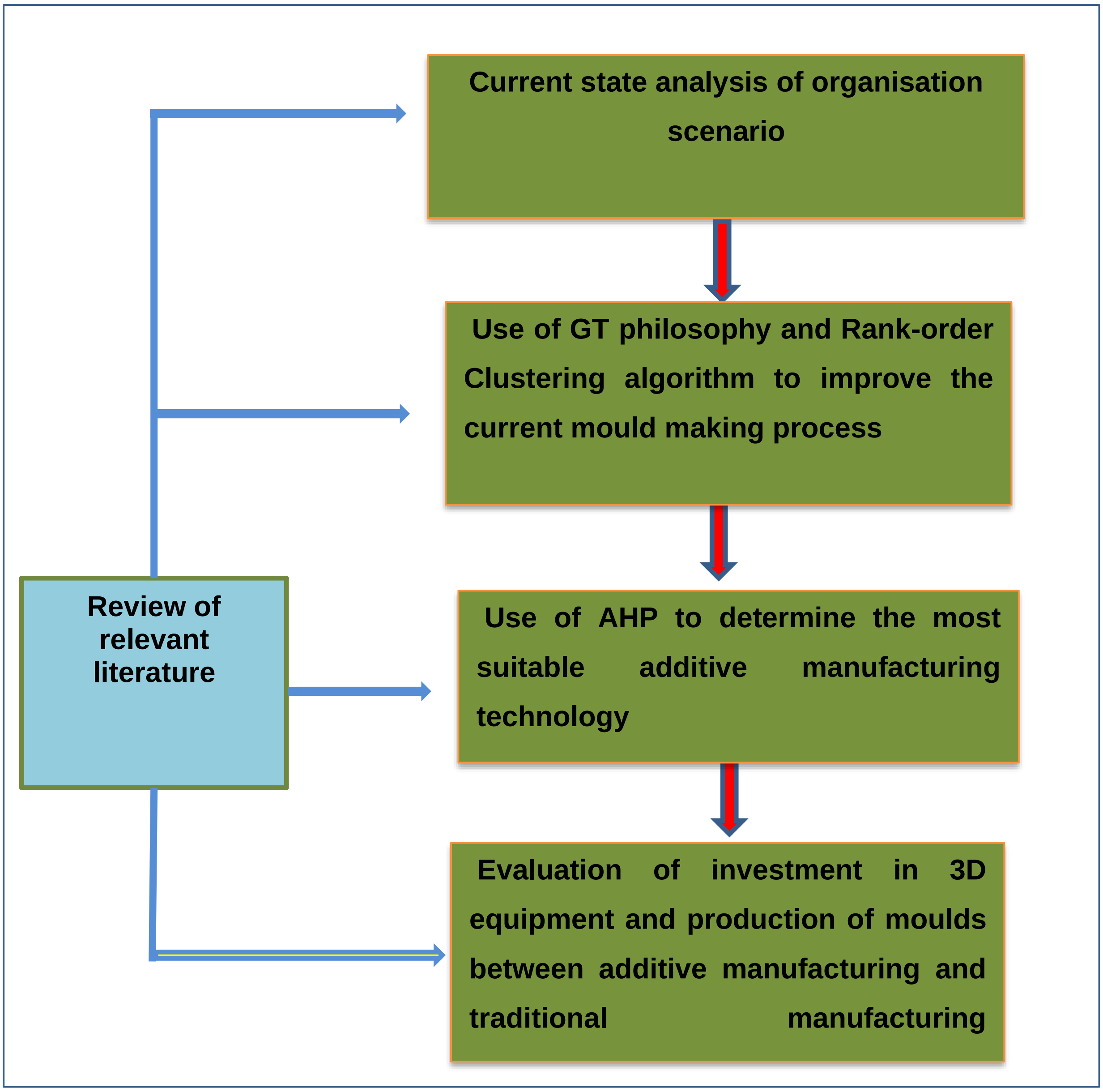

Figure 4.1: Research framework

A comparative analysis was done between the traditional injection mould making and adopting 3D printing technologies which will be configured using the Rank-order Clustering algorithm. The research embraces proposing a process for evaluation of investment in 3D equipment and production of dies between additive manufacturing and traditional manufacturing technologies using operational and financial key performance indicators.

4.3 Methods for Objective 1

The first objective of the study was to establish the current operating environment that characterise the case study organisation. The research approach that was adopted commenced with conducting a current state analysis of the case study organization. Current state analysis or As-Is process analysis is a process management approach that is aimed to identify and evaluate a firm's current processes (De Carolis *et al.* 2017). The focus of current state analysis was specific injection moulding processes within a department with the view to improve existing processes or creating new processes that embraced additive manufacturing technology for the manufacture of moulds for the injection moulding machines. Value stream mapping (VSM) is a process of mapping the steps involved in the material and information flow required to make a product from order to delivery (Manos 2006). VSM is an invaluable tool that is used to identify and document waste in day-to-day operations. A value stream map was developed to provide a detailed visualization of all steps that characterized the injection moulding process and the steps that were followed include:

- Step 1: Gather preliminary information on the history of product mix from the previous year's demand and the product volumes for each mould from the previous year.
- Step 2: Create a product quantity routing analysis by creating a product quantity routing analysis, by listing all of the moulds built by IMC.
- Step 3: Group products according to type and sort mould families by build sequence by constructing a process quantity routing analysis to identify mould families according to a similar build sequence.
- Step 4: Choose one value stream to begin with, using ABC mould demand classification analysis for annual demand of the moulds.
- Step 5: Create an operations flow chart for the value stream.
- Step 6: Walk the shop floor and collect the data from IMC SAP database. The data would include mould average lead time, mould average weight, average

assembly time, average machining time and number of moulds in process, setups, control and rework times, material movement distances and workstations uptime.

- Step 7: Construct the VSM using symbols to indicate what is happening at each process and use Kaizen burst events to show where wasteful activities occur.

4.4 Methods for Objective 2

The second objective of the study was to investigate the usage of group technology and rank-order clustering algorithm as mechanisms to aid the reduction of manufacturing lead time for the traditional mould making process. The research approach embraced group technology philosophy in which similar parts are identified and grouped together was adopted to take advantage of their similarities during production. identified for a well-defined purpose, a part family is a group of similar parts that share specific design or manufacturing characteristics (Debnárová et al., 2014). In line with the previously mentioned third step in creation of VSM, the steps followed in applying group technology include determining the critical part attributes that represent the criteria for part family membership and allocation of parts to established families. The information required for the GT coding system was divided into two groups, that is geometrical and dimensional data. The mould making process information for GT code followed a chain structure characterised by the following:

- Part type - The material type of each mould was coded and currently, there are 30 diverse material types used by IMC mould making.
- Part weight - wherein the weight of each part was coded and since weight is a continuous variable, the mould weights were divided into ten categories
- Dimensional specifications - These specifications include maximum length, width and height) of each mould.

According to King (1980), considering a binary part-machines n-by-m matrix b_{ij}, the following steps are used:

1. Compute the number $\sum_{j=1}^{m} b_{ij} \times 2^{m-j}$ for each row i;

2. Order the rows in accordance to the descending numbers that were computed previously
3. Compute the numeral $\sum_{i=1}^{n} b_{ij} \times 2^{n-i}$ for each column j
4. Order the columns in accordance to the previously computed descending figures
5. If no reordering occurred on steps 2 and 4, then proceed to step 6, otherwise execute step 1
6. Stop

It is worth noting that in conventional processing technologies, design or manufacturing features, as well as related geometric features was identified as attributes to represent parts. However, as posited by Zhang and Bernard (2014), geometric features are not so handy to design or manufacture in AM since AM processing is not so sensitive to the geometric attributes of a part. Hence, new different attributes should be identified and added to properly articulate the part's information which is valuable to the production in AM.

4.5 Methods for Objective 3

The third objective of the study was to determine the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds. Analytic Hierarchical Process (AHP) was used as criteria for comparison and selection of the suitable 3D printing technologies that would meet the part characteristics, which are surface finish, dimensional accuracy, cost and manufacturing lead time. The following steps were followed to ascertain the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds:

- Step 1: Definition of alternatives - The AHP process commences by defining the alternatives that are to be evaluated. In this case, these alternatives are additive manufacturing technologies for rapid tooling for the manufacture of moulds;

- Step 2: Define the problem and criteria - The next step was to define the problem and model the problem by breaking it into a hierarchy of smaller problems. The criteria for comparison of the 3D printing technologies are surface finish, dimensional accuracy, cost and manufacturing lead time. Criteria to evaluate the solutions emerge in the process of breaking down the sub-problem;
- Step 3: Establish priority amongst criteria using pairwise comparison - Pairwise comparison is used in the AHP to create a matrix for evaluating the intensity of importance. Quality circles meetings were conducted every Monday morning by management and employees of IMC.

  The underlying mathematics is that the pairwise comparison matrix for a decision maker with m objectives is an m × m matrix, B = $[b_{ij}]$ such that:

  $b_{ij} > 0$ for i, j = 1, . . . , m, (1)

  and

  $b_{ji} = \frac{1}{b_{ij}}$ for i, j = 1, . . . , m (2)

  where i, and j are the compared objectives

In the context of the study, the i values refers to part characteristics i.e. surface finish, dimensional accuracy, cost and manufacturing lead time, while j values refers to the four alternative additive manufacturing technologies.

A matrix B is defined to be a positive matrix if it satisfies the condition in equation (1). If B satisfies condition in equation (2), then it is regarded as a reciprocal matrix.

- Step 4: Check consistency- Checking for consistency of the judgments, taking note that inconsistent data gives inconsistent results;

  In order to ensure consistent decision making, then the pairwise comparison matrix B should satisfy the conditions that were mentioned in step 3 and

$$b_{ik} = b_{ij}b_{jk} \quad \text{for i, j, k = 1, . . . , m} \tag{3}$$

Assuming w_i is the weight of objective i, assuming that each of the weights is positive, and the weights sum to 1, then for consistent decision making, the ij entry of B is written as shown in equation (4):

$$b_{ij} = \frac{w_i}{w_j} \tag{4}$$

$$Consistency\ index\ (CI) = \frac{\lambda_{max} - number\ of\ elements\ in\ matrix\ B}{number\ of\ elements\ in\ matrix\ B - 1}$$

where λ_{max} is the largest eigenvalue.

$$Consistency\ ratio\ (CR) = \frac{CI}{RI} \tag{5}$$

where RI is the random index.

- Step 5: Compute the relative weights - Mathematical calculations were done based on the data and assignment of the relative weights to the criteria.

As shown in equation (6), assuming consistent a decision making from m objectives, with B as the corresponding pairwise comparison matrix, and w the weight vector. Then w is an eigenvector of B with corresponding eigenvalue $\lambda = n$.

$$Bw = m\begin{bmatrix} w_1 \\ w_2 \\ \\ w_m \end{bmatrix} = mw \tag{6}$$

Alternative AM technologies were then evaluated against the criteria of surface finish, dimensional accuracy, cost and manufacturing lead time to derive the best solution that matched the production of moulds. The ranking of alternatives was based on benchmarking results from studies as well technical specifications from equipment suppliers. The final stage was to construct an Option Performance Matrix (OPM) of the criterion weights or eigenvectors for the four alternative AM technologies in terms of what IMC required for the manufacture of moulds for injection moulding.

4.6 Methods for Objective 4

The fourth objective of the study was to determine the viability of 3D printed rapid tools for injection moulding. The research embraces proposing a process for evaluation of investment in 3D equipment and production of moulds between additive manufacturing and traditional manufacturing technologies using operational and financial key performance indicators which will be explained in detail below. The operational indicators constituted the build times and characteristics such as production time, scan time, height of build and build volume. The research approach further embraced determining cost estimates and the amount of operational time available for the 3D printer to operate and evaluating the feasibility of achieving production volumes as prescribed by the demand. In summary, the following process steps will be adopted:

1. Identification of candidate parts - The first step is to identify a tool or set of tools that are potential candidates for 3D printing. These parts would be relatively complex in geometry or small in size. Several key variables concerning the part dimensions are derived from the bounding box, and these include the cross-sectional area a_{cs} and the height of the bounding box along the z-axis, h_{box}. The volume of space required by the bounding box v_{box} is computed as shown in equation (7) below.

   $$v_{box} = a_{cs} \times h_{box} \quad (7)$$

   However, v_{box}, only reflects the amount of space needed for the mould, and does not accurately show the actual part.

2. Selection of the suitable machine according to the results of the AHP process. The material properties as reported by both the industry users and manufacturer are the minimum acceptability criteria in this stage.

   The total build volume (v_{build}) is calculated by taking the three dimensions of the build envelope as Cartesian coordinate axis dimensions as shown in equation (8).

$$v_{build} = d_x \times d_y \times d_z \quad (8)$$

As shown in equation (9), considering that the chosen machine is powder bed system, the maximum volumetric scan rate (S_{vol}) is computed from the machine's scan speed (S_{scan}), layer thickness (t_{layer}) and focus diameter (d_f). Material density (ρ) can be used to compute deposition rates (S_{dep}) as shown in equation (10).

$$S_{vol} = S_{scan} \times d_f \times t_{layer} \quad (9)$$

$$S_{dep} = S_{vol} \times \rho \quad (10)$$

3. Determining current production information and associated costs of the identified candidate part or parts, as made by traditional die manufacturing technique; it was also vital to evaluate the production quantities that are achievable, by approximating VELO3D's capabilities by determining the amount of time available for the machine tool to operate and ability to meet annual demand.

