Additive Manufacturing Costing Parameter Sensitivity

by

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at Stellenbosch University

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Co-supervisor: Prof DJ de Beer

December 2019

DECLARATION

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ABSTRACT

Additive manufacturing (AM) offers a perfect solution for the development and manufacturing of many products, but the burning issue is to determine which products should be manufactured in such a way? Also, of extreme importance, is to understand the economy of scale for the use of AM competitively. The latter requires knowledge-based decision-making systems based on product geometry, complexity, size, tolerance, material requirements, and mechanical properties, parallel with AM machine or process capabilities. Although directly involved in the material research and platform development from the onset, the Massachusetts Institute of Technology (MIT) classified AM as only one of ten breakthrough technologies in 2013. Forbes depicts AM as the technology that will equip manufacturers with the ability to turn product development into their competitive advantage. With the advancement in computer and software capabilities, it will rapidly dominate 40% of the market share (Gartner 2015). Capability alone will not suffice, however. To increase market share, focus should be placed on the analysis of AM costing. The thesis aims to determine if a more simplistic but accurate cost determination method can be developed to augment online costing opportunities that are fully integrated with the Enterprise Resource Planning (ERP) system. Costing is one of the critical business functions of any advanced manufacturing operation. This critical business function is also known as enterprise resource planning application components. Examples of these are aspects that allow an AM unit to use a system of integrated applications to manage the business and automate various back-office functions related to technology. It also allows for services and human resources to develop the data capturing, manipulations, calculation, and validation for a unique enterprise resource-planning model that is founded in a fail-safe quality management system (QMS).

OPSOMMING

Laagvervaardiging (LV) beklee tans ŉ unieke posisie. Die vraag wat indringend beantwoord moet word, is of produkte en komponente op hierdie metode vervaardig behoort te word? Alhoewel die Massachusetts Institute of Technology (MIT) van meet af direk by die wesenlike navorsing en platformontwikkeling betrokke was, klassifiseer die Massachusetts Institute of Technology (MIT) LV in 2013 as een van slegs tien deurbraak-tegnologieë. Forbes beeld LV uit as dié tegnologie wat vervaardigers met die vermoë sal toerus om produkontwikkeling tot ŉ mededingende voordeel te vernuwe. Vooruitgang in rekenaartegnologie, rekenaarvaardigheid en die vermoë van ondersteuningsagteware, sal verseker dat LV in die nabye toekoms 40% van die vervaardigingsmarkaandeel kan oorneem (Gartner, 2015). Dit is dus nodig dat behoorlike fokus op die ontleding van LV-kostes geplaas word. Die doel van die tesis is om te bepaal of ŉ vereenvoudigde maar akkurate kostebepalingsmetode ontwikkel kan word om aanlynkoste-geleenthede ten volle met die ondernemingsstelsel te integreer. As deel van die sake-prosesbestuursaspekte, is LV-kostes een van die kritieke besigheidsfunksies van enige gevorderde vervaardigingsonderneming. Hierdie kritieke besigheidsfunksie staan ook as die ondernemingshulpbron-beplanning-toepassing-komponent bekend. Voorbeelde hiervan is aspekte wat 'n LV-eenheid toelaat om 'n stelsel van geïntegreerde toepassings te gebruik om die besigheid en verskeie steundienstefunksies verwant aan die tegnologie te outomatiseer en te bestuur. Dit stel ook dienste en menslike hulpbronne in staat om die data-vaslegging, -manipulasies, -berekening en -validering vir 'n unieke onderneming-hulpbronbeplanningsmodel wat in 'n onfeilbare gehaltebestuurstelsel gevestig is, te ontwikkel.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D CAD	Three-dimensional Computer-aided Design
3DP	3D printing
ABS	TM Acrylonitrile-Butadiene-Styrene
AI	Artificial Intelligence
AM	Additive Manufacturing
AMP	Additive Manufacturing Precinct
API	Application Programming Interface
BOK	Body of Knowledge
CAD	Computer-Aided Design
CNC	Computer Numerical Control
DLP^{TM}	Digital Light Processing ^{TM}
DMD^{TM}	Direct Metal Deposition ^{TM}
DMLS^{TM}	Direct Metal Laser Sintering ^{TM}
EBAM^{TM}	Electron Beam Additive Manufacturing
EBM^{TM}	Electron Beam Melting ^{TM}
ERP	Enterprise Resource Planning
FDM^{TM}	Fused Deposition Modelling ^{TM}
FLM	Fused Layer Manufacturing
ICT	Information and Communication Technology
LBM	Laser Beam Melting
LENS^{TM}	Laser Engineered Net Shaping ^{TM}
LLM	Layer Laminated Manufacturing
LMD	Laser Metal Deposition
LOM^{TM}PC	Laminated Object Modelling ^{TM} Polycarbonate
PDM	Product Data Management
PI	Polyimide
PLA	Polylactic acid
PMMA	Poly (Methyl Methacrylate)
SLA^{TM}, STL	Stereolithography
SLM^{TM}	Selective Laser Melting ^{TM}
SLS^{TM}	Selective Laser Sintering ^{TM}
STL	Standard Triangulation Language, Stereo-lithography or Surface Tessellation Language
QMS	Quality Management System
NIPMO	The National Intellectual Property Management Office

1. INTRODUCTION

The general convenience of AM is already proven in modern manufacturing planning. In some fields, additive manufacturing (AM) and production is a certainty, and not exclusively for custom-designed products (Ruffo et al., 2006). In fact, AM minimises time and costs, including the design phase right through to manufacturing, since there is no investment in pre-production or production tooling or moulds, which negate the need for designing tools, moulds, or commissioning the manufacturing of the necessary tooling and fixtures. Nevertheless, the financial gain, efficiency growths, and process improvements in design, analysis, testing, and manufacturing are far greater. With regard to time, a further AM advantage is that once the part design is released, the production begins immediately. Delays due to the manufacturing of moulds, fixtures, or tooling, which usually takes several weeks of work, are avoided. However, delays are costly and the norm in instances where tooling is involved. Eliminating those lead times saves time, with considerable financial benefit.

Present-day students are already using AM and understand how to leverage these new skills. By having access to this disruptive technology, a new generation of engineers will create innovative changes in the workplace. To gain better understanding of what is happening for example in the AM hearing aids business, with sales of five million devices per annum in 2018, 95% of the enclosures (shells) were made of AM components. The outlook in 2018 is that one of the eight technologies shown in Table 1.1 will be the correct fit for one’s company. Gartner (2015) states that late adopters of AM are delaying the purchase of AM technology based on the cost of technology and manufacturing. Companies that have already incorporated AM report savings. An example can be seen in a product development cost decrease between 2,9% and 3%, an inventory cost decrease between 3% and 4%, and a manufacturing cost decrease of 7%. Present research (Öberg, Shams & Asnafi, 2018) shows a trend of AM democratisation parallel with revolutionary designs. Hybrid production is used to repair used parts, and AM has a strong presence in the component replacement market. The integration of the South African manufacturing sector with the global manufacturing industry has introduced challenges with implementing the National Development plan in the industrial area. Globalisation, strong-handed competition, and a change to a buyers’ market are aspects that need to be faced and considered. Flexible and effective manufacturing practice always has been the foundation of a successful enterprise. Gartner (2015) indicates that international supply chain managers are prospecting for sustainable, affordable, innovative, quality products. In the modern world, industrialists are dealing with a decreased economic life span of consumer products, with the requirement of a shorter time to market and the pressure to have more short development cycles. The fast development and short life cycles are complicated further by the growing demand for mass customisation.

1.1 Problem statement

The problem statement stems from INDUSTRY 4.0 concepts. Since there are no longer any unmarked products, product DNA (electronic signature) follows it through all processes. All parameters, norms, and standards are already documented clearly and concurrently as part of the virtual product development.

The problem statement guides the costing tool development, recognising thesis objectives to engage in analysing the existing costing algorithm, and qualifying the existing algorithm with empirical results. The results will be benchmarked with a full cost model, considering all the activities and resultant cost elements influencing cost and guiding the process to a simplified methodology that functions in the virtual ambit to ensure quick and accurate quotations.

Wallace and Kremzar (2001) state, “The problem is to recognize the need for better decision-making processes, enhanced coordination, and greater responsiveness both internally and within their extended supply chain.”