As shown in equation (11), machinery fixed costs would include costs for the initial machine, overheads, complementary machines, labour, utilities, transportation, software, installation, maintenance, safety certification and spare parts.

$$c_{m,annual} = c_{OH} + c_{labor} + c_{software} + c_{maint} + c_{spares} + c_{utilities} + c_{safety} \quad (11)$$

The cost per unit of build volume (c_{vol}) is computed by using equation (12) and equation (13) represents the cost per deposition rate (c_{dep}).

$$c_{vol} = \frac{c_{machine}}{v_{build}} \quad (12)$$

$$c_{dep} = \frac{c_{machine}}{s_{dep}} \quad (13)$$

Equation (14) was used to determine the number of parts capable on a single build layer.

$$p_{layer} = \frac{d_x \times d_y}{a_{cs} \times (1 + b_{space})} \quad (14)$$

Material, file and machine preparation are referred to as pre-build ($t_{build,pre}$) and the build phase (t_{build}) is time for actual machine operation commencing from the deposition of the first layer to completion of the last layer. Post-build ($t_{build,post}$) is the time from build completion to when the moulds are ready for use; this includes part removal, any post-processing required and machine cleaning.

$$t_{production} = t_{build,pre} + t_{build} + t_{build,post} \quad (15)$$

4. Evaluating production quantities that are achievable, by approximating additive manufacturing capabilities by determining the amount of time available for the machine tool to operate and ability to meet annual demand.

   The number of operational days available (t_{days}) can be determined by equation (16).

$$t_{days} = 365 - t_{weekends} - t_{holidays} - t_{vacation} - t_{maintenance} \quad (16)$$

   The VELO3D machine annual time capacity ($t_{capacity}$) is computed by using equation (17). Consistent with build time units, the value is multiplied by 24 to convert the number of days into hours.

$$t_{capacity} = t_{days} \times 24 \quad (17)$$

   The possible maximum number of builds in a given year (n_{builds}), and the maximum number of annual part production (n_{parts}) are computed by using equations (18) and (19) where u is the utilization rate variable.

$$n_{builds} = \frac{t_{capacity} \times u}{t_{production}} \quad (18)$$

$$n_{parts} = n_{builds} \times p_{build} \quad (19)$$

5. Determination of performance indicators

   It was also crucial to determine performance indicators that include break-even point and throughput rate, T. Throughput gives a production metric concerning the magnitude of system output over a given time interval. Throughput was not calculated in terms of the annual availability but in terms of production in this case.

$$T = \frac{p_{build}}{t_{production}} \quad (20)$$

   Breakeven point was computed from the number of years required to reach the breakeven point (B_{time}), as shown in equation (21). The investment should not be pursued if the value of the breakeven point is larger than the project lifespan.

$$B_{time} = \frac{B_{units}}{n_{parts}} \quad (21)$$

6. Making a final decision through comparison of additive versus traditional manufacturing capabilities in tool production. In order to ensure a fair comparison, additive manufacturing cost must be reported in a likewise manner to the conventional manufacturing cost's structure. The candidate part must fulfil the requirements stated in steps 1 to 5.

It is vital to ensure that the candidate part meets the bounding box constraints and that the suitable AM machine is selected according to the results of the AHP process in order to derive unbiased results.

4.7 Conclusion

The research methodology proposed the use of analytic tools, philosophies and concepts such as value stream mapping, ABC mould demand classification analysis, group technology and Rank-order Clustering algorithm. The research framework embraced current state analysis, criteria for comparison and selection of the best 3D printing technologies that would meet the part characteristics. The methodology also embraced comparative analysis of traditional die making and adopting 3D printing technologies, as well as evaluation of investment in 3D printing equipment and production of moulds between additive manufacturing and traditional manufacturing technologies. The following chapter focuses on the detailed analysis of the manufacturing processes that characterise IMC.

CHAPTER 5 : RESULTS AND DISCUSSION

5.1 Introduction

The previous chapter focused on the case study background, highlighting that IMC offers die casting services and custom precision mould manufacturing services through the fabrication of injection moulding tools according to the demand of tooling specification. The essence of this chapter is to provide comprehensive results on the current status of operations and processes and identify areas for improvement in line with the stated objectives. The results focus on the discussion of the use of AHP to determine the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds, which is then input to determining the viability of 3D printed rapid tools for injection moulding. A comprehensive discussion of the results on the development of a business case for increasing the production rate and reduce operational costs for the manufacture of moulds and dies will ensue.

5.2 Establishing the current operations and processes

The first objective of this study is to establish the current operations and processes that characterise the IMC. The overarching goal is to establish the demand of various mould types that are produced by IMC, develop a value stream map of product that ranks highest, and thereafter gain insight into economic implications of adopting additive manufacturing to fabricate the part.

5.2.1 Product Analysis

Product analysis was done with the intention to comprehend the demand of different moulds and dies that were produced by IMC. The product listing of the moulds that were produced at IMC were pulled out from the SAP database and it was noted that about 600 different moulds had been fabricated since the last two years. Table 5.1 shows the annual demand and cumulative percent for top 16 moulds produced by IMC. The results show a total of 144 000 moulds that were produced in year 2020.

Table 5.1: Annual demand for top 16 moulds produced by IMC

Mould type	Annual demand	Percent of Total	Cumulative Percent
Switch cover	25200	17.50%	17.50%
Smart phone	23400	16.25%	33.75%
Helmet shell	21500	14.93%	48.68%
Air filter housing	11200	7.78%	56.46%
Automotive dashboard	10600	7.36%	63.82%
Television Cabinet	10450	7.26%	71.08%
Battery Casing	9647	6.70%	77.78%
Printer casing	4700	3.26%	81.04%
Power-tool housing	4620	3.21%	84.25%
Automotive bumper	4556	3.16%	87.41%
Plastic syringe	4400	3.06%	90.47%
Remote control	3851	2.67%	93.14%
Toy	2616	1.82%	94.96%
Bottle cap	2440	1.69%	96.65%
Pocket comb	2420	1.68%	98.33%
Wheelie bin	2400	1.67%	100.00%
Total	**144 000**	**100.00%**	

ABC mould demand classification analysis (ABC analysis) was conducted for the top 16 moulds that were produced by IMC. The results in Figure 5.1 show that under the A-category of the ABC mould demand classification analysis, the moulds for the switch cover, smart phone and helmet shell contributed 48.68% to the total demand of moulds that were fabricated by IMC.

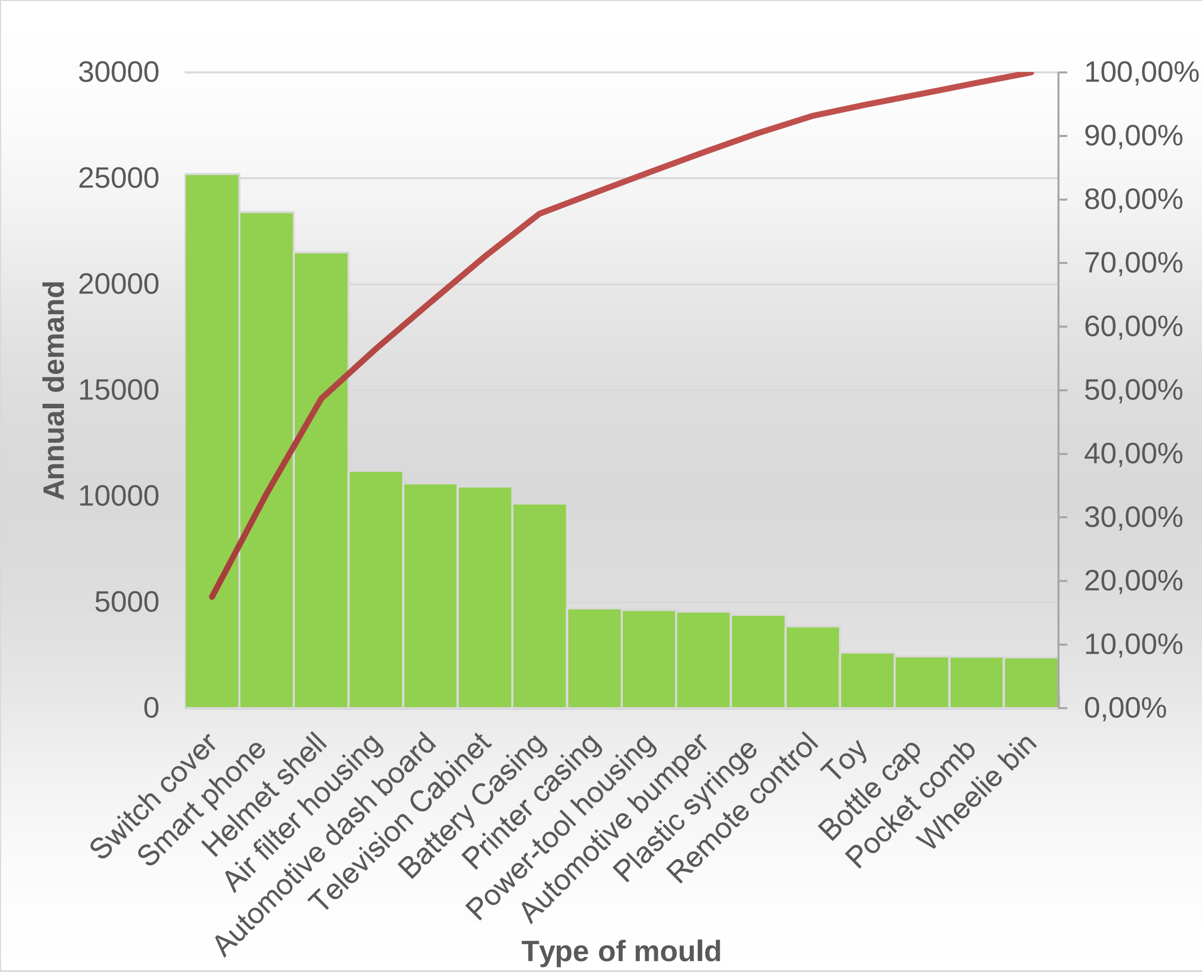

Figure 5.1: ABC mould demand classification analysis for demand of mould types

The B-category of the ABC mould demand classification analysis consisted of air filter housing, automotive dashboard, television cabinet and battery casing moulds that contributed 29.1% to the total demand of moulds that were fabricated by IMC. On the other hand, the C-category of the ABC mould demand classification analysis contributed 22.22% to the total demand of moulds that were fabricated by IMC.

5.2.2 Production Flow Analysis

As highlighted in Chapter 1, the key concern for IMC is lengthy production lead time for the mould and die manufacture and this becomes a problem since clients expect quick product delivery. IMC is a vertically integrated organisation is currently facing challenges in providing rapid response and overseeing production that would translate to shorter lead times and on-demand delivery. Value stream mapping was deployed as a tool for production flow analysis to reveal the areas where waste occurs and improve the flow of material and information so that the product is delivered to the client on time. Figure 5.2 represents the value stream map for the switch mould. The lead time is sum of all value-added time and non-value-added time that a product takes through the process from beginning to end. The demand for the moulds is 12000 numbers per month and the daily requirement is 545 numbers per day. The takt time is equal to the ratio of effective operating time per shift to the quantity that is required per shift by the customer and is 126 seconds in this case.

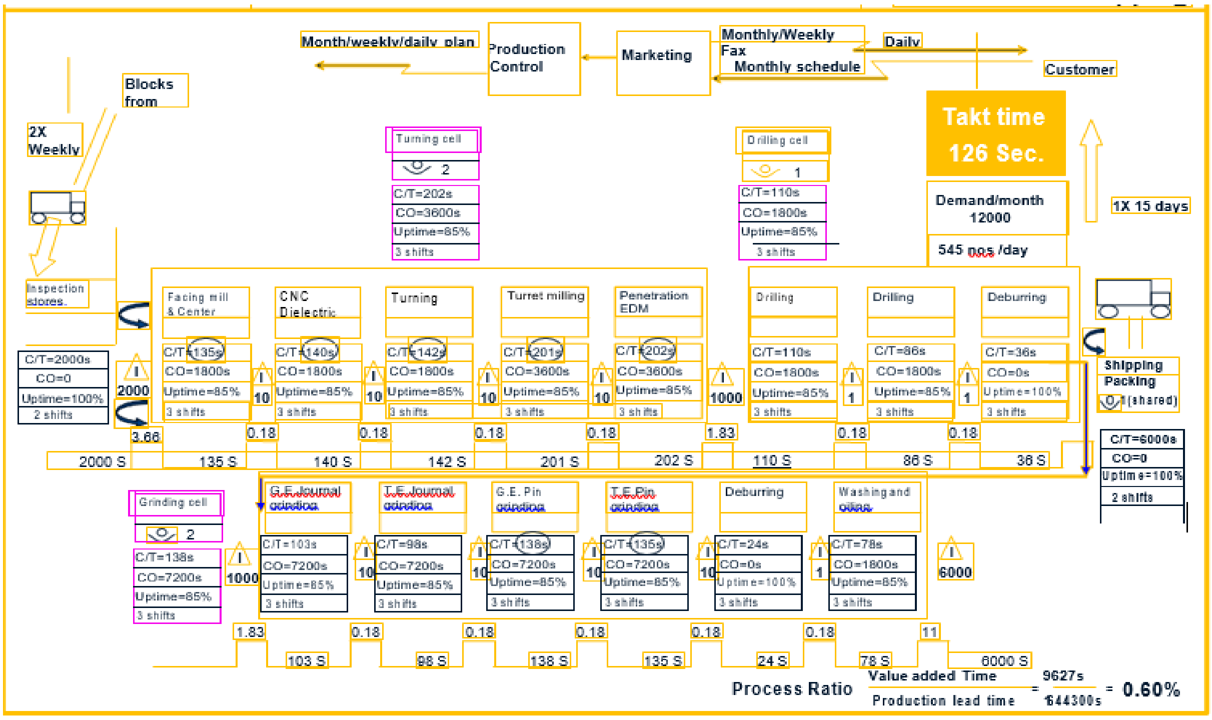

Figure 5.2: Value stream map for the manufacture of moulds

The organisation uses a three-month firm schedule requirements for the production department to develop a production plan for the following month's production. The process for mould manufacturing cell commences from receiving of mould forgings from the incoming stores and moved using a trolley to the facing and centring machine. Subsequent turning, drilling, deburring, and grinding operations are executed. Five operators are used when the machining is done in batch mode and the distance travelled by the material is 98 meters. The process ratio was found to be 0.60%, which was a cause for concern. This was caused by excessive time used for machining and grinding which was above the takt time.