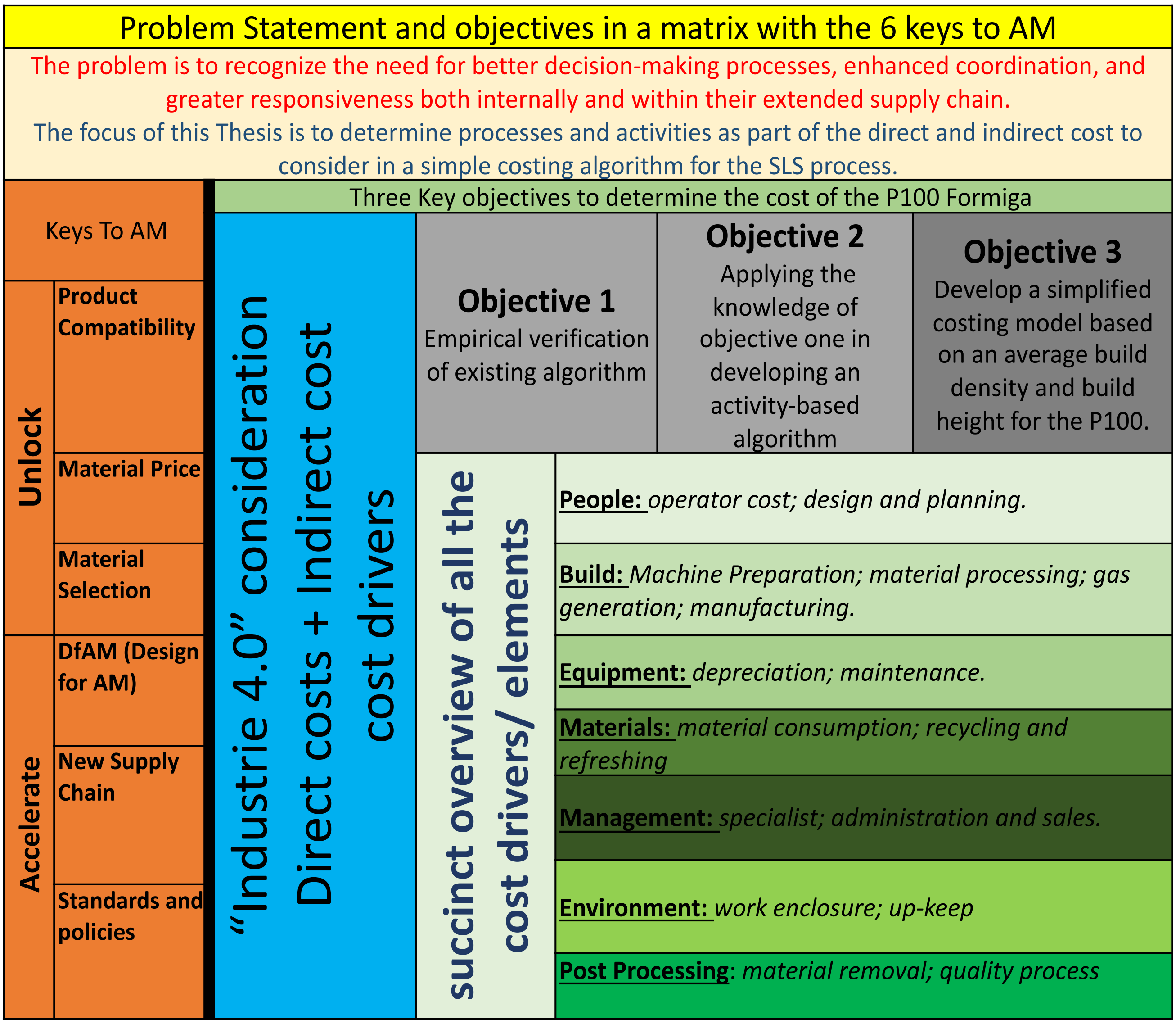
The scope of this thesis is not to incorporate the science of AM in developing the costing algorithm but rather to recognise the full integration of AM with the digital manufacturing enterprise. This could mean converting completely to an AM system, where appropriate integration consideration is taking place on an existing production line or supply chain.

In Table 1.4, the correlation between the problem statement and the objectives of the thesis is brought into perspective. Product data management (PDM) is used in Objective 1 to set the scene for the research and the benchmarking and to take the project to Objective 2; consequently, the project develops into the elegant solution using the information of the previous objectives in finalising Objective 3. Finally, an existing web-based quoting system is consulted to provide further confirmation that the proposed methodology is indeed accurate.

The Easter egg wrapper was chosen as an ideal product for this thesis based on the following criteria:

- It is designed uniquely for additive manufacturing.
- The product can be manufactured only on an AM platform.
- It involves a low-volume, once-off production requirement.

Table 1.1: Synoptic overview of the problem statement and objective intercorrelation



Problem Statement and objectives in a matrix with the 6 keys to AM

The problem is to recognize the need for better decision-making processes, enhanced coordination, and greater responsiveness both internally and within their extended supply chain.

The focus of this Thesis is to determine processes and activities as part of the direct and indirect cost to consider in a simple costing algorithm for the SLS process.

Keys To AM

Unlock
- **Product Compatibility**
- **Material Price**
- **Material Selection**

Accelerate
- **DfAM (Design for AM)**
- **New Supply Chain**
- **Standards and policies**

"Industrie 4.0" consideration

Direct costs + Indirect cost cost drivers

Three Key objectives to determine the cost of the P100 Formiga

Objective 1
Empirical verification of existing algorithm

Objective 2
Applying the knowledge of objective one in developing an activity-based algorithm

Objective 3
Develop a simplified costing model based on an average build density and build height for the P100.

succinct overview of all the cost drivers/ elements

People: *operator cost; design and planning.*

Build: *Machine Preparation; material processing; gas generation; manufacturing.*

Equipment: *depreciation; maintenance.*

Materials: *material consumption; recycling and refreshing*

Management: *specialist; administration and sales.*

Environment: *work enclosure; up-keep*

Post Processing: *material removal; quality process*

1.2 The Eluding Questions (EY's Global 3D Printing Report, 2016)

Most businesses can benefit from AM The question is which of the eight manufacturing platforms will assist you to optimise your business. The information in the following list will assist in making a decision:

- There is a choice of 8 different platforms; one can choose the most suitable one for one's product and business: 1. Material extrusion; 2. Vat polymerisation; 3. Powder bed fusion (polymer); 4. Material jetting; 5. Binder jetting; 6. Powder bed fusion (metal) or directed energy deposition; 7. Sheet lamination; 8. Continuous liquid process.
- Where (in terms of differentiated location) or when (in terms of volume, complexity, and time requirements) is AM appropriate?
- Which products or components (i.e., load bearing) can be manufactured best in an additive process?
- Which materials are required to manufacture mission-critical components?
- What is the best approach to qualify or certify components made by AM?

Selecting the optimal AM process for a particular design can be a challenging experience. The range of AM methods and materials means that several processes often are suitable for a design, with each offering different properties regarding dimensional accuracy, surface finish, and post-processing requirements.

1.3 Scope

The focus of this thesis is to determine processes and activities as part of the direct and indirect cost to consider in a simple costing algorithm for the SLS process, using the PA2000 polymer as raw material in the process.

Exclusions:

- Integration with an ERP system.
- The full supply chain cost and benefits are referred to for a more holistic understanding, although it is not considered in the final algorithm.
- Accreditation-related cost.

Component parts are for general application and exclude costing for the medical, aerospace, and electronic manufacturing markets, except general-purpose enclosures.

The Formiga P100 and P110 polymer SLS process is deemed a more established platform with fast sources of production data. The industry accepts that the early adopters of the technology are still concerned about pricing.

1.4 Other Aspects that Need to be Highlighted

Properties of AM components are not the same in all directions (anisotropic); for example, printing specimens in the ZXY (or vertical) build orientation can be difficult due to the capability of a given AM platform (Torrado & Roberson, 2016).

The following need to be considered:

- The belief that materials still lack the expected durability.
- Uniform high quality with high repeatability is still questionable.

1.5 Problem Context

1.5.1 Aspects that affect costing

Development of systems to improve quality and repeatability;

The initial step is to interrogate the current product development management system to predict build outcomes and repeatability. The main goals of this thesis are to simplify, improve and verify this against the current costing algorithm (Baldinger & Duchi, 2013).

1.5.1.1 Quality management system and accreditation

A good quality management system (QMS) is required to be able to clearly communicate the services of any manufacturing unit that are accurate, economic, and cost effective and conform to the needs of all the different groups of customers. Implementation of a QMS takes time, involves resources, and needs commitment from all staff members involved. The QMS incorporates the ISO 9001:2008 requirements for commercial customers to be able to show predictable outcomes of processes that will feed into industrial production lines.

1.5.1.2 Mastering and implementation of a design for AM

The design for AM offers a variety of prototyping and manufacturing technologies, including 3D printing (3DP) and laser sintering (LS). This requirement should develop the ability to create usable prototype and final components quickly and accurately, in a variety of materials, supporting local industry and entrepreneurs, as well as provide research support to local and international researchers.

1.5.1.3 The speed of production is still evolving (EY's Global 3D Printing Report, 2016)

Companies like the Ford Motor Company and Johnson & Johnson are set to integrate part of the operations with continuous liquid interface production (CLIP), a high-speed photo polymerisation process. Speed of production is still an issue that needs further debate. Emerging technologies enhance the appeal of 3DP. Fast printing of products with a high-quality surface differentiates CLIP technology.

1.5.1.4 Development of human capital

Reasons why companies do not consider AM manufacturing include lack of information, limited awareness about the technology, and a shortage of in-house skills. Companies with no or limited experience and inadequate knowledge cause scepticism about the capabilities of modern systems regarding part sizes, materials, and the quality of AM products.

In this regard, it can be remarked that:

- a skilled workforce with required vocational skills does not exist in South Africa;
- personnel with "Design for AM ability" need to be developed; and
- local service bureaus that focus on prototyping need to become available.

1.5.1.5 Hardware development and collaboration

Machine platforms are Eurocentric, with most manufacturers in Europe.

The AM systems market offers a wide choice of platforms from different manufacturers and service providers globally. Generally, AM systems can be divided into desktop systems (price < R10 000) and the so-called industrial systems (price > R500 000).

AM compliments other INDUSTRY 4.0 technologies by combining AI Robotics with AM, for example to enable companies to overcome space limitations. Most maintenance services still originate from Europe.

1.5.1.6 The South African Collaborative Programme for Additive Manufacturing (CPAM)

The goal of the CPAM is to improve the application and adoption of AM as an accepted advanced manufacturing technology by the South African manufacturing industry. The programme conducts research and development in metal and polymer additive manufacturing processes, creates reliable process chains to establish qualification procedures for the technology, and validates new technology developments in the field of AM technology. Design for additive manufacturing pertinently strengthens design competence to ensure good benefit from the advantages offered by AM. Lastly, it is underpinned by a focus on knowledge transfer to industry and educational/outreach projects.

The research and development (R&D) programme is designed to increase human capital, skill awareness aspects, and the technological readiness of AM. Projects in the programme have a direct effect on the manufacturing of medical devices and implant needs, commercial aerospace parts, and a myriad of applications in the more traditional manufacturing sectors. Throughout, emphasis is placed on generating new knowledge and developing intellectual property. The programme supports human capital development (HCD) to establish the next generation of scientists, engineers, and technologists skilled in AM. CPAM helps to share knowledge, with some UOTs and traditional universities participating in the programme. Standards and accreditation need attention, and due to competitive advantage, local industry is unwilling to share information.