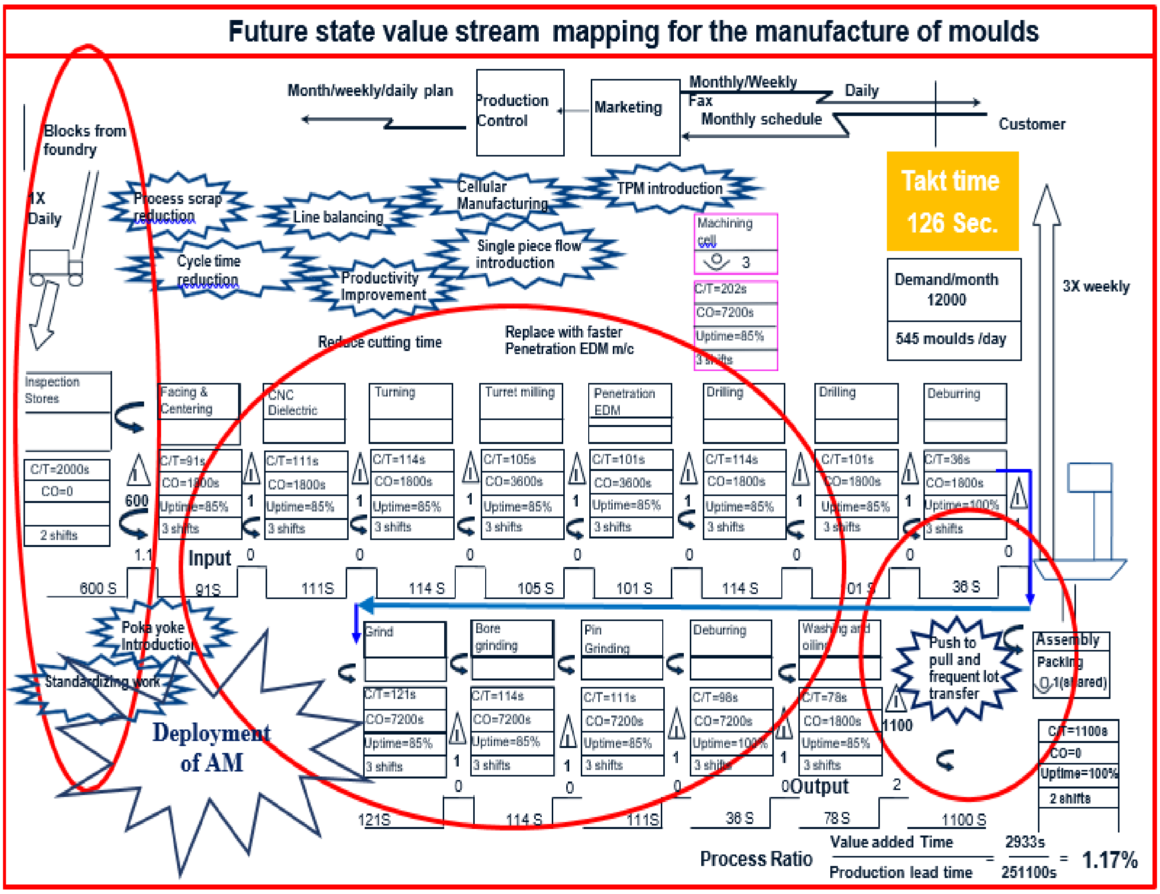

Figure 5.3: Future state value stream mapping for manufacture of moulds

As shown with the Kaizen burst events in Figure 5.3, the value stream map revealed that there was room for improvement in terms of push to pull and frequent lot transfer, standardising work, reducing cutting time and process scrap, as well as introducing poka yokes and cellular manufacturing. The plunge facing and centering operation was completed on both sides of the mould through development of special tooling that was characterised by cartridges fitted with inserts mounted on the tool face and a centre drill mounted on the tool centre. The modification resulted in elimination of the facing operation and plunge facing, centre drilling and facing operations were combined. The kaizen event led to a reduction of the cycle time from 140 seconds to 60 seconds. After studying the existing process parameters for roughing operation and finishing operation, basing on the process parameters and cutting force calculation, the speed and feed were optimised for roughing and finishing operations. It was noted that there was no deterioration on the tool life due to increasing feed and speed. Without compromising quality, by changing the process parameters, the cycle time reduced from 150 seconds to 110 seconds. After the process improvement initiatives, the process ratio improved from 0.60% to 1.17%. The takt time does not change since it is dictated by the customer demand. Further to developing a conventional future state value stream map, it was proposed to initiate process improvements or radically investigate the viability of 3D printed rapid tools for injection moulding.

5.3 Improvement of the current mould making process

The first research objective of this study embraces the current operating scenario that characterise IMC, establishing the product demand and whether the moulds can be grouped into families to affect some process improvement. The second objective of the study was to investigate the usage of group technology and rank-order clustering algorithm as mechanisms to aid the reduction of manufacturing lead time for the traditional mould making process. Table 5.1 shows the machine types and top 9 moulds from ABC mould demand classification analysis in the previous chapter. Similar parts were identified and grouped together to take advantage of their similarities during production. Master moulds and master unit dies for quick-change for the traditional injection mould making were proposed through the composite part concept. The Rank-order Clustering algorithm (ROCA) is an easy-to-use and efficient algorithm for grouping machines into cells and in this case was used to group the mould manufacturing equipment. The occupied locations in the matrix were arranged in a randomized manner for the commencing mould-machine incidence matrix that was compiled to document the mould routings for the machine shop.

Table 5.2: Coded parts and machines selected for ROCA

Code	Mould type	Code	Machine type
R	Switch cover	1	Joemars EDM Model 322
S	Smart phone	2	CNC Dielectric Fluid EDM S50
T	Helmet shell	3	Conytrok GS600 high precision CNC
U	Air filter housing	4	Turret milling machine CF-A2
V	Automotive dashboard	5	CNC Wire Cutting EDM DK7740
W	Television Cabinet	6	Aristech CNC 430 Die sinking EDM
X	Battery Casing	7	ONA-S64 penetration EDM
Y	Printer casing	8	Sodick AG35L EDM CNC
Z	Power-tool housing		

ROCA was used to reduce the mould-machine incidence matrix to a set of diagonalized blocks that represented mould families and related machine groups. Commencing with the initial mould -machine incidence matrix shown in Table 5.2, the algorithm that was highlighted in Section 4.6 was followed.

Table 5.3: Initial mould -machine incidence matrix

	Mould								
Machines	R	S	T	U	V	W	X	Y	Z
1	1								1
2		1					1		
3			1		1			1	
4		1				1	1		
5			1					1	
6						1	1		
7	1			1					
8			1		1				

1. For each row in the matrix, the series of 1s and 0s (blank entries = 0s) from left to right was read as a binary number. The rows were thereafter ranked in order of diminishing value. The rows were ranked in the same order as they appeared in the current matrix in the event of a tie.

Step 1

	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0		
	R	S	T	U	V	W	X	Y	Z	**DE**	Rank
1	1								1	257	2
2		1					1			132	4
3			1		1			1		82	5
4		1				1	1			140	3
5			1					1		66	7
6						1	1			12	8
7	1			1						288	1
8			1		1					80	6

2. Numbering from top to bottom, the current order of rows was checked to see if it was the same as the rank order determined in the previous step. The results were found to be negative.

Step 2

	R	S	T	U	V	W	X	Y	Z	
7	1			1						2^7
1	1								1	2^6
4		1				1	1			2^5
2		1					1			2^4
3			1		1			1		2^3
8			1		1					2^2
5			1					1		2^1
6						1	1			2^0
DE	192	48	14	128	12	33	49	10	64	
Rank	1	5	7	2	8	6	4	9	3	

3. Commencing from the top, the rows in part-machine incidence matrix were reordered by listing in decreasing rank order.

Step 3

	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0		
	R	U	Z	X	S	W	T	V	Y	**DE**	Rank
7	1	1								384	1
1	1		1							96	2
4				1	1	1				56	3
2				1	1					48	4
3							1	1	1	7	6
8							1	1		6	7
5							1		1	5	8
6				1		1				40	5

4. The series of 1s and 0s, with blank entries = 0s, were read from top to bottom as a binary number for each column of the matrix. The columns were thereafter read in order of decreasing value. The columns were ranked in the same order as they appeared in the current matrix in the event of a tie.

Step 4

	R	U	Z	X	S	W	T	V	Y	
7	1	1								2^7
1	1		1							2^6
4				1	1	1				2^5
2				1	1					2^4
6				1		1				2^3
3							1	1	1	2^2
8							1	1		2^1
5							1		1	2^0
	192	128	64	56	48	40	7	6	5	
Rank	1	2	3	4	5	6	7	8	9	

5. The current order of columns was found to be the same as the rank order determined in the previous step when numbering from left to right,

The final part families and machine groups at the end of the ROCA were:

I = (R, U, Z) and (7, 1); II = (X, S, W) and (4, 2, 6); III = (T, V, Y) and (3, 8, 5)

The value stream map from Figure 5.3 revealed that there was room for improvement in terms of reducing material movements and reducing setup times through group introducing manufacturing cells. These results demonstrate that the moulds for the switch cover, air filter housing and power-tool housing (coded as R, U and Z respectively) can be processed on cell 1 with ONA-S64 penetration EDM and Joemars EDM Model 322 machines (coded as 7 and 1). Similarly, the moulds for battery casing, smart phone and television cabinet (coded as X, S and W respectively) can be processed on cell 2 with Turret milling machine CF-A2, CNC Dielectric Fluid EDM S50 and Aristech CNC 430 Die sinking EDM (coded as 4, 2 and 6). Lastly, the moulds for helmet shell, automotive dashboard and printer casing can be processed on cell 3 with Conytrok GS600 high precision CNC, Sodick AG35L EDM CNC and CNC Wire Cutting EDM DK7740. However, it was also proposed to initiate radical process improvement by investigating the viability of 3D printed rapid tools for injection moulding.

5.4 Analytic Hierarchical Process for selection of best 3D printing technology

The third objective of the study was to determine the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds. As highlighted in the literature review, the understanding of material properties that are required for a die or mould is vital in selecting the applicable AM technology that can be adopted o fabricate these tools or components.

5.4.1 Characteristics of the mould

The results from ABC mould demand classification analysis for demand of mould types shown in Figure 4.6 in the previous chapter revealed that the switch cover mould is the number one in demand, hence the subsequent sections will cover the viability of its fabrication through AM. The first step in the Analytic Hierarchical Process for selection of best 3D printing technology was comprehending the characteristics of the mould under study. Figure 5.4 and Figure 5.5 show the design of the inner switch mould plate and the outer switch mould plates respectively.

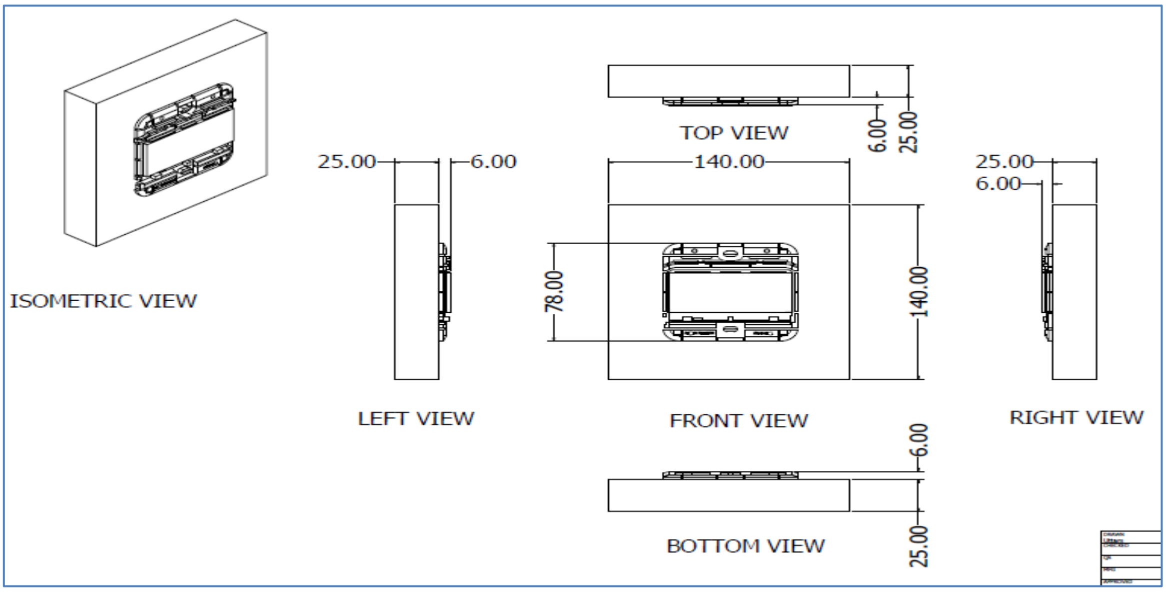

Figure 5.4: Drawing for inner switch mould plate

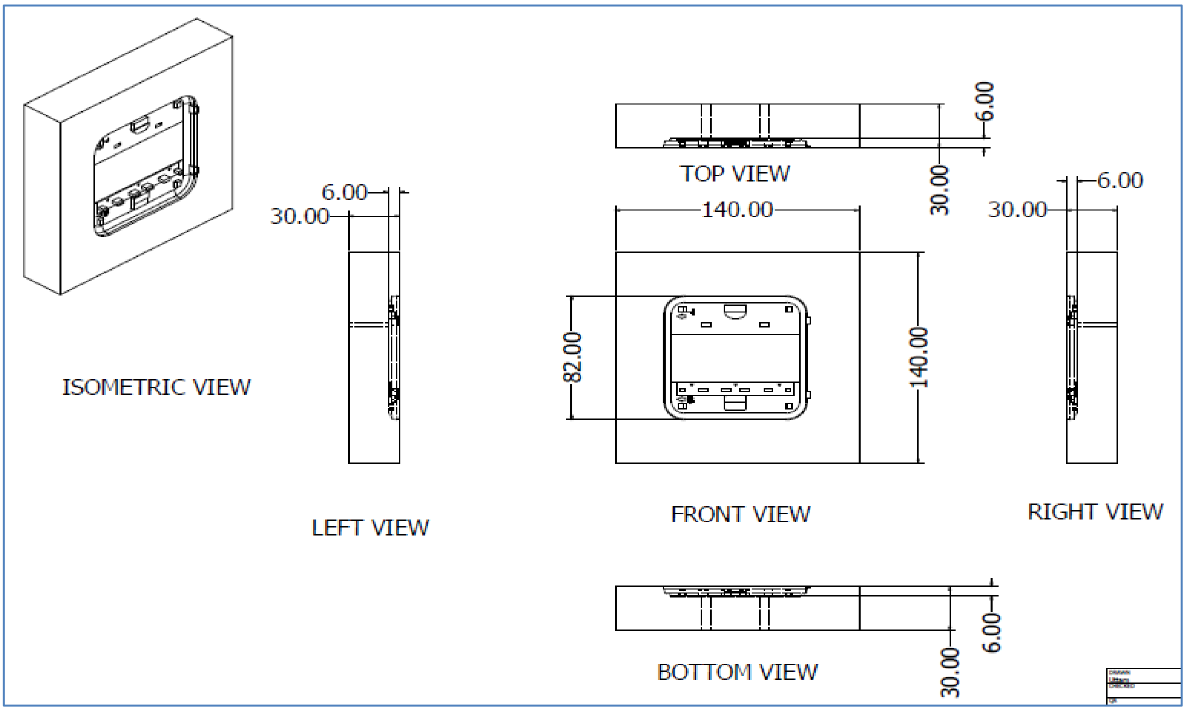

Figure 5.5: Drawing for outer switch mould plate

The roughness values of the contact surfaces should be between 1.2 and 1.8µm. The plates are made of 301 stainless steel and hardness of the material is Rockwell 89 HRC. Table 5.4 show the physical and material properties of inner switch mould and the outer switch mould plate.

Table 5.4: Physical and material properties of inner switch mould plate

Material	Stainless Steel
Density	8 g/cm^3
Mass	4.22429 kg
Area	61823.5 mm^2
Volume	528037 mm^3
Center of Gravity	x=0.0409664 mm y=0.060921 mm z=-13.9072 mm

Name	Stainless Steel	
General	Mass Density	8 g/cm^3
	Yield Strength	250 MPa
	Ultimate Tensile Strength	540 MPa
Stress	Young's Modulus	193 GPa
	Poisson's Ratio	0.3 ul
	Shear Modulus	74.2308 GPa
Part Name(s)	Switch Mold_Cover_CR_Base	

The material for the inner switch will start to yield when the von Mises stress reaches the yield strength. The injection moulding process is characterized by complex loading and the von Mises stress shown in Figure 5.4 is used to predict when the steel will yielding from the results of uniaxial tensile loads.

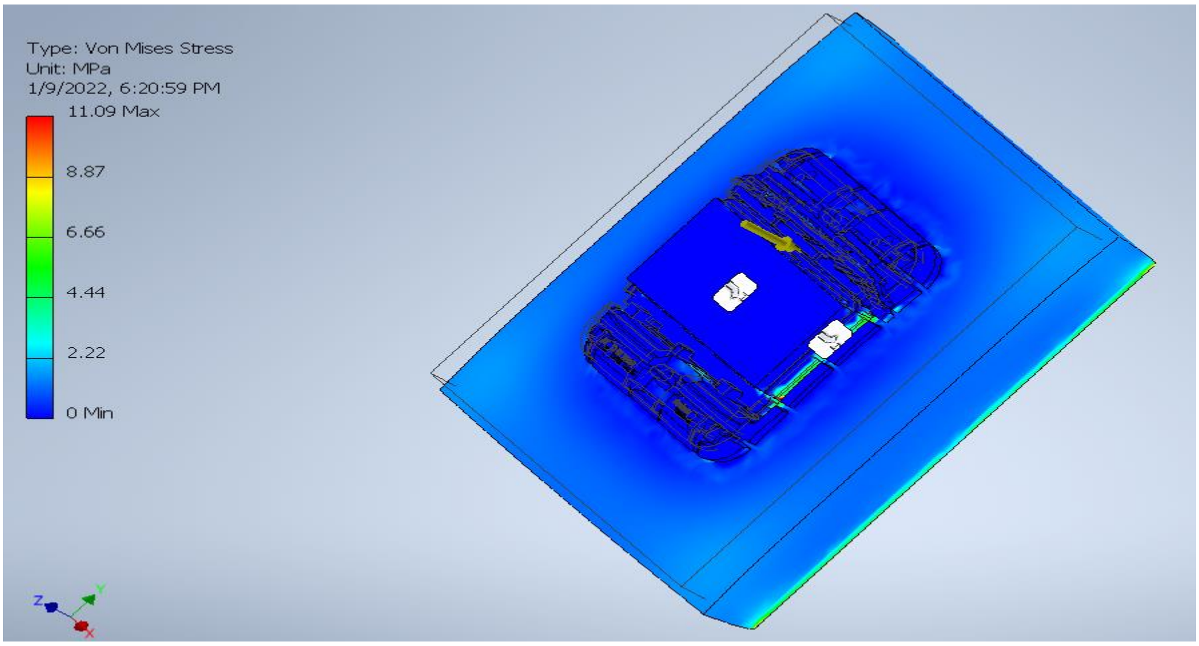

Figure 5.6: Von Mises stress analysis of inner switch mould plate

Table 5.5: Physical and material properties of outer switch mould plate

Material	Stainless Steel
Density	8 g/cm^3
Mass	4.27483 kg
Area	58315.1 mm^2
Volume	534353 mm^3
Center of Gravity	x=-0.0639471 mm y=-0.0364839 mm z=13.7107 mm

Name	Stainless Steel	
General	Mass Density	8 g/cm^3
	Yield Strength	250 MPa
	Ultimate Tensile Strength	540 MPa
Stress	Young's Modulus	193 GPa
	Poisson's Ratio	0.3 ul
	Shear Modulus	74.2308 GPa
Part Name(s)	Switch Mold_Cover_CV_1	

Figure 5.4 show the Von Mises stress analysis of inner switch mould plate, and these results reveal that the mould is reasonably loaded and will not be overstressed during the injection moulding process.

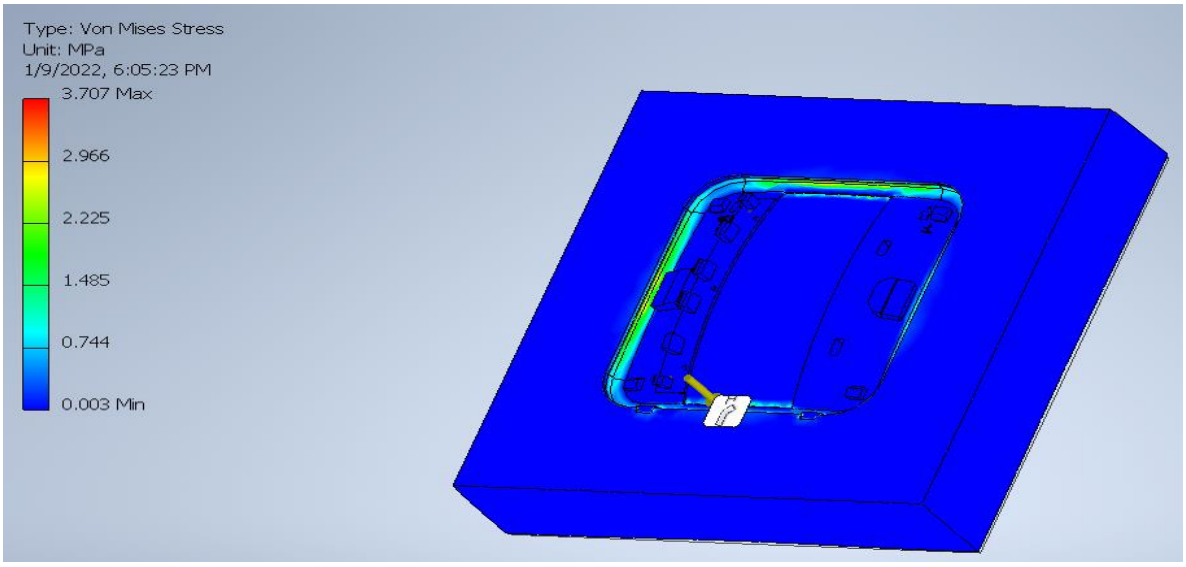

Figure 5.7: Von Mises stress analysis of outer switch mould cover mould

5.4.2 Decision, Options, and Criteria

The first step in the AHP is making a decision to ascertain the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds. Four options that include Multilevel Concurrent Printing (MCP) from Aurora Labs, MELD technology from MELD Manufacturing Corporation, HP's Metal Jet 3D printer (HPMJ3DP), and Intelligent Fusion from VELO^{3D}. The four most important criteria in the selection of the best 3D printing technology from among the recent AM technologies are surface finish, dimensional accuracy, manufacturing cost and manufacturing lead time requirements.

5.4.3 Pairwise Comparisons of Criteria

5.4.3.1 Importance scale and Pairwise Comparisons

Table 5.6 shows importance scale for allocation of criteria in AHP, with the scale ranging from one to nine. The number 1 implies that the two elements are equally important, preferred or the same, while number 9 implies that one element is extremely more important or preferred than the other one in a pairwise matrix.

Table 5.6: Importance scale in AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour oneover the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

The clients in the plastic industry would generally prefer quick delivery in order to promptly introduce new products into the market. Therefore, these customers are willing to pay a higher price for the tool rather than waiting longer.

Table 5.7 shows the pairwise comparison of criteria using the information that was extracted from the quality circles meetings that were conducted every morning by management and employees of IMC to gain perceptions of the respective importance with regards to the criteria. The surface finish and the dimensional accuracy criteria were found to be of equal importance, but more than the manufacturing time and cost for the additively manufactured parts. The manufacturing lead time is in turn strongly to very strongly important when compared to the manufacturing cost. Conversely, an intensity of 7 was allocated to both the mould surface finish and dimensional accuracy when compared to the manufacturing lead time, an indication that mould quality is more strongly preferred than cost and manufacturing lead time.

Table 5.7: Pairwise comparisons of criteria

	Surface finish	Dimensional accuracy	Cost	Manufacturing lead time

Surface finish	1	1/2	5	4
Dimensional accuracy	2	1	4	3
Cost	1/5	1/4	1	1/3
MLT	1/4	1/3	3	1

5.4.3.2 Importance Weights

The completed matrix is thereafter used to compute the importance weights, which outline the extent to which each criterion will influence the final decision. The first step in determining the weight of a criterion is to compute the geometric mean by multiplying all the relative importance scores from the row and computing the 4th root of this product, where 4 is the total number of criteria. For instance, the geometric mean for surface finish is computed as:

$$\left(1 \times \frac{1}{2} \times 5 \times 4\right)^{1/4} = 1.778$$

Normalisation is the second step in determining the weight of a criterion. This is accomplished by dividing the criterion's geometric mean by the sum of the geometric means of all the criteria. For instance, the criterion weight for surface finish is computed as:

$$\frac{1.778}{5.058} = 0.352$$

Table 5.8 shows the final results for the geometric mean and criterion weight (eigenvector). The criterion weight or eigenvector is a column vector but, in this study, will be written as a row to save space and called a Relative Value Vector (RVV). The resultant decimal is the weight of that criterion, and this method ensures that the sum of all weights equals 100% since each criterion accounts for a portion of the entire decision.