1.6 Significance and Motivation

1.6.1 Objectives

The solution proposed is human interface technology ensuring an interactive operation study, and document integration that will affect real transformational efforts to understand and ensure an effective INDUSTRY 4.0 system that will improve the AM business. The specific gap that was identified is the complex nature of the current costing models. Furthermore, the cost per build and not the cost per part needs to be the main consideration. This thesis will endeavour to prove that this can be simplified.

The ISO/ASDTM 52900 terminology standard defines AM as the process of joining materials to make a part from 3-D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methods. Historical terms include additive manufacturing, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid free-form manufacturing, and free-form manufacturing (Atzeni et al., 2014).

From the above-mentioned terminology standard, it is clear that additive manufacturing is the accepted ISO terminology (Wohlers, 2018).

The objective is to use the previous projects as case studies to develop this link to the development of the algorithm. The following factors need to be considered:

- Understand the cost parameters that will affect dynamics and integrity of the system.
- Map the process chain.
- Develop the algorithm (make the decision to allocate a resource that is best to manage the process to minimise the risk).
- Validate the algorithm against an existing quoting system.

- Test and benchmark the new costing algorithm empirically, and benchmark with other models.

1.6.2 Research design of objectives

How should one establish a relationship between the variables? The relationships between objectives are portrayed graphically in Figure 1.1.

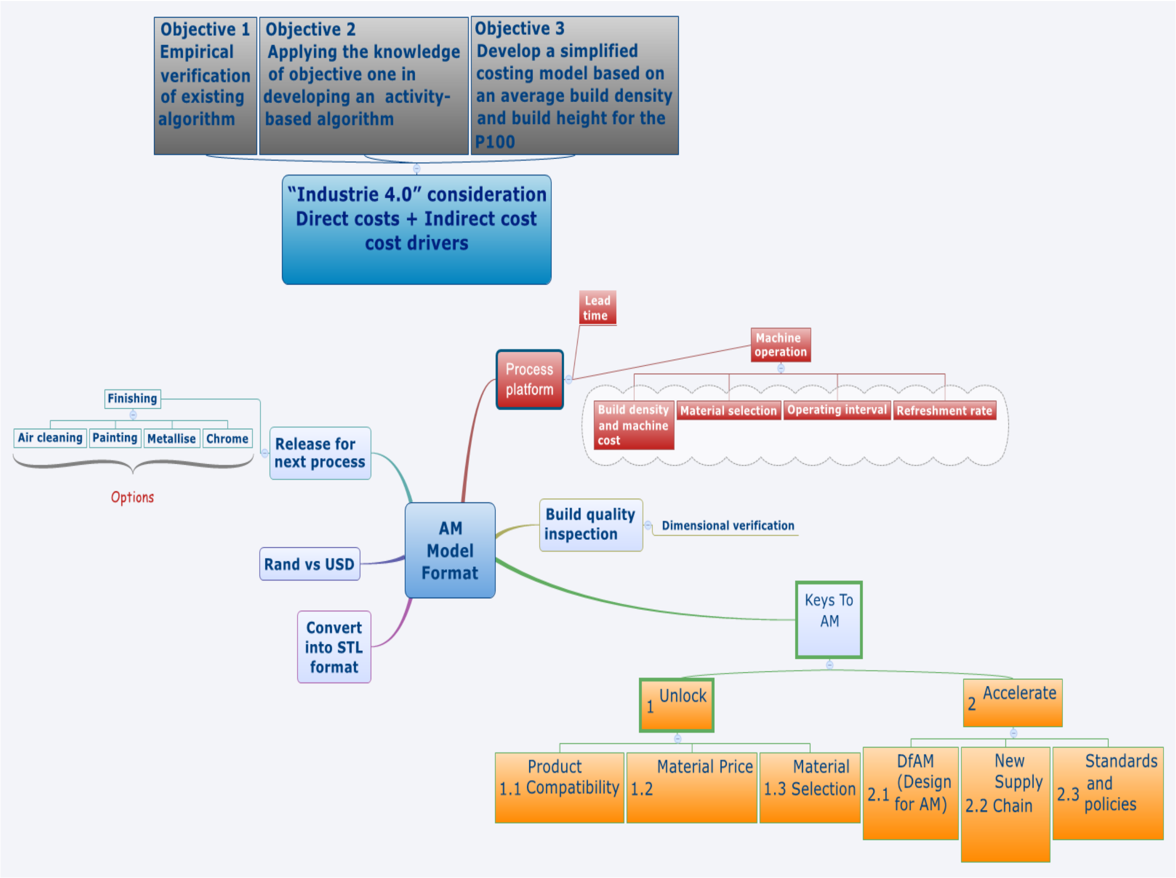


Figure 1.1: Research design of objectives.

1.6.3 Overview of objectives 1 – 3

1.6.3.1 Objective 1

Verify the existing algorithm empirically.

- Verify all the cost drivers in the existing costing algorithm.
- Require costing from the existing algorithm for the Easter egg wrapper.
- Verify this costing exercise with empirical data from 4 x builds amounting to 1500 units.
- The existing system operates on a loss factor to incorporate material losses and rejects.

- Material cost is based on material-specific cost (PA R2000 /kg).
- The empirical calculations were based on the verified builds, material usage, and measured times and weights.
- All material properties were verified.

1.6.3.2 Objective 2

Apply the knowledge of Objective 1 in developing an activity-based algorithm.

All the cost rates and elements, which will be divided into indirect cost and direct cost, should be defined clearly. Special attention will be given to the production overhead rate and administration overhead rate, and to determine the depreciation, the machine purchase price will be considered. All calculations will be based on the cost rates for the different cost elements that were considered in Objective 1. Important aspects such as energy consumption will be based on "calculation", based on the body of knowledge information and research done in the past.

1.6.3.3 Objective 3

Develop a simplified costing model based on an average build density and build height for the P100.

- The average build density of builds on the P100;
- Build height of a full build and build density from the product data management system;
- The refresh rate and the discarding of material after six builds;
- Bulk density of the material matrix g/cm^3;
- Bulk density of the sintered material g/cm^3;
- The fixed cost is available (Objective 2); and
- Full build material cost is available.

1.6.4 Methodology

To support the objectives, the data used in development and research methodology were based on the production and customer data for the past four years, as recorded in the PDM system. Owing to the nature of this thesis, the before- and after-effect relationship will be measured empirically only once data capturing, manipulations, calculation, and validation has been implemented. Correspondingly, the requirements for skills, expertise, technologies and services are wide. The process begins and ends with the customer, as can be seen in Figure 1.2 below.

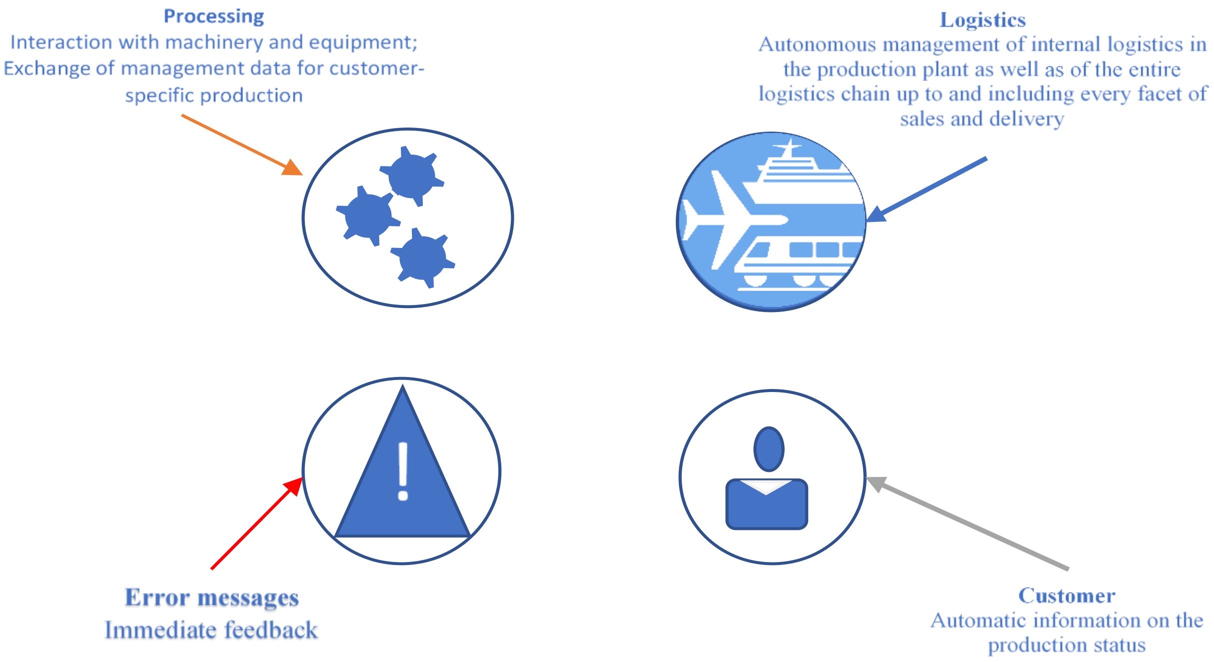


Figure 1.2: Areas affected (Adopted from: Building the factory of the future, 2014, pp. 1–12).

1.6.4.1 Description of business process

The process is based on the logic of sequential activities of a project, as shown in Figure 1.3.