Table 5.8: Geometric mean and criterion weight

	Geometric mean	Criterion weight
Surface finish	1.778	0.352
Dimensional accuracy	2.213	0.438
Cost	0.359	0.071
MLT	0.707	0.140
Total	**5.058**	**1.000**

For instance, dimensional accuracy accounts for 43.8% of the overall decision in selecting the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds. On the other hand, cost accounts for 7.1% of the overall decision in selecting the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds.

5.4.3.3 Checking consistency

The next stage is to calculate λ_{max}, where λ is an eigenvalue, and then compute Consistency Index (CI) and the Consistency Ratio (CR). Table 5.9 shows a summary results for eigenvalue and consistency index. The matrix of judgements is multiplied by the eigenvector to obtain a new vector. The calculation for the first row in the matrix is:

(1 x 0.352) + (1/2 x 0.438) + (5 x 0.071) + (4 x 0.140) = 1.484

and the remaining three rows give 1.844, 0.297 and 0.586. The four estimates of λ_{max} are found by dividing each component of (1.484, 1.844, 0.297 and 0.586) by the corresponding eigenvector element. This gives 1.484/0.352=4.223 together with 4.214, 4.185 and 4.196. The mean of these values or estimate for λ_{max} is 4.205 and if any of the estimates for λ_{max} had turned out to be less than n, or 4 in this case, then there would have been a calculation error.

Table 5.9: Summary results for eigenvalue and consistency index

Criterion	Surface finish	Dimensional accuracy	Cost	MLT	Geometric mean	Criterion weight	Vector	λmax
Surface finish	1	0.50	5	4	1.778	0.352	1.484	4.223
Dimensional accuracy	2	1	4	3	2.213	0.438	1.844	4.214
Cost	0.20	0.25	1	0.33	0.359	0.071	0.297	4.185
MLT	0.25	0.33	3	1	0.707	0.140	0.586	4.196
Total					5.058	1.000		
						mean		4.205
						CI		0.068

The Consistency Index (CI) for a matrix is calculated from:

$$\frac{\lambda_{max} - n}{n - 1}$$

where λ is an eigenvalue and, since n=4 (from number of criteria) for this matrix, the CI is 0.062. The final step is to calculate the CR gives 0.068/0.90 = 0.0759, that is according to Saaty (1987) who argued that when CR > 0.1, it indicates that the judgements are at the limit of consistency. However, in this instance, it means that the pairwise judgements are not random and are completely trustworthy.

5.4.4 Background of alternative additive manufacturing technologies

The next step of the AHP is to investigate the potential additive manufacturing technologies. Four sets of pairwise comparisons of MCP, MELD, HPMJ3DP and VELO3D are done in terms of how well these additive manufacturing technologies perform in terms of the four criteria, surface finish, dimensional accuracy, cost and manufacturing lead time. It is worth giving a background of these additive manufacturing technologies before conducting the pairwise comparisons.

As opposed to conventional powder bed technologies that print one layer at a time MCP is based on powder bed fusion technology, and prints multiple layers simultaneously in a single pass (Manufacturing 2019). MCP technology has a grid-like recoater mechanism and multiple laser beams that has the capability to print around 30 layers at a time. The recoater mechanism features multiple hoppers, slides over the print bed when the print begins, with each hopper depositing dissimilar layers of powder in a single pass. As a layer is deposited, it becomes fused by a laser thereby reaching the powder though the distinct gaps designed in the recoater. Subsequent layers are deposited and fused successively by lasers during that same pass (Manufacturing 2019).

MELD Manufacturing Corporation developed a novel solid-state process to 3D print metals without melting. The metal wires or powders are passed through a hollow rotating tool, where friction and pressure deform the metal and stir it into the material beneath it. The key advantage of this technology is that parts that are fully dense are created, and they do not require subsequent heat treatment. MELD technology can be used not only to manufacture parts but also to repair and coat existing components or create custom metal alloys. The technology is able to scale and build or repair very large parts (Manufacturing 2019). Another unique capability of MELD technology is that one can take an existing part, place it in the machine and add additional material, whether a wear resistance coating on a very lightweight material, or adding the material to repair a worn surface. There is more freedom for creating larger parts from MELD's 3D printer since it does not require an enclosure and the process takes place in an open environment. However, the technology has a challenge of printing overhangs and also requires significant investment, with a single machine costing around R10 million.

HP's Metal Jet 3D printer is synonymous with high-precision and speed and uses binder jetting whereby a thin layer of powdered metal is deposited onto the print bed. Jetting tiny drops of a binder, a line of print heads moves above the print bed. After printing, the final part remains in a "green" state and must undergo a sintering operation to burn out the binder and create a dense solid part. The process uses less binder, making the sintering process faster and cheaper, and with twice as many printheads compared to existing systems, the metal jet printer is up to 50 times more productive than comparable conventional binder and laser sintering machines (Manufacturing 2019).

VELO^{3D}'s Intelligent Fusion technology permits printing of extreme overhangs without the need to use support structures (Aniwaa 2020). The lack of repeatability and the need to print support structures are two of the biggest challenges of metal 3D printing. The Sapphire 3D printer by VELO^{3D} is based on a powder bed fusion process, whereby a laser beam would melt and fuse metal powder layer by layer to form a part. In order to improve part consistency, the system is extensively equipped with sensors that enable the closed-loop melt pool control (Aniwaa 2020). On the software side, CAD files are used instead of STL files, since using CAD from the outset results in higher accuracy, whereas the STL format approximates the surface of a CAD model with triangles. Moreover, when using STL files, processing of files cumbersome and the size of STL files can be very large. Switching to CAD as an initial file format thus makes the print preparation workflow easier and faster (Manufacturing 2019).

Furthermore, the software has been developed to be very process-aware, meaning that one can run a simulation before a print starts, as well as predict and prevent failures before they occur. Combining the software with Sapphire's closed-loop control capabilities, an intelligent process that provides extreme reliability is derived.

5.4.5 Comparison of additive manufacturing technologies against criteria

Mathematical calculations were done based on the data and assignment of the relative weights to the criteria. Alternative AM technologies were then evaluated to derive the best solution that matched the production of moulds. The ranking of alternatives was based on benchmarking results from studies as well technical specifications from equipment suppliers.

Table 5.10 shows a comparison of alternative AM technologies considering surface finish as the criterion. The eigenvector for this matrix is (0.141, 0.113, 0.251, 0.494), and as expected, the CR is 0.072, so the judgements are reasonably consistent. The results demonstrate that MCP is preferred than MELD, while HPMJ3DP is more preferred than MELD, with VELO3D as the most preferred technology with regards to surface finish. Instead of using STL format that approximates the surface of a CAD model with triangles, CAD files are used with VELO3D instead of STL files, hence resulting in better accuracy.

Table 5.10: Comparison of alternative AM technologies on surface finish

	MCP	MELD	HPMJ3DP	VELO3D
MCP	1	2	0.5	0.2
MELD	0.5	1	0.5	0.33
HPMJ3DP	2	2	1	0.5
VELO3D	5	3	2	1

Table 5.11 shows a comparison of alternative AM technologies considering dimensional accuracy as the criterion. The eigenvector for this matrix is (0.167, 0.118, 0.262, 0.453), and as anticipated, the CR is 0.072, so the judgements are reasonably consistent. The results demonstrate that MCP and HPMJ3DP are preferred than MELD, with VELO3D as the most preferred technology with regards to dimensional accuracy. MCP and MELD technologies have a challenge when printing overhangs.

Table 5.11: Comparison of alternative AM technologies on dimensional accuracy

	MCP	MELD	HPMJ3DP	VELO3D
MCP	1	2	0.5	0.33
MELD	0.5	1	0.5	0.33
HPMJ3DP	2	2	1	0.5
VELO3D	3	3	2	1

Table 5.12 presents a comparison of alternative AM technologies considering manufacturing cost as the criterion. The eigenvector for this matrix is (0.141, 0.113, 0.251, 0.494), and as anticipated, the CR is 0 (perfect consistency), so the judgements are reasonably consistent. The results demonstrate that MELD is the more preferred than MCP, while HPMJ3DP is more preferred than MELD, with VELO3D as the least preferred technology with regards to manufacturing cost.

Table 5.12: Comparison of alternative AM technologies on manufacturing cost

	MCP	MELD	HPMJ3DP	VELO3D
MCP	1	0.33	4	3
MELD	3	1	0.5	5
HPMJ3DP	0.25	2	1	2
VELO3D	0.33	0.2	0.5	1

Table 5.13 presents a comparison of alternative AM technologies considering manufacturing lead time as the criterion. The eigenvector for this matrix is (0.127, 0.298, 0.489, 0.085), the CR is 0.059, so the judgements are reasonably consistent. The results demonstrate that MELD is the more preferred than MCP and VELO3D. HPMJ3DP was found to be the most preferred technology with regards to manufacturing lead time, the metal jet printer is up to 50 times more productive than comparable conventional binder and laser sintering machines.

Table 5.13: Comparison of alternative AM technologies on manufacturing lead time

	MCP	MELD	HPMJ3DP	VELO3D
MCP	1	0.33	0.167	3
MELD	3	1	0.33	5
HPMJ3DP	6	3	1	2
VELO3D	0.33	0.2	0.5	1

5.4.6 Option Performance Matrix and Determination of Overall Priority Vector

The final stage is to construct an Option Performance Matrix (OPM) of the criterion weights or eigenvectors for MCP, MELD, HPMJ3DP and VELO3D.

Table 5.14: Option Performance Matrix

	Surface finish	Dimensional accuracy	Cost	Manufacturing lead time
MCP	0.141	0.167	0.314	0.127
MELD	0.113	0.118	0.368	0.298
HPMJ3DP	0.251	0.262	0.223	0.489
VELO3D	0.494	0.453	0.095	0.085

The OPM in Table 5.14 summarizes the respective capabilities of the four alternative AM technologies in terms of what IMC requires for the manufacture of moulds for injection moulding. These results are only part of the story, and the final step is to take into account the IMC's judgements as to the relative importance of surface finish, dimensional accuracy, manufacturing cost and manufacturing lead time. Finally, it is crucial to weight the value of making a decision by the respective abilities of MCP, MELD, HPMJ3DP and VELO3D to achieve the desired criteria by multiplying the RVV with the OPM. Technically, multiplying the OPM in Table 5.11 by the RVV (0.352, 0.438, 0.071, 0.140) would obtain the vector for the respective abilities of these alternative AM technologies to manufacture of moulds for injection moulding. It comes out to (0.163, 0.159, 0.287, 0.391) for MCP, MELD, HPMJ3DP and VELO3D respectively.

Figure 5.8 depicts the comprehensive AHP with all the weighted scores of criteria and associated alternatives. The final results indicate that the VELO3D is better than other additive manufacturing technologies for rapid tooling for the manufacture of moulds.

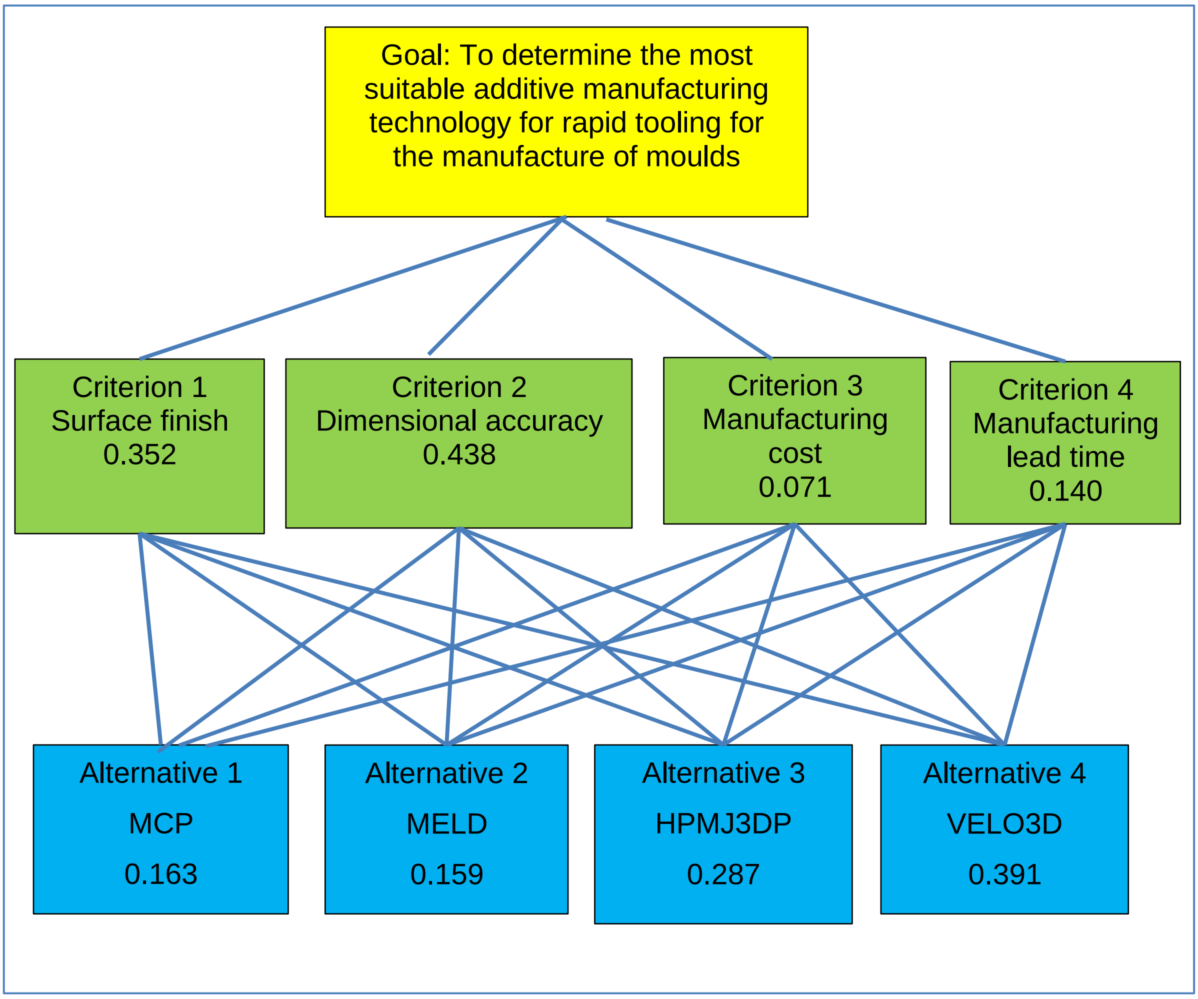

Figure 5.8: AHP with weights of criteria and alternatives

The final overall preferences obtained were highly dictated by the higher rankings for surface finish and dimensional accuracy when compared to manufacturing lead time and manufacturing cost.