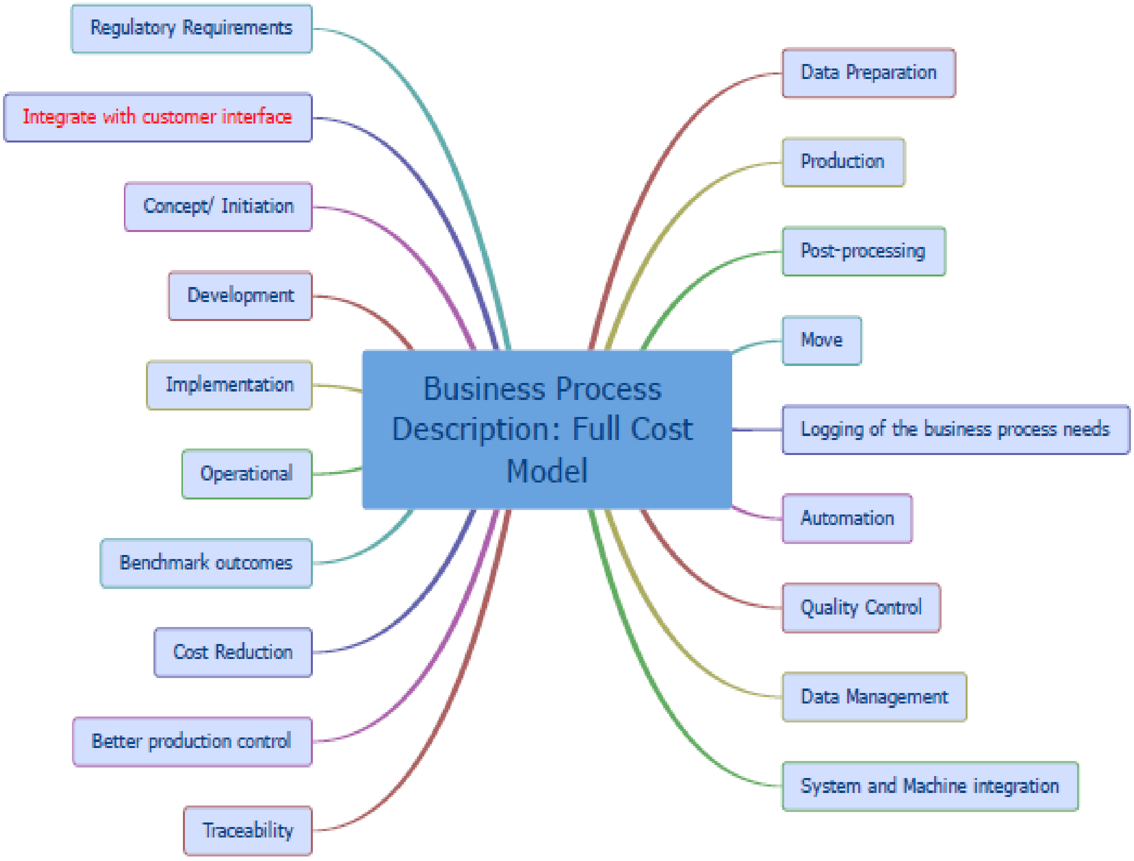


Figure 1.3: Description of a business process applying a full cost model according to the NIPMO specifications *(Buchholz, 2011).*

The diagram intends to identify all the activities in the full cost model that can be considered in the business process. Only the costing elements that affect the SLS platform directly were considered in the three objectives of this thesis. However, cognisance is taken of the elements incorporated in the overall product life cycle management and integration in an encompassing ERP system.

The logical interface (Figure 1.4), as with all the builds in an additive manufacturing environment, begins with the customer and the capturing of his details for traceability. The customer needs and requirements are analysed and augmented when the customer model is accessed with the commencement of the customer STL file investigation. The process culminates in the overall objective of all business to produce a quotation for customer acceptance and approval as an igniter for the AM process.

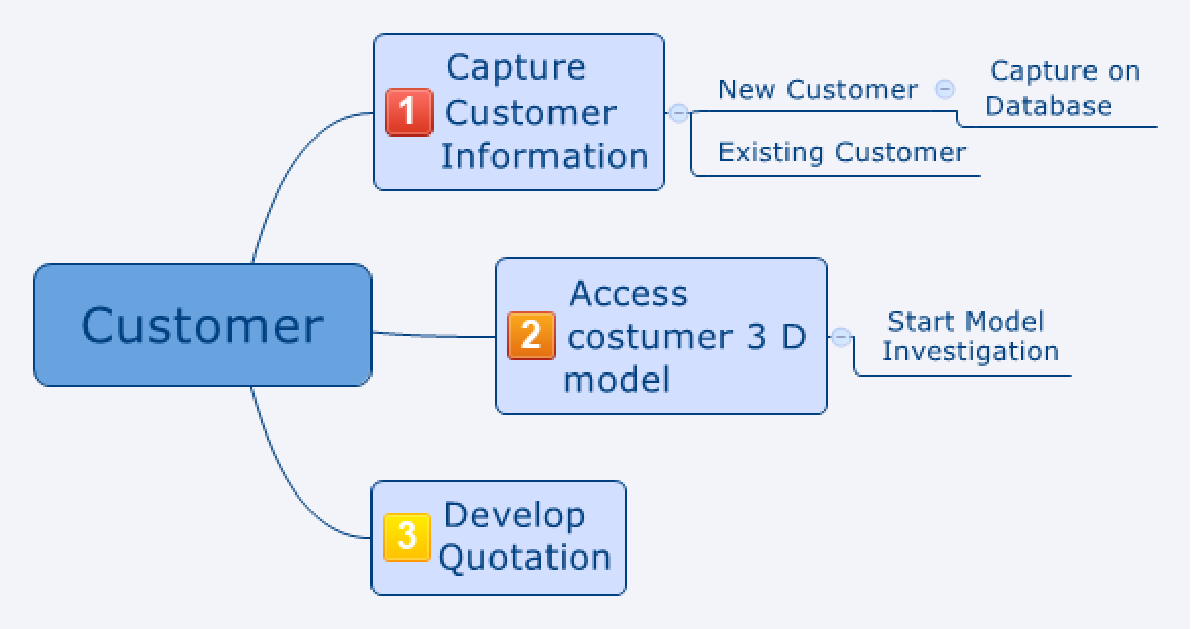


Figure 1.4: The logical sequence for the project begins with the customer interface.

1.7 Definitions, Assumptions, and Limitations

1.7.1 Identify end-to-start outcome

Begin with the total system approach – discovery phase:

- Needs analysis: customer as well as AM.
- In-situ understanding and logging of process requirements.
- Interface fit/gap analysis.

Understand the links required in the process in relation to the different platforms.

- Safety and risk issues.
- Standard operating procedures (SOPs).
- Quality management systems (QMS) requirements.

The scope of the thesis is to bring the different costing objectives in relation to the needs analysis and benchmarked data.

Introduction to the analysis begins with the development of the data capturing, manipulations, calculation, and validation elements of the process.

The aim of all AM-based projects are to begin with the customer expressing his need for an AM product and to end with a product, part, or prototype as envisaged by the customer. This will begin the process to consider the digital manipulation of the customer's interaction with the tools on the AM website (Figure 1.5).

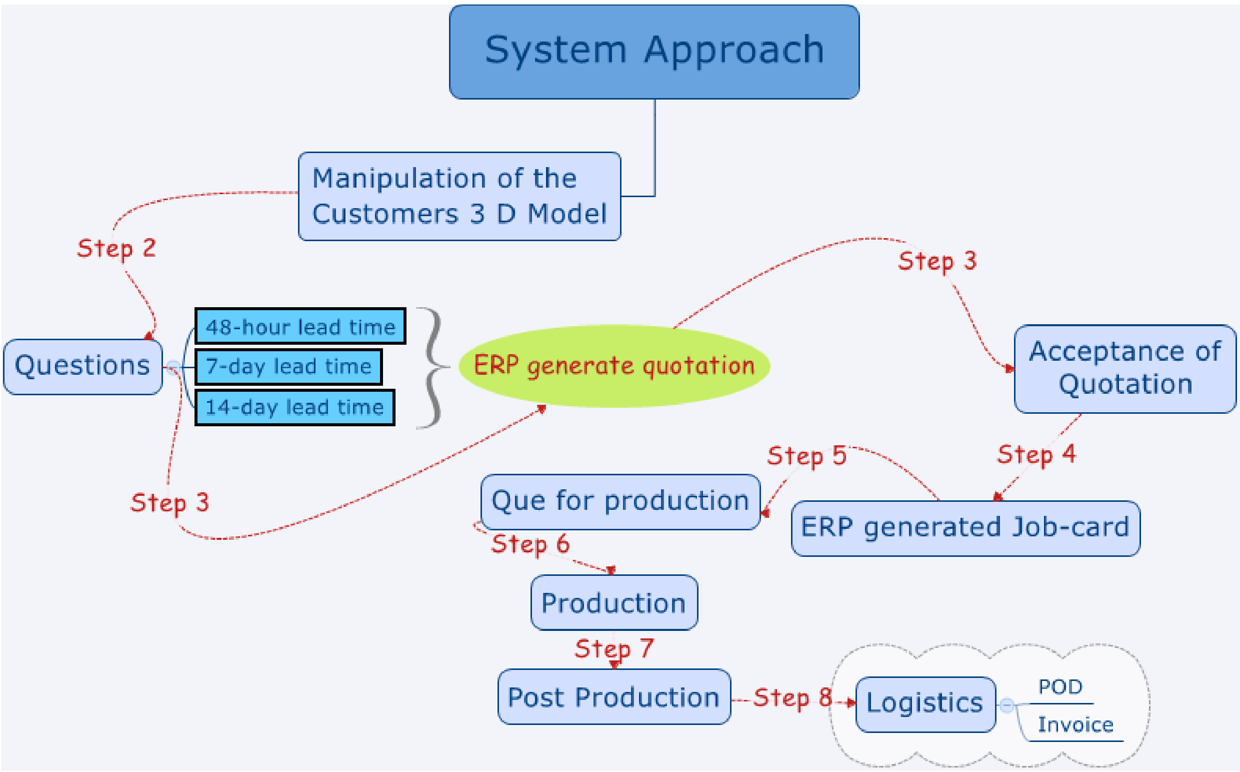


Figure 1.5: The digital manipulation of the customer's interaction.

1.7.2 Analysis

The initial step is to begin an in-house evaluation and testing phase and run the new costing algorithm concurrently with the existing system to compare results. To finalise this digital integration according to INDUSTRY 4.0 and complete the exploratory aspects of the thesis, the following inputs from other research are vital and will be required:

- Full cost model.
- AM body of knowledge.
- Existing costing model for comparison.
- Results from existing quotations.

1.7.3 Predictive analysis

The data capturing, manipulations, calculation, and validation encompass the entire system and customer interface from sale to final delivery. The inner workings and digitisation of all information need to run on a platform for software development. The scope of the thesis focuses solely on the data capturing, manipulations, calculation, and validation development, and tests will be conducted to demonstrate, measure, compare, and fine-tune the costing model. The predictive costing considerations in Figure 1.6 form the basis of the narrative in the costing models presented in the next chapters in this thesis.

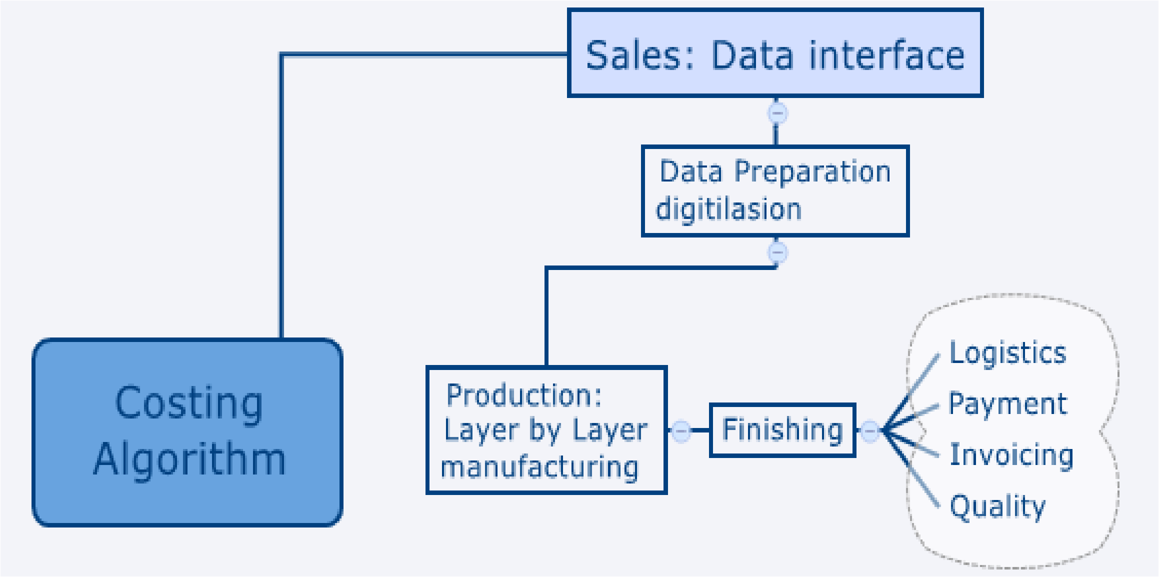


Figure 1.6: Costing considerations in the chapters to follow in the thesis.

1.7.4 Project road map

The nature of this research project is to combine the different building blocks sensibly into a sophisticated platform for digitisation of all inputs. It involves the manipulation of all information to manage the AM units at the Vaal University of Technology (VUT) sustainably with improved customer satisfaction, productivity and accuracy. In Figure 1.7, the thinking process in relation to the objectives link to the fishbone in Figure 1.8.

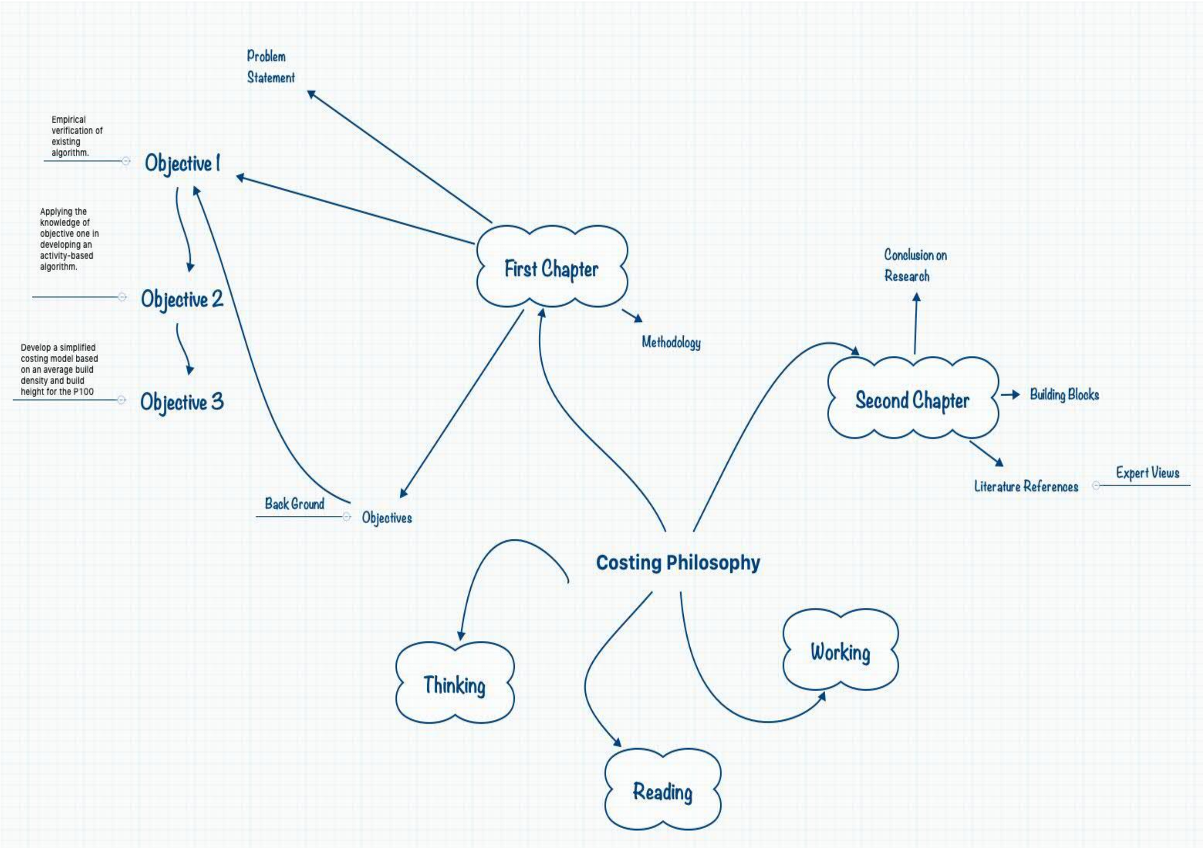


Figure 1.7: Project road map to order cognitive process to assist in the overall planning process.

1.7.5 Ethical considerations

The engineers taking responsibility for health, safety, and related issues need to join the debates surrounding ethical considerations where measurement and validation aspects are involved in a relatively new environment like AM. Green fields innovation is part of everyday business in the AM arena. Further aspects, for instance customisation and finishing of 3D printed parts or artefacts and post-production processing of these components, would be included. The Occupational Health and Safety Amendment Act, No. 181 of 1993, would be considered. Responsibility towards all participants involved and affected by this research would be a key consideration. The nature of this thesis implied the participation of several co-workers and the *de facto* and truthful reflection of data generation, analysis, publishing, and acknowledgement of their work.

All data collected would be captured appropriately as discussed with supervisors. It is the right of the researcher to report the research for the advancement of scientific knowledge by publishing the findings in journals, books, or other media.

Ethical clearance was investigated through the University of Stellenbosch, and the guide for ethical clearance was perused to obtain a clear understanding regarding requirements for ethical clearance through the appropriate policies of the university. The criteria of the University of Stellenbosch indicated that this thesis did not require any qualification pertaining to the issue of ethical clearance.

The appropriate personal protective equipment (PPE) were supplied to all co-workers gathering the relevant data for the thesis. The ethical considerations were based on the guidelines from the University of Stellenbosch (see ADDENDUM **No table of figures entries found.**1). The reader should also be made aware that, because the nature of emerging technologies is new, this causes a grey area for ethical consideration.

All research conducted to finalise the thesis would promote research to find workable solutions and establish a professional and conducive research environment among the universities. In pursuit of excellence, responsibility towards integrity, honesty and human dignity will not be neglected (Bezuidenhout, 2017). In conducting the research, the researcher always adhered to the principles of scientific integrity, common dignity, and social responsibility.

1.7.6 Conclusion

The implementation of a costing algorithm is not risk free; it is an expensive solution. To integrate such a system completely is time consuming and can take a long time. The acceptance and trust of the system can lead to challenges of its own.

The number one risk to complete the research and the framework for this thesis successfully was the complexity of the planning, development, and training needed, as well as the level of expertise that one needs to consult in the process.

1.8 Thesis Delineation and Research Questions

The answers to the research questions would provide a holistic approach to deriving an elegant solution for a costing model compatible with the ERP system.

In Figure 1.18, the final full costing algorithm is considered, based on the following equation:

Cost of a build = Direct cost + Indirect cost

The most cost-influencing factors would be the following:

- Investment and load factor;
- The economics of AM is fundamentally linked to the distinct advantages it offers when it comes to design freedom;
- The effect of design for AM on cost;
- The advantage when small products are manufactured; and

- Effect of order quantity

Figure 1.8 gives a succinct overview of all the cost drivers.