5.5 Viability of 3D printed rapid tools for injection moulding

The fourth objective of the study was to determine the viability of 3D printed rapid tools for injection moulding. As a follow-up to the results of the AHP process in section 5.3.6, the research proposes a process for evaluation of investment in VELO3D for the manufacture of switch moulds using operational and financial key performance indicators.

5.5.1 Identification of candidate parts and potential machines

The first step is identification of candidate parts that are potential candidates for additive manufacturing. These parts would be relatively small in size or complex in geometry. As highlighted in section 5.3.1, the switch cover mould will be assessed for viability of fabrication through AM. A bounding box was developed as shown in Figure 5.9 that contains simplified information regarding the shape and size of the mould.

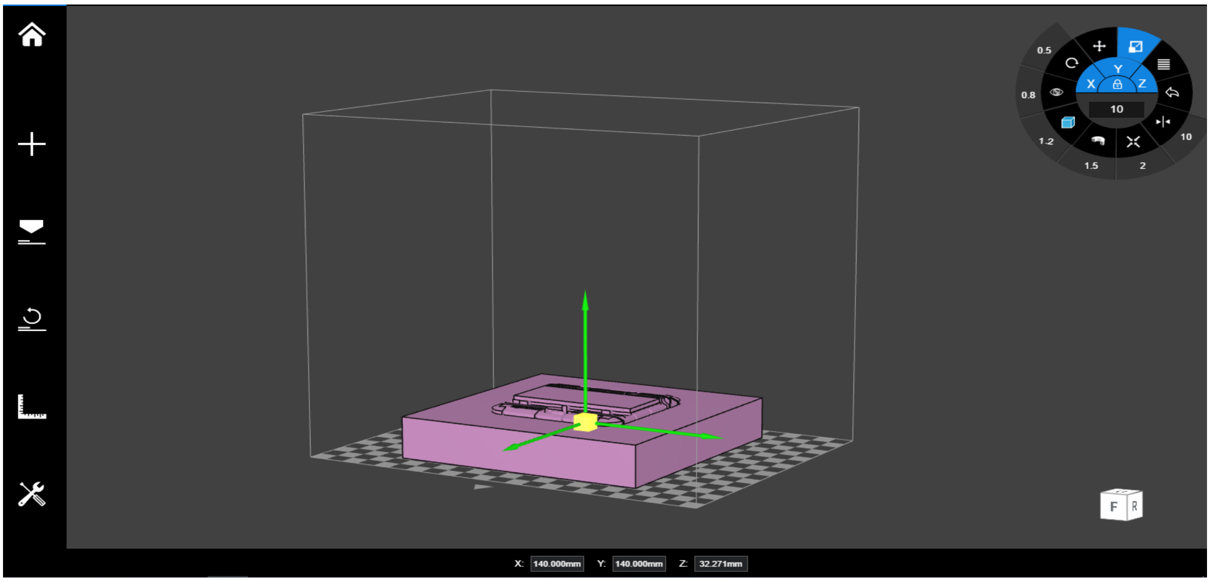

Figure 5.9: Bounding box for inner switch mould plate

In many cases, when fabricating a product through AM, part orientation, can significantly influence production costs and volumes, as it determines the overall build height, the number of parts that can be placed on a single build plate, as well as the location and amount of support material. It might be crucial to position the part in a particular orientation to accommodate load expectation, especially when considering moulds for injection moulding since tensile strength is typically weakest along the z-axis. Quantifying potential processes and machines according to the tool's material. The material properties as reported by both the industry users and manufacturer are the minimum acceptability criteria in this stage. As previously highlighted in the results of the AHP process, the research proposes a process for evaluation of investment in VELO3D machine.

5.5.2 Determining current production information and evaluating viable production quantities

As highlighted in section 4.8, the annual demand for the switch cover moulds is 25200 units. Table 5.15 shows the annual production capabilities for the switch moulds by using VELO3D machine.

Table 5.15: Annual production capabilities for VELO3D

Description	Value
Number of operational days	230 days
Machine Capacity ($t_{capacity}$)	5000 hours
Number of annual builds (n_{builds})	36
Number of parts produced annually (n_{parts})	5200

5.5.3 Comparison of financial and operational expectations

The Velo3D Sapphire XC with a build volume of 600mm x 550mm x 400mm costs $250 000 which is about R4 million (Aniwaa 2020). The final step was to compare additive manufacturing versus traditional manufacturing capabilities in mould production. As shown in Table 5.16 that depicts the build times and characteristics, the parts per build (p_{build}) is 150 units (from product of number of parts per layer and number of rows per build), with a build time of 48 hours, which cascades to 75 moulds per day.

Table 5.16: Build times and characteristics

Description	Value
Number of parts per layer	25
Number of rows per build	6
Number of parts per build (p_{build})	150
Volume of material in mm^3	528 083
Production time in hours ($t_{production}$)	105.95
Build time in hours (t_{build})	48
Scan time in hours	68.75
Height of build in mm	200
Build volume mm^3	12,750,000

Number of build layers	6,500

The evaluation of production quantities that are achievable was accomplished by determining the amount of time available for the VELO3D AM machine to operate and ability to meet annual demand. The cost estimation values were pulled from IMC's financial accounting database. Breakeven analysis was also conducted using estimated values shown in Table 5.17.

Table 5.17: Variables used for cost estimation

Description	Value
Spare parts cost per year	R50000
Utilities cost per year	R50000
Transportation cost	R10000
Installation cost	R5000
Facility cost per year	R750000
Labour cost per year	R140000
Software cost per year	R160000
Maintenance cost per year	R40000
Pre-build time	4 hr
Post-build time	8 hr
Utilization rate	75%
Recoat time	5 s
Cooling time	5 s
Weekend days	104
Holiday days	10
Vacation days	10
Maintenance days	10
Breakeven units (B_{units})	25200 units
Breakeven time (B_{time})	5 years

Figure 5.10 shows a comparison of breakeven period and part value, and the results reveal that the larger the mould value the smaller is the breakeven period. The breakeven units and breakeven time parameters from Table 5.17 was used to obtain the graphs for Figure 5.10 and 5.11. Considering IMC policy, a breakeven period of 5 years or less is considered as acceptable and that corresponds to a total mould value of R5 million. The sensitivity analysis indicated that for the investment to break even at the end of project life, the system must either produce 25200 units annually or value each mould per part at R198.

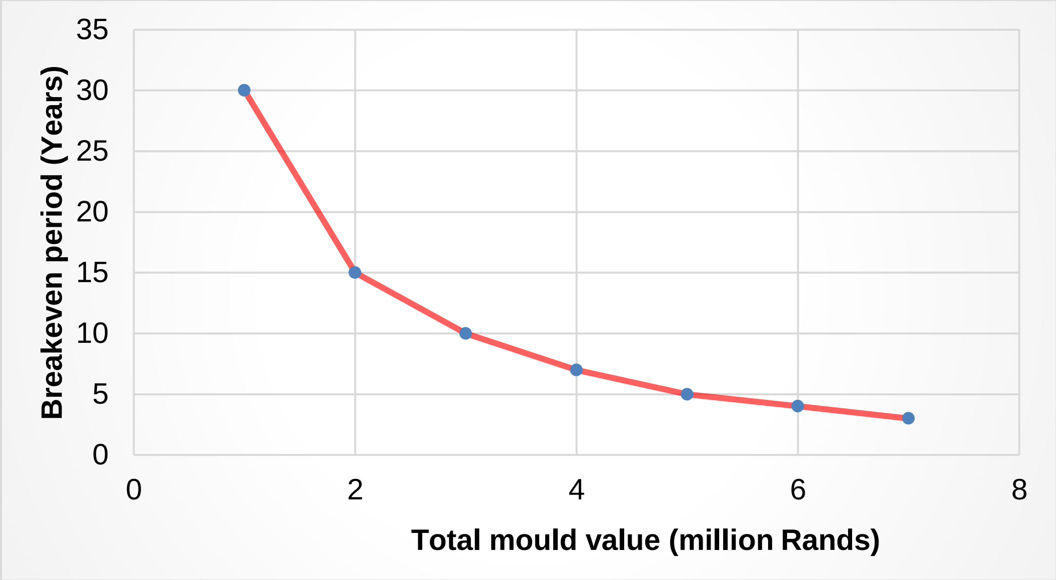

Figure 5.10: Comparison of breakeven period and part value

Rather than basing break-even period on the cost, in this case, the sensitivity analysis was based mould value. Figure 5.11 shows a comparison of cost per mould against number of moulds per day.

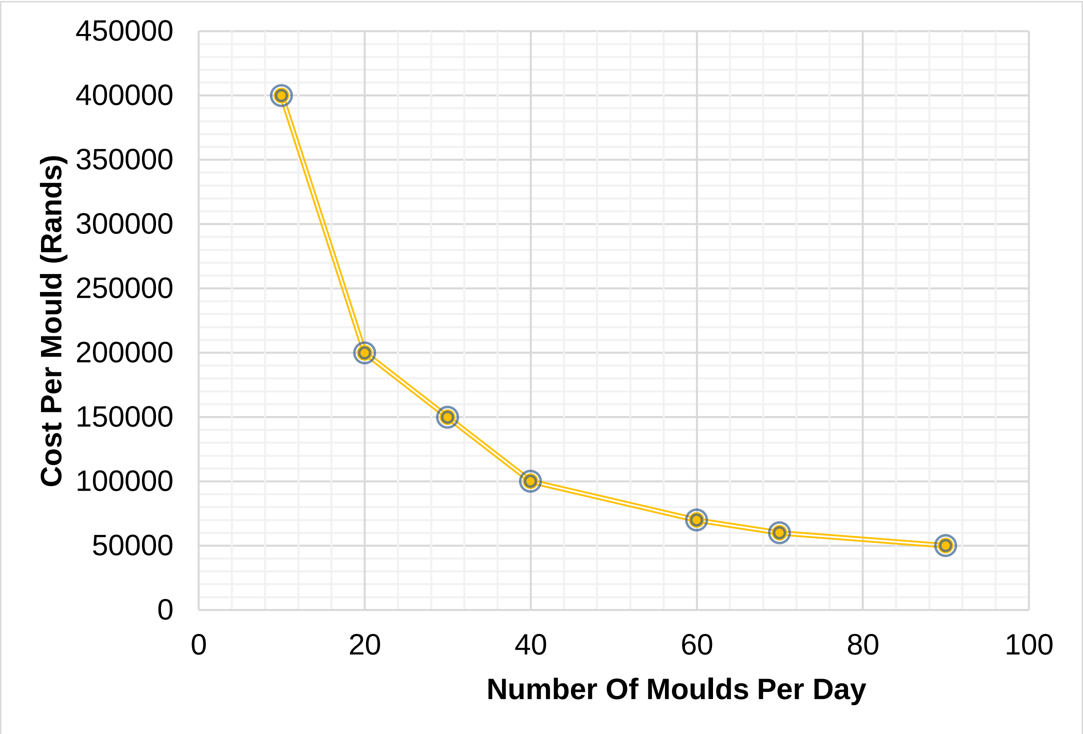

Figure 5.11: Comparison of cost per mould against number of moulds per day

The least number of moulds per day is 10 with a cost of R400000 each while the highest number of moulds is 90, at a cost of R50000 each. As previously highlighted in section 4.7, the annual demand for switch cover mould is 25200 units, which cascades to around 75 moulds a day when factoring in holidays and weekends.

5.5.4 Comparison of additive versus traditional manufacturing capabilities

A final decision was made through the comparison of additive manufacturing technology, VELO3D versus traditional manufacturing capabilities in tool production. In order to ensure a fair comparison, additive manufacturing costs were reported in a likewise manner to the conventional manufacturing cost's structure. Figure 5.12 shows the results of comparison of additive versus traditional manufacturing capabilities in tool production, and these results demonstrated that VELO3D outperformed the traditional approach from a cost perspective. The performance of VELO3D would increase the production rate and reduce operational costs for IMC.