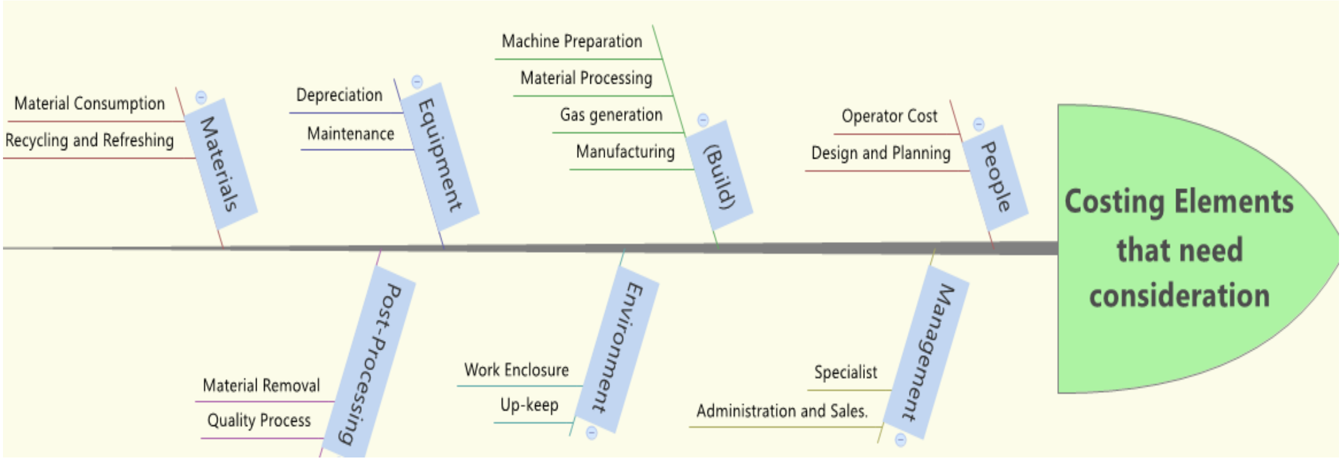


Figure 1.8: Cost drivers in direct and indirect cost.

1.9 Objectives of the Chapters in this Thesis

Chapter 1: The chapter gives an overview of the nature of AM, the time scale for ethical consideration, and the scope of the project or thesis.

Chapter 2: The chapter provides support for the view in this thesis that the economical consideration with reference to AM is more supply chain orientated than the cost involved in analysing one single platform. The literature review focuses on previous work regarding the cost resulting from calculating the activity-based cost on the P100 material platform. The principle was to calculate cost from within an engineering view but to escalate the thinking based on the whole supply chain.

Chapter 3: The chapter focuses on the methodology used to gather information from the existing source of knowledge generated by the current operating system in the AM Department.

Chapter 4: The chapter deals with aspects regarding the empirical verification of the existing algorithm to verify the accuracy. The goal was to question the existing costing algorithm implemented at the AM Department. Their current system was compared empirically with the data generated to be used for builds on the P100 platform. All of this newfound knowledge was used to develop a new costing model, simplifying the approach to calculating cost on the P 100 platform.

Chapter 5: The chapter deals with a full cost model approach, considering the activities and cost elements.

Chapter 6: The chapter concludes the thesis with the establishment of a simplified solution that deals with a volume-based system linked to a full build costing analysis.

Chapter 7: The chapter succinctly deals with the proof of the argument.

Chapter 8: The chapter introduces a discussion affecting the findings in the previous chapter, critically considering the methodology currently propagating cost and case studies to support the three objectives.

Chapter 9: The chapter presents a global perspective, concluding the thesis findings and effect on the industry.

Chapter 10: The chapter emphasises the focus of the thesis on the global perspective with reference to AM and how the specific attributes will affect the economics of manufacturing.

2 LITERATURE REVIEW

The research to support this thesis began in 2016, and quantitative analyses of the latest survey data, webinars referencing AM or three-dimensional printing (3DP) reveal one aspect that will change the future of manufacturing. AM is now deemed as part of a bigger manufacturing value chain. Other disciplines apart from the engineering-orientated areas have entered the AM production world and emphasised the fact that if an industry is to survive in this rapidly changing environment, the manufacturing units will have to adopt one of the eight AM platforms.

A question should then be considered; not only about what additive manufactured components cost, but also about the influence it will have on the cost of product development, inventory, and logistics. The new hypothesis underlying the discussion is that AM ensures localised competitiveness. An aspect that needs serious consideration is the significant retraining of skilled people to support what is coming.

The diffusion of AM technology in a conventional production environment and to adopt a new technology production cost were the most important factors to analyse. The aim of this thesis was limiting, and a more integrated approach was required (Fera et al., 2017).

Most cost models in the literature reviewed still support the narrow view of cost as pointed out in this thesis:

Total cost per part = Machine cost per part

+ Labour cost per part

+ Material cost per part

The new reality of integration with large-scale production shifts the focus away from this simple view.

Equation 1: Cost per Build (Baumers, Holweg & Rowley)

$$C_{\text{Build}} = (\dot{C}_{\text{Indirect}} \times T_{\text{Build}}) + (w \times P_{\text{Raw material}}) + (E\text{Build} \times P_{\text{Energy}})$$

$\dot{C}_{\text{Indirect}}$	Indirect machine cost per hour [R/h]
T_{Build}	Total build time [h]
w	Total weight of the part in the build (including support structure) [kg]
$P_{\text{Raw material}}$	Price per kilogram of raw material [R/kg]
E_{Build}	Total energy consumption per build [MJ]
P_{Energy}	Mean price of electricity [R/MJ]

An evident limitation of the literature for the compilation of this thesis is that few economic assessments recognise the significance of the capability of AM technologies to produce multiple potentially unrelated parts concurrently in a single build. Underutilising the available build volume leads to low utilisation and is detrimental to economic performance.

Existing literature explores the most relevant cost models for AM, and it became clear that little recognition had been given to the integration and multiplier effect of the technology.

2.1 Research Method

One of the aspects affecting the cost model to focus on the use of AM techniques was shown to be advantageous for parts that have a high buy:fly ratio, have a complex shape, a high cost of raw material used for machining from solid, slow machining rates, and are difficult and expensive to produce using a machine (Steenhuis & Pretorius, 2015; Allen, 2006).

The costing elements include the following:

- Fixed costs.
- Variable costs.
- Economies of scale.
- Economies of scope.

The paper “Cost models of additive manufacturing: A literature review” was handy in making sense of and finding relevant literature pertaining to cost models (Costabile et al., 2017).

The knowledge obtained from the literature search referred back to the body of knowledge about AM at the VUT. The literature presented new developments in the AM domain, like functionally graded additive manufacturing (FGAM). “FGAM is a layer-by-layer fabrication process that involves gradationally varying the material organisation within a component to achieve an intended function. FGAM establishes a radical shift from contour modelling to performance modelling by having the performance-driven functionality built directly into the material. FGAM can strategically control the density and porosity of the composition or can combine distinct materials to produce a seamless monolithic structure” (Loh et al., 2018). The aforementioned is an example of the rapid technological advancement in the AM field.

The problem of more emphasis on the engineering endeavour rather than the economic aspects that was identified forces one to realise that to understand the magnitude of the literature generated from the inception of AM in 1967 until now is no easy task.

Research between 1997 to 2017 indicated 66 764 papers using keywords like the following in connection with AM (Costabile et al., 2017):

- technology overview;
- cost model;
- business model;
- mechanical properties;
- sustainability;
- lifecycle cost.

Earlier papers focus on the use of AM mainly for rapid prototyping and rapid tooling. The first costing models and analyses were basically to compare AM with conventional injection moulding. Out of these comparisons, the myopic reasoning that AM is economical only in the case of complex geometries and low volumes became clear. The problem with most of the engineering cost models is that they primarily focus on a complex mathematical equation, and the usual analysis and comparison show strength and weaknesses. The reality is that results of the simple and more complex scenarios are close together due to the nature of the AM process.

The literature review was narrowed down to 7285 papers dealing with “AM supply chain”, 3001 papers dealing with “AM cost model and AM business model”, 1022 papers dealing with “AM lifecycle cost”, and 2466 papers dealing with “AM sustainability”.

AM supply chain (Khajavi, Partanen & Holmström, 2014): This aspect needs more consideration as AM evolves and diffuses into the production process of manufacturing end-use components. The key aspect is the effect on other supply chain configurations. The potential of decentralised manufacturing replaces current inventory practices.

AM cost model and AM business model (Schröder, Falk & Schmitt, 2015): In the approach to develop a business model and evaluate cost structures, one needs to consider that customisation of products is one of the most important trends for industrial enterprises. The objective will be to apply proper cost and investment calculations; an enterprise can improve price calculations of products. Cost drivers need to be evaluated, and adaptation of business-relevant technology is paramount to success.

AM lifecycle cost (Lindemann & Jahnke, 2017): AM technology has many advantages and it is evolving rapidly but is not yet subject to implementation in mainstream industry. General predictions are that adoption in the main stream occurs 3 to 5 years from realisation. Cost of the technology and the need for in-depth understanding of AM structure seem to be critical factors. It is clear that thorough understanding of the processes in AM implies understanding the cost drivers.

2

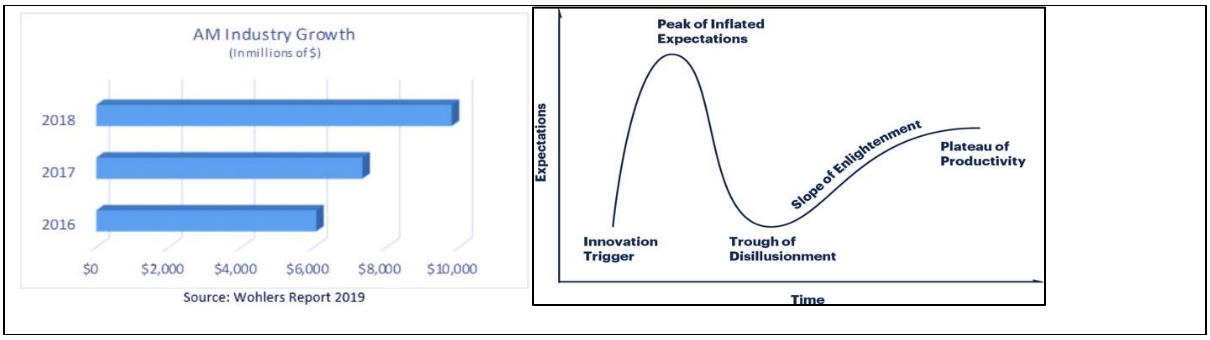


Figure 2.1: **AM Industry year-on-year growth and Gartner's Technology Hype graphically display time vs. expectations.** *(Wohler, 2019)*

AM sustainability (Ford & Despeisse, 2016): The focus is on consumer demand for more differentiation; hence, more customised end-use components and services affect the scale and distribution of manufacturing. The interrogation of the sources of innovation, business models, and configuration of value chains describes the advantages and challenges and discusses the implications of AM. The Gartner Technology Hype indicates that AM is entering the productivity phase.