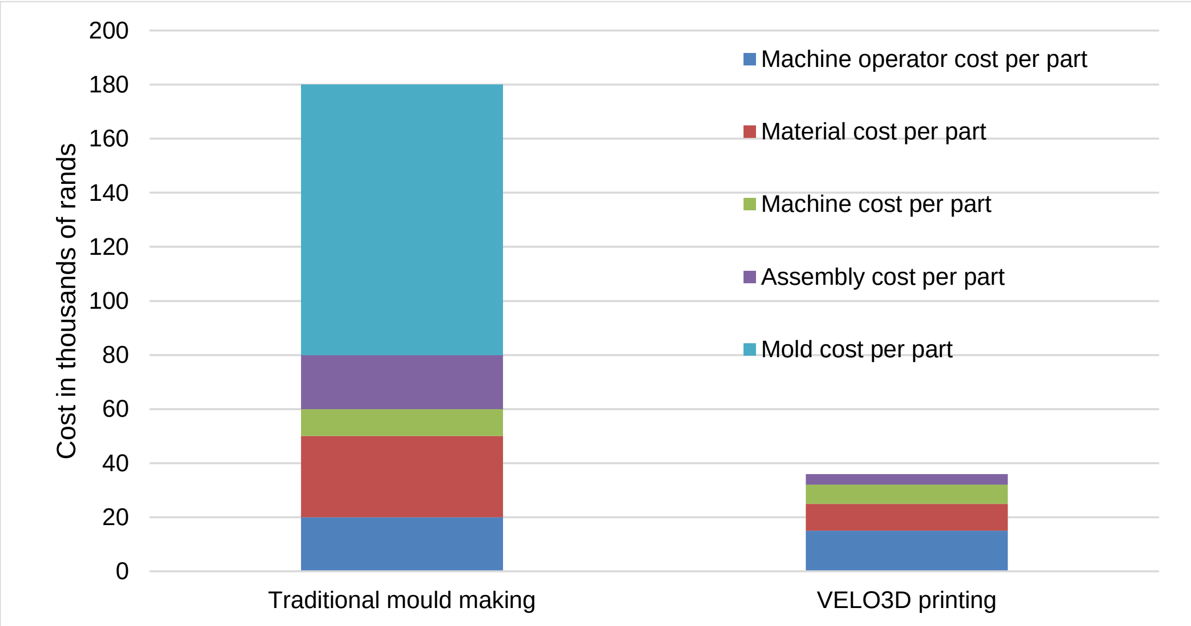

Figure 5.12: Comparison of additive versus traditional manufacturing capabilities in tool production

The traditional manufacturing is characterised by a huge mould cost of R100 000 which is avoided when additive manufacturing technology is adopted, leading to an 80% overall cost savings from AM. However, as highlighted before, the initial high cost of VELO3D is a major hindrance for most manufacturing firms.

5.6 Conclusion

AM has played a crucial role in customised production, especially with a potential in the mass customisation production. It has the advantage of manufacturing more complex parts against traditional processing technologies. The ABC mould demand classification analysis that was conducted for the top 16 moulds revealed that under the A-category, the moulds for the switch cover, smart phone and helmet shell contributed the bulk of the total demand of moulds that were fabricated by IMC. The value stream map revealed that there was room for improvement and rather than developing a conventional future state value stream map, it was proposed to radically investigate the viability of 3D printed rapid tools for injection moulding.

Through the deployment of group technology and rank clustering algorithm, three mould families and three machine cells were derived to improve the mould fabrication process by reducing material movements and reducing setup times. AHP was deployed as criteria for comparison and selection of the best 3D printing technology from among the recent AM technologies that would meet surface finish, dimensional accuracy, cost and manufacturing lead time requirements. The first step in the Analytic Hierarchical Process for selection of best 3D printing technology was comprehending the characteristics of the mould under study.

Four options that include Multilevel Concurrent Printing (MCP) from Aurora Labs, MELD technology from MELD Manufacturing Corporation, HP's Metal Jet 3D printer (HPMJ3DP), Intelligent Fusion from VELO3D. The final results indicated that the VELO3D is better than other additive manufacturing technologies for rapid tooling for the manufacture of moulds. The switch cover mould was assessed for viability of fabrication through AM. The research proposed a process for evaluation of investment in VELO3D machine. A final decision was made through the comparison of additive manufacturing technology, VELO3D versus traditional manufacturing capabilities in tool production. The traditional manufacturing was found to be characterised by a huge mould cost which was absent when additive manufacturing technology is adopted. The results demonstrated that VELO3D outperformed the traditional approach from a cost perspective.

CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The previous chapter outlined the deployment of group technology and rank clustering algorithm for process improvement, and AHP as criteria for comparison and selection of the best 3D printing technology. Four AM options were cited, and the final results indicated that the VELO3D is better than other additive manufacturing technologies for rapid tooling for the manufacture of moulds. The switch cover mould was assessed for viability of fabrication through AM. This chapter focuses on the research conclusions and recommendations, as well as area for further research.

6.2 Research Conclusions

ABC mould demand classification analysis can be used for simple decision-making to assess competing problems and quantifying the impact of sorting them. It was concluded that vertically integrated organisations may face challenges in providing rapid response and overseeing production that would translate to shorter lead times and on-demand delivery. The key concern for IMC is lengthy production lead time for the mould and die manufacture and this becomes a problem since clients expect quick product delivery. It was concluded from the ABC mould demand classification analysis that the moulds for the switch cover, smart phone and helmet shell contributed highest to the total demand of moulds that were fabricated by IMC.

Value stream mapping can be deployed as a tool for production flow analysis to reveal the areas where waste occurs and improve the flow of material and information so that the product is delivered to the client on time. The deployment of group technology and rank clustering algorithm to derive mould families and machine cells can improve the mould fabrication process by reducing material movements and reducing setup times. AHP deployment as criteria for comparison and selection of the best 3D printing technology can yield realistic results, the final results indicated that the VELO3D is better than other additive manufacturing technologies for rapid tooling for the manufacture of moulds.

The estimation of cost of part manufacturing is a critical and vital undertaking for industrial firms since it feeds into price evaluation which aids an organisation's competitiveness in the marketplace (Bouaziz, Younes and Zghal 2006). The understanding of material costs in additive manufacturing can be of significance in making key decisions regarding the adoption of the technology by organisations. While maintaining the necessary performance, additive manufacturing permits products to be produced using less material. However, the price of materials for additive manufacturing can often surpass the price materials for traditional manufacturing (Thomas and Gilbert 2014). It was also concluded from the research results that the traditional manufacturing is characterised by a huge mould cost which was absent when additive manufacturing technology is adopted. The results demonstrated that VELO3D outperformed the traditional approach from a cost perspective.

6.3 Recommendations

Whlean and Sheahan (2019) posited that AM could provide benefits in various ways in manufacturing and tooling by producing the complex geometries and customization that would be difficult to produce using conventional methods. It is recommended that an in-house production, IMC should invest in AM machines and operates these machines for their own production. High-capacity utilisation is necessary in order for the machines to pay off. Some of the measures that should also be taken into consideration in order to ensure that the overall costs as low as possible include ensuring a tight filling of the installation space with components. It is also vital to maximise the share of actual exposure time in the overall throughput time, for instance through high installation space utilisation.

Furthermore, the time factor and component quality must be weighed against each other in additive manufacturing, since better quality is aligned to increased time required for production. For IMC, the selected parameters are decisive, for instance, layer thickness. Thicker layers result in reduced accuracy and poor surface quality but require less production time and thereby reducing overall costs. Cost estimation is directly linked to business performance and represents the basis for development of the key decision variable of additive manufacturing, which is the product cost (Busachi *et al.* 2017).

IMC can also consider an alternative to in-house production, which is external procurement. If capital investment is going to be a challenge, external procurement is the simplest method for IMC to gain access to AM technologies. No specific knowledge about the operation of the machines is required and no major investments would need to be done in advance. It is worth noting that the decision for external procurement results in reduced risks and price fluctuations in production for IMC, as the efficient use of additive manufacturing equipment is the supplier's responsibility.

6.4 Area for further research

This study focused on the viability of AM from an economic perspective. The area of further research would embrace establishing the viability from a life-cycle analysis perspective. It is also vital to comprehend the environmental aspects and the influence of fourth and fifth industrial revolution on viability of these AM technologies.

6.5 Conclusion

The study was focused on assessing the viability of additive manufacturing for rapid tooling. The first research objective was concerned with establishing the current operating environment that characterise the IMC. The objective was achieved, IMC was noted as a vertically integrated organisation that specialises on the manufacture of die castings and precision mould manufacturing services to other firms. IMC was noted as having 15 injection moulding machines and striving to use less energy and generate less waste from injection moulding without sacrificing quality. ABC mould demand classification analysis was conducted for the top 16 moulds revealed that the moulds for the switch cover contributed the demand of moulds that were fabricated by IMC. The value stream map revealed that there was room for improvement and through the deployment of group technology and rank clustering algorithm, three mould families and three machine cells were derived to improve the mould fabrication process by reducing material movements and reducing setup times.

The second research objective was concerned with improving the current mould making process through the use of group technology and Rank-order Clustering algorithm. The objective was achieved through the deployment of group technology and rank clustering algorithm, three mould families and three machine cells were derived to improve the mould fabrication process by reducing material movements and reducing setup times.

The third research objective focused on determining the most suitable additive manufacturing technology for rapid tooling for the manufacture of moulds. The objective was achieved through AHP which was deployed as criteria for comparison and selection of the best 3D printing technology from among the recent AM technologies that would meet surface finish, dimensional accuracy, cost, and manufacturing lead time requirements. Four options that include Multilevel Concurrent Printing (MCP) from Aurora Labs, MELD technology from MELD Manufacturing Corporation, HP's Metal Jet 3D printer (HPMJ3DP), Intelligent Fusion from VELO3DThe final results indicated that the VELO3D is better than other additive manufacturing technologies for rapid tooling for the manufacture of moulds.

The fourth research objective was to determine the viability of 3D printed rapid tools for injection moulding. This objective was achieved, the research proposed a process for evaluation of investment in VELO3D machine. A final decision was made through the comparison of additive manufacturing technology, VELO3D versus traditional manufacturing capabilities in tool production. The traditional manufacturing was found to be characterised by a huge mould cost which was absent when additive manufacturing technology is adopted. The results demonstrated that VELO3D outperformed the traditional approach from a cost perspective.

References

Abdelhadi, A. 2018. Maintenance scheduling based on PROMETHEE method in conjunction with group technology philosophy. *International Journal of Quality & Reliability Management*,

Afonso, D., de Sousa, R. A., Torcato, R. and Pires, L. 2019. Fundamentals of Rapid Tooling. In: *Incremental Forming as a Rapid Tooling Process*. Springer, 1-22.

Albayrak, E. and Erensal, Y. C. 2004. Using analytic hierarchy process (AHP) to improve human performance: An application of multiple criteria decision making problem. *Journal of intelligent manufacturing*, 15 (4): 491-503.

Altaf, K., Qayyum, J. A., Rani, A. M. A., Ahmad, F., Megat-Yusoff, P. S., Baharom, M., Aziz, A. R. A., Jahanzaib, M. and German, R. M. 2018. Performance analysis of enhanced 3D printed polymer moulds for metal injection moulding process. *Metals*, 8 (6): 433.

Amruthnath, N. and Gupta, T. 2016. Modified rank order clustering algorithm approach by including manufacturing data. *IFAC-PapersOnLine*, 49 (5): 138-142.

Aniwaa. 2020. *Velo3D Sapphire XC*. Available: https://www.aniwaa.com/product/3d-printers/velo3d-sapphire-xc/#:~:text=The%20Velo3D%20Sapphire%20XC%20price%20is%20approximately%20%24250%2C000. (Accessed 20 December 2021).

Astakhov, V. P. 2018. Mechanical properties of engineering materials: relevance in design and manufacturing. In: *Introduction to Mechanical Engineering*. Springer, 3-41.

Atzeni, E., Iuliano, L., Minetola, P. and Salmi, A. 2010. Redesign and cost estimation of rapid manufactured plastic parts. *Rapid Prototyping Journal*,

Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Rosamond, E. and Hague, R. 2013. Transparency built-in: Energy consumption and cost estimation for additive manufacturing. *Journal of Industrial Ecology*, 17 (3): 418-431.

Bhatt, P. M., Kabir, A. M., Peralta, M., Bruck, H. A. and Gupta, S. K. 2019. A robotic cell for performing sheet lamination-based additive manufacturing. *Additive Manufacturing*, 27: 278-289.

Bouaziz, Z., Younes, J. B. and Zghal, A. 2006. Cost estimation system of dies manufacturing based on the complex machining features. *The International Journal of Advanced Manufacturing Technology*, 28 (3): 262-271.

Busachi, A., Erkoyuncu, J., Colegrove, P., Martina, F., Watts, C. and Drake, R. 2017. A review of Additive Manufacturing technology and Cost Estimation techniques for the defence sector. *CIRP Journal of Manufacturing Science and Technology*, 19: 117-128.

Butt, J. 2020. Exploring the interrelationship between additive manufacturing and Industry 4.0. *Designs*, 4 (2): 13.

Campi, F., Mandolini, M., Favi, C., Checcacci, E. and Germani, M. 2020. An analytical cost estimation model for the design of axisymmetric components with open-die forging technology. *The International Journal of Advanced Manufacturing Technology*, 110 (7): 1869-1892.

Chan, S. L., Lu, Y. and Wang, Y. 2018. Data-driven cost estimation for additive manufacturing in cybermanufacturing. *Journal of manufacturing systems*, 46: 115-126.

Chen, C., Wang, Y., Ou, H., He, Y. and Tang, X. 2014. A review on remanufacture of dies and moulds. *Journal of Cleaner Production*, 64: 13-23.

Culkin, N. and Simmons, R. 2018. Smaller Firms: Engines of Innovation. In: *Mastering Brexits Through The Ages*. Emerald Publishing Limited.