Supply chain functionaries cannot wait for factory or consulting service estimators to prepare quotations anymore. There is a growing need to access a script on the website of the company to generate quotations directly.

Table 2.1: ***AM technologies Defined courtesy Gartner online webinar**. (Gartner, 2015)*

The Originals	**"Print-like"**	**Metals and More**	**Paper, Metals and…**
Material extrusion	Binder jetting	Direct energy deposition	Sheet lamination
Stereolithography	Material jetting	Powder bed fusion	Multi jet fusion

The diagram in Figure 2.2 is an example of a guide to assist companies to generate a quotation with a typical "self-help" quotation and order system. To achieve this, the user need to develop an elegant algorithm for each manufacturing platform.

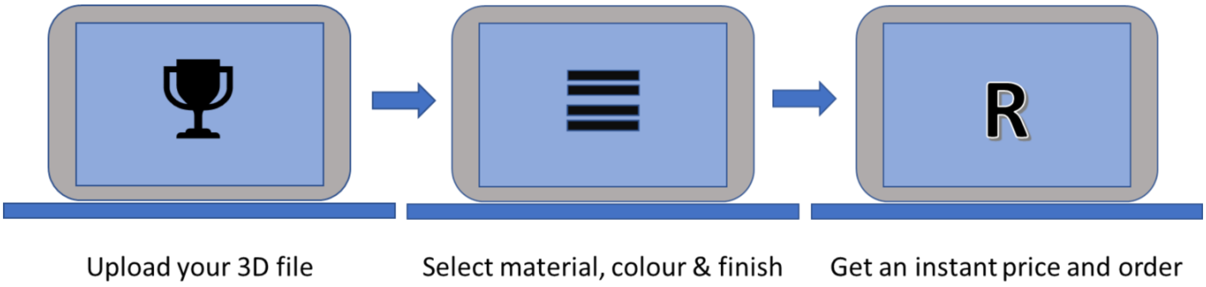


***Figure 2.2**: **Online 3D printing service. Upload your 3D model, choose from 100+ different finishes and materials, select the size of your print, and receive a price quote instantly.** (Own graph)*

Although the thesis is focusing on Selective Laser Sintering ™ (SLS™) of polymers, this model could form the basis of developing answers for other AM technologies with different materials, energy sources, and standard operating procedures. It should be noted that all of these have similar processes. (Costabile et al. 2017). The following list of activities is a simple task sequence of the AM process:

- Three-dimensional (3D) computer-aided design (CAD) model.
- Convert 3D CAD model into "standard triangle language" format (STL).
- Slice the STL into perpendicular, cross-sectional layers.
- Construct the model layer by layer.
- Clean and finish the model.

In Figure 2.3, the five steps are explained in more detail. Specific reference to the measurable activities and the circular nature of INDUSTRY 4.0 is also clear, starting with the customer and finishing with the customer.

Steps 1-2:

Following from interaction with a customer, a computer-generated concept will be produced in specific software to create a digital model by applying computer-aided design (CAD). When existing prototypes or products need to be reverse engineered, a 3D scanner can be utilised to produce a working template.

Step 3:

To manufacture a part, a CAD model must be converted into a format that an AM platform is able to interpret. The norm is converting the CAD model into a standard triangle language (STL) file. The STL file generated for this purpose is now imported into a slicing program that slices the design into the layers that will be used to build up the part. A simplified explanation is that the program takes the STL file and converts it into reverse G code. G-coding is a numerical control program language used in CAM to control automated machines such as Computer Numerical Control (CNC) machines and AM platforms.

Step 4:

In Step 4, each of the different AM technologies will use a different method (seven potential platforms) to build the part or parts.

Step 5:

Like most cases with AM technology (powder or supporting material), removal of the print is as simple as separating the printed part from the build platform for the powder matrix. For industrial platforms, the removal of the build is a highly technical process involving specific methodology of part cleaning and finishing. In the case of the P100, which uses a powder bed process, the cleaning involves bead blasting and the removal of the excess powder.

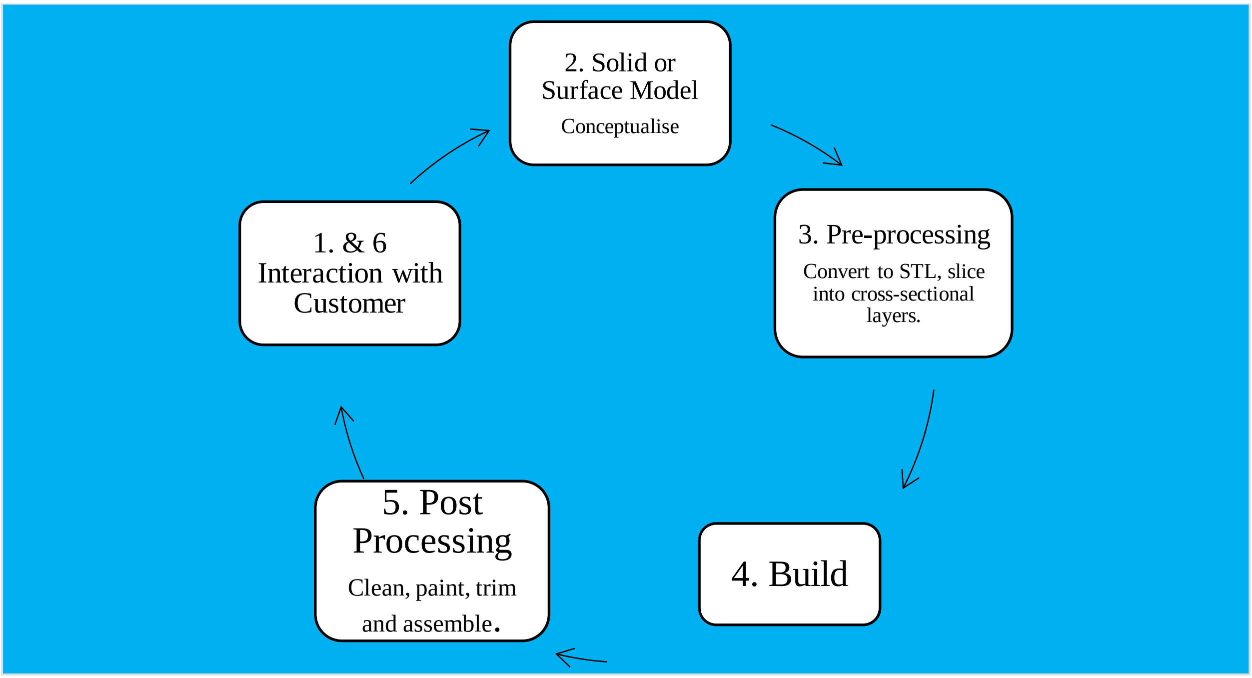


Figure 2.3 : AM process steps for manufacturing to give the costing activities.

The current design and manufacturing advantages of AM depicts AM as a digital technology that allows the user freedom of:

- freedom of materials;
- freedom of design; and
- freedom of manufacturing.

Some companies that have already embraced the full potential of AM can be deemed the early adopters of emerging technology. In the narrative below, some examples of companies that have adopted the technology are quoted.

Empire Cycles:

Through redesigning their mountain bike aluminium extruded seat post and down post with the assistance of Renishaw, the new AM product is using titanium, is 44% lighter, and stronger (Figure 2.4).

Figure 2.4: Titanium Seat Posts and Downtube *(Courtesy of Renishaw, 2014).*

Airbus:

AM is used to produce the nacelle hinge bracket for the Airbus A320 (Figure 2.5).

Figure 2.5:The Nacelle hinge bracket. *(Image by courtesy of https://www.stampa3d-forum.it/come-funziona-stampante-3d/elecBoeing, Airbus, Adidastron-beam-melting-ebm-schema-funzionamento-*

stampante-3d-metallo-stampa-3d-forum-6/)

Efesto:

AM is used to manufacture the critical rocket nose cone using Inconel steel in Figure 2.6.

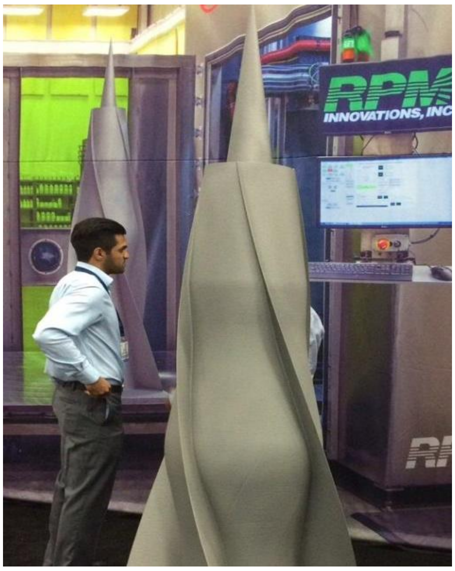


Figure 2.6: Rocket nose cone*. By courtesy of Gartner online webinar (Gartner, 2015) retrieved from https://www.gartner.com/it-glossary/additive-manufacturing*

Legacy Effects:

In Figure 2.7 below, AM was used to manufacture the Avatar character with Stratasys Connex 3.