Danilovic, M. and Ilic, O. 2019. A novel hybrid algorithm for manufacturing cell formation problem. *Expert Systems with Applications*, 135: 327-350.

De Carolis, A., Macchi, M., Negri, E. and Terzi, S. 2017. A maturity model for assessing the digital readiness of manufacturing companies. In: Proceedings of *IFIP International Conference on Advances in Production Management Systems*. Springer, 13-20.

Debnárová, L., Krchová, D. and Kuric, I. 2014. Group technology in context of the product classification. *Advances in Science and Technology Research Journal*, 8 (21): 78--81.

Deshmane, S., Kendre, P., Mahajan, H. and Jain, S. 2021. Stereolithography 3D Printing Technology in Pharmaceuticals: A Review. *Drug Development and Industrial Pharmacy*, (just-accepted): 1-37.

Dilberoglu, U. M., Gharehpapagh, B., Yaman, U. and Dolen, M. 2017. The role of additive manufacturing in the era of industry 4.0. *Procedia Manufacturing*, 11: 545-554.

Duda, T. and Raghavan, L. V. 2018. 3D metal printing technology: the need to re-invent design practice. *Ai & Society*, 33 (2): 241-252.

Dutta, B., Babu, S. and Jared, B. H. 2019. *Science, technology and applications of metals in additive manufacturing*. Elsevier.

Equbal, A., Sood, A. K. and Shamim, M. 2015. Rapid tooling: A major shift in tooling practice. *Manufacturing and Industrial Engineering*, 14 (3-4)

Favi, C., Germani, M. and Mandolini, M. 2017. Analytical cost estimation model in high pressure die casting. *Procedia Manufacturing*, 11: 526-535.

Fernandes, C., Pontes, A., Viana, J., Nóbrega, J. and Gaspar-Cunha, A. 2014. Modeling of Plasticating Injection Moulding–Experimental Assessment. *International Polymer Processing*, 29 (5): 558-569.

Francis, S. 2018. *Evolution of Technology in the Digital Arena: Theories, Firm-level Strategeis and State Policies*. Centre for WTO Studies, Indian Institute of Foreign Trade.

Frazier, W. E. 2014. Metal additive manufacturing: a review. *Journal of Materials Engineering and performance*, 23 (6): 1917-1928.

Fu, J. and Ma, Y. 2019. A method to predict early-ejected plastic part air-cooling behavior towards quality mould design and less moulding cycle time. *Robotics and Computer-Integrated Manufacturing*, 56: 66-74.

Ganorkar, A. B., Lakhe, R. R. and Agrawal, K. N. 2019. Cost and productivity analysis of the manufacturing industry using TDABC & MOST. *South African Journal of Industrial Engineering*, 30 (1): 196-208.

Gao, M., Li, L., Wang, Q., Ma, Z., Li, X. and Liu, Z. 2021. Integration of Additive Manufacturing in Casting: Advances, Challenges, and Prospects. *International Journal of Precision Engineering and Manufacturing-Green Technology*: 1-18.

Gawdzinska, K., Nabialek, M., Sandu, A. V. and Bryll, K. 2018. The Choice of Recycling Methods for Single-Polymer Polyester Composites. *MATERIALE PLASTICE*, 55 (4): 658.

Gibson, I. 2017. The changing face of additive manufacturing. *Journal of Manufacturing Technology Management*,

Gibson, I., Rosen, D., Stucker, B. and Khorasani, M. 2021a. Sheet Lamination. In: *Additive Manufacturing Technologies*. Springer, 253-283.

Gibson, I., Rosen, D. W., Stucker, B. and Khorasani, M. 2021b. *Additive manufacturing technologies*. Springer.

Griffin, C. C. 2017. Viability of Additive Manufacturing for Production and Tooling Applications: A Development of the Business Case.

Hopkinson, N. and Dicknes, P. 2003. Analysis of rapid manufacturing—using layer manufacturing processes for production. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 217 (1): 31-39.

Huang, Z. and Li, D. 2010. A hybrid approach of Case-Based Reasoning and Group Technology for injection-mould design. *International Journal of Materials and Product Technology*, 38 (2-3): 275-286.

Irons, B. T. 2020. Current and Future Applications of 3D Printing Using Custom-Made Materials.

Ishizaki, K., Komarneni, S. and Nanko, M. 2013. *Porous Materials: Process technology and applications*. Springer science & business media.

Jahan, A. and Souri, S. 2020. Cell Formation Based on Similarity in Parts Design Using Multiattribute Decision-Making Algorithm. In: *Sustainability Modeling in Engineering: A Multi-Criteria Perspective*. World Scientific, 203-227.

Joshi, S. C. and Sheikh, A. A. 2015. 3D printing in aerospace and its long-term sustainability. *Virtual and Physical Prototyping*, 10 (4): 175-185.

Kamran, M. and Saxena, A. 2016. A comprehensive study on 3D printing technology. *MIT Int J Mech Eng*, 6 (2): 63-69.

Kaweesa, D. V., Spillane, D. R. and Meisel, N. A. 2017. Investigating the impact of functionally graded materials on fatigue life of material jetted specimens. In: Proceedings of *Solid Free. Fabr. Symp*. 578-592.

Kengpol, A. and O'brien, C. 2001. The development of a decision support tool for the selection of advanced technology to achieve rapid product development. *International Journal of Production Economics*, 69 (2): 177-191.

Khamhong, P., Yingviwatanapong, C. and Ransikarbum, K. 2019. Fuzzy Analytic Hierarchy Process (AHP)-based Criteria Analysis for 3D Printer Selection in Additive Manufacturing. In: Proceedings of *2019 Research, Invention, and Innovation Congress (RI2C)*. IEEE, 1-5.

King, J. R. 1980. Machine-component grouping in production flow analysis: an approach using a rank order clustering algorithm. *International Journal of Production Research*, 18 (2): 213-232.

Kumar, K. V. 2016. Subtractive and additive manufacturing technology in moulding industry.

Lee, J.-Y., An, J. and Chua, C. K. 2017. Fundamentals and applications of 3D printing for novel materials. *Applied materials today*, 7: 120-133.

Liang, S. Y. 2019. Subtractive Processes—Traditional Operations: Cutting, Grinding, and Machine Tools. *Handbook Of Manufacturing*: 17.

Liu, Z., Li, C., Fang, X. and Guo, Y. 2018. Energy consumption in additive manufacturing of metal parts. *Procedia Manufacturing*, 26: 834-845.

Low, M. and Lee, K. 2008. Mould data management in plastic injection mould industries. *International Journal of Production Research*, 46 (22): 6269-6304.

Lv, X., Ye, F., Cheng, L., Fan, S. and Liu, Y. 2019. Binder jetting of ceramics: Powders, binders, printing parameters, equipment, and post-treatment. *Ceramics International*, 45 (10): 12609-12624.

Manos, T. 2006. Value stream mapping-an introduction. *Quality Progress*, 39 (6): 64-69.

Mantoux, P. 2013. *The industrial revolution in the eighteenth century: An outline of the beginnings of the modern factory system in England*. Routledge.

Manufacturing, A. 2019. *ten Exciting 3D Printing Technologies That Have Emerged in the Last 12 Months*. Available: https://amfg.ai/2019/06/11/10-exciting-3d-printing-technologies-that-have-emerged-in-the-last-12-months/ (Accessed

Martí, R. and Reinelt, G., 2022. Heuristic methods. In *Exact and Heuristic Methods in Combinatorial Optimization* (pp. 27-57). Springer, Berlin, Heidelberg.

Minguella-Canela, J., Morales Planas, S., los Santos-López, D. and Antonia, M. 2020. SLM Manufacturing Redesign of Cooling Inserts for High Production Steel Moulds and Benchmarking with Other Industrial Additive Manufacturing Strategies. *Materials*, 13 (21): 4843.

Nyembwe, K. D. 2012. Tool manufacturing by metal casting in sand moulds produced by additive manufacturing processes. Bloemfontein: Central University of Technology, Free State.

Parry, E. J., Best, J. M. and Banks, C. E. 2020. Three-dimensional (3D) scanning and additive manufacturing (AM) allows the fabrication of customised crutch grips. *Materials Today Communications*, 25: 101225.

Peng, T., Kellens, K., Tang, R., Chen, C. and Chen, G. 2018. Sustainability of additive manufacturing: An overview on its energy demand and environmental impact. *Additive Manufacturing*, 21: 694-704.

Pereira, A.M., Silva, M.R., Domingues, M.A. and Sá, J.C., 2019. Lean six sigma approach to improve the production process in the mould industry: A case study. *Quality Innovation Prosperity*, *23*(3), pp.103-121.

Prakash, K. S., Nancharaih, T. and Rao, V. S. 2018. Additive manufacturing techniques in manufacturing-an overview. *Materials Today: Proceedings*, 5 (2): 3873-3882.

Qudeiri, J. E. A., Zaiout, A., Mourad, A.-H. I., Abidi, M. H. and Elkaseer, A. 2020. Principles and characteristics of different EDM processes in machining tool and die steels. *Applied Sciences*, 10 (6): 2082.

Ranjan, R., Kar, S. and Patowari, P. K. 2020. Parametric Optimization of Drilling on Titanium Grade-2 in Die-Sinking Electrical Discharge Machining. In: *Techno-Societal 2018*. Springer, 551-559.

Rezaei, J. 2018. Piecewise linear value functions for multi-criteria decision-making. *Expert Systems with Applications*, 98: 43-56.

Ruffo, M., Tuck, C. and Hague, R. 2007. Make or buy analysis for rapid manufacturing. *Rapid Prototyping Journal*,

Ruiz-Morales, J., Tarancón, A., Canales-Vázquez, J., Méndez-Ramos, J., Hernández-Afonso, L., Acosta-Mora, P., Rueda, J. M. and Fernández-González, R. 2017. Three dimensional printing of components and functional devices for energy and environmental applications. *Energy & Environmental Science*, 10 (4): 846-859.

Saaty, R. W. 1987. The analytic hierarchy process—what it is and how it is used. *Mathematical modelling*, 9 (3-5): 161-176.

Saaty, T. L. 2008. Decision making with the analytic hierarchy process. *International journal of services sciences*, 1 (1): 83-98.

Shi, Z., Peng, Y. and Wei, W. 2014. Recent advance on fused deposition modeling. *Recent Patents on Mechanical Engineering*, 7 (2): 122-130.

Silver, P. and McLean, W. 2008. *Fabrication*. Routledge.

Singh, G. and Verma, A. 2017. A Brief Review on injection moulding manufacturing process. *Materials Today: Proceedings*, 4 (2): 1423-1433.

Singh, P. R., Gupta, A., Verma, R., Satija, S. and Alok, U. 2021. One time plastics and eco friendly alternatives: A study of consumer behaviour. *Asian Journal of Research in Social Sciences and Humanities*, 11 (6): 28-47.

Sousa Ribeiro, C. and Soares, N. 2010. GROUP TECHNOLOGY TO SOLES DESIGN. *Annals of DAAAM & Proceedings*,

Stewart, F. and Kelley, K. 2020. Connecting Hands and Heads: Retooling Engineering Technology for the "Smart" Manufacturing Workplace. *Economic Development Quarterly*, 34 (1): 31-45.

Stolt, R., André, S. and Elgh, F. 2018. Introducing inserts for die casting manufactured by selective laser sintering. *Procedia Manufacturing*, 17: 309-316.

Telenko, C. and Seepersad, C. C. 2012. A comparison of the energy efficiency of selective laser sintering and injection moulding of nylon parts. *Rapid Prototyping Journal*,

Thomas, D. S. 2017. Economics of additive manufacturing. In: *Laser-Based Additive Manufacturing of Metal Parts*. CRC Press, 285-320.

Thomas, D. S. and Gilbert, S. W. 2014. Costs and cost effectiveness of additive manufacturing. *NIST special publication*, 1176: 12.

Vargas, R. V. and IPMA-B, P. 2010. Using the analytic hierarchy process (AHP) to select and prioritize projects in a portfolio. In: Proceedings of *PMI global congress*. 1-22.

Varotsis, A. B. 2019. Introduction to Material Jetting 3D Printing. *3dhubs. com*,

Vlachopoulos, J. and Strutt, D. 2003. Polymer processing. *Materials science and technology*, 19 (9): 1161-1169.

Whlean, C. and Sheahan, C. 2019. Using additive manufacturing to produce injection moulds suitable for short series production. *Procedia Manufacturing*, 38: 60-68.

Wong, K. V. and Hernandez, A. 2012. A review of additive manufacturing. *International scholarly research notices*, 2012

Yadav, P., Fu, Z., Knorr, M. and Travitzky, N. 2020. Binder Jetting 3D Printing of Titanium Aluminides Based Materials: A Feasibility Study. *Advanced Engineering Materials*, 22 (9): 2000408.

Yuan, J., Chen, C., Yao, D. and Chen, G. 2020. 3D printing of oil paintings based on material jetting and its reduction of staircase effect. *Polymers*, 12 (11): 2536.

Zhang, J., Allardyce, B. J., Rajkhowa, R., Wang, X. and Liu, X. 2021. 3D printing of silk powder by Binder Jetting technique. *Additive Manufacturing*, 38: 101820.

Zhang, Y. and Bernard, A. 2014. Grouping parts for multiple parts production in Additive Manufacturing. *Procedia Cirp*, 17: 308-313.

Ziaee, M. and Crane, N. B. 2019. Binder jetting: A review of process, materials, and methods. *Additive Manufacturing*, 28: 781-801.