Figure 2.7: The Avatar character created with AM technology. *By courtesy of the online webinar by Gartner, 2015). Retrieved from https://www.gartner.com/it-glossary/additive-manufacturing*

The transformation required to convert knowledge and expertise into an innovation captured in the digital environment is depicted in the value chain represented in Figure 1.7. All the elements in the value chain ensure harmonising to enhance the disruptive nature of AM technology in the supply chain (Roper et al., 2008).

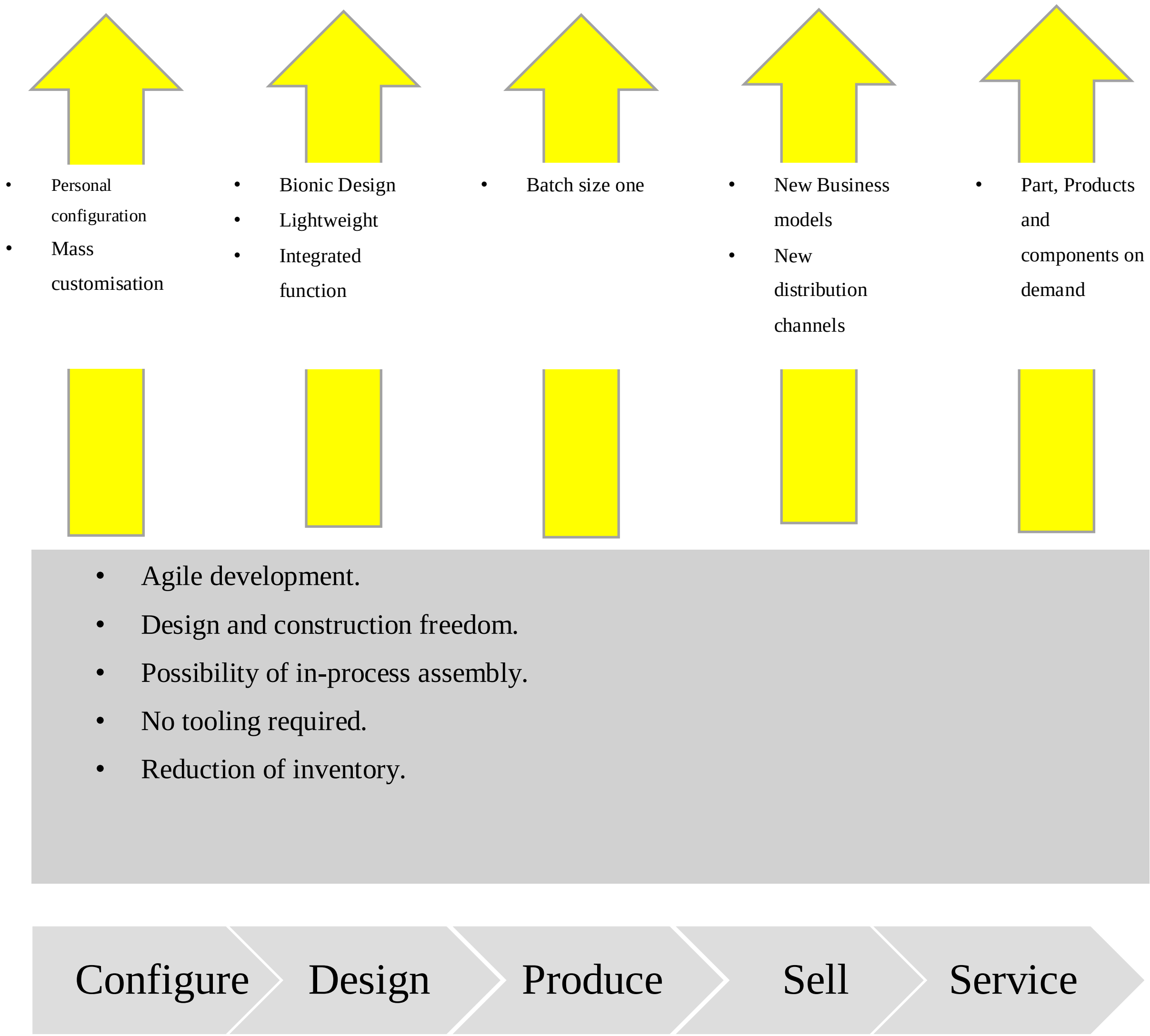


Figure 2.8: Advantages of AM as a strong driver for digitalisation along the entire value chain.

Companies like Additive Works (Table 2.2) have developed the ASAP principle, which is complimentary to the innovation design for AM and the adaptation of the technology to fit into the future supply chain. This is also the endorsement on the technological readiness level of the AM technology to be incorporated in the production process.

*Table 2.2:**ASAP principle as per EOS Conference***

> *"The ASAP-Principle for metal systems describes four ideal steps on the way to a stable, efficient and reliable process chain: Assessment, Simulation, Adaption and the Process itself. By examining all possible build-up orientations concerning economical and physical aspects of the process on the Assessment stage, both, limitations of the design and optimal orientations can be calculated. The integration of simulation-based, automatic generation of optimized support structures and fast process simulation tools into the pre-processing chain on the Simulation stage ensures geometric accuracy and increases process stability while tremendously reducing the costs of process preparation. Finally, on the Adaption stage, process parameters should be controlled concerning thermal and mechanical aspects via hatch re-orientation and parameter adaption. After going through these steps of pre-processing, on the last stage the first-time-right process itself concludes the ASAP-Principle."*
>
> *(EOS Xcellence Conference, 2018)*

The documented drawback of AM is captured in four important disadvantages (Thomas, 2016), which are depicted in the diagram in Figure 2.9. The most important disadvantage is the high cost of the material and platform.

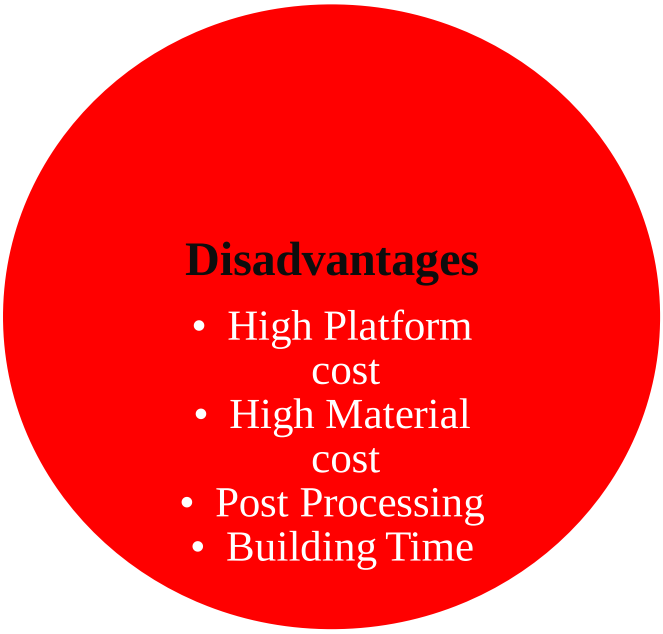


***Figure 2.9: Disadvantage of AM** (Thomas & Gilbert, 2014)*

The proper assessment of these emerging technologies brings the understanding that AM is ready for inclusion in an enterprise resource planning (ERP) system, which is the ultimate objective. The commercialisation of this technology dictates an entirely new approach to managing this system. This is indicated clearly if the abovementioned technology is studied carefully, which identifies that more companies are deciding to take this manufacturing route. If one analyses the disadvantages quoted in

Figure 2.9, the reality of the influence of AM on the entire supply chain must be considered (Hoch & Dulebohn, 2013).

The conventional way of a cost comparison does not answer the questions when analysing the cost of AM. Often the governing factor behind how a part will be manufactured provides general insight into how the cost of manufacturing (cost per piece) differs from the number of parts being produced. There is little doubt that this philosophy leads to inflated inventory, and the entire site and supply chain should be considered in analysing AM sensitivity.

It is a *fait accompli* that AM is changing the manufacturing world indefinitely. AM is disrupting industries and speeding up the way in which components, products, and systems are designed and manufactured. The international community of practice use the buzz words *"the time is now",* implying that the manufacturing industry is ready to deploy AM technology. The rapid uptake of the technology did not happen by chance. Years of research and development by universities, institutes, innovation precincts, and global and local enterprises have led to this point. Business specialists refer to an amazing global opportunity. Closer inspection shows dynamic, transformative industries speeding up activities, fuelled by the digital transformation. AM reduces the cost for many applications and offers freedom of material, design, and manufacturing platforms. To keep up with this accelerating phenomenon, the effect on the current marketplace, shifts in factory floor and other skills requirement, and the adaptation of supply chain philosophies and business models are requirements. AM specialists and equipment manufacturers bring an unparalleled new norm of material science and application expertise to the global manufacturing industry. New parts and components using AM technologies include products that were not possible in a previous era.

The company Electro Optical Systems (EOS GmbH) in Krailing, Germany, emphasises the fact that AM, including 3D printing technologies, has "been among the most heavily explored manufacturing innovations in the history of modern manufacturing" (The Additive Journey, n.d.). The layer-by-layer principle forms the heart of 3D printing or AM. The additive journey compiled by GE emphasises this development as captured from the document in Figure 2.10. Owing to the added value of the information, the entire section is quoted verbatim below in Figure 2.10

The additive journey: **The time is now**: Industry 3D hosted by GE. "*The use of 3D printing technology dates back to the 1980s for polymer applications, but the ability to print functional parts from metal alloys has spurred significant interest and investment into AM over recent years. AM experts estimate that approximately US$13 billion have been spent on 3D printers, materials, software and services over the past four years – with half of that being spent during 2017 alone. They project more than US$280 billion will be invested in additive manufacturing over the next ten years. Similarly, according to the recent 2018 Wohlers Report, "the additive manufacturing industry grew 21% from 2016 to 2017 globally, reaching $7.3B". These huge growth rates are represented in business leaders' sentiments toward additive according to the 2018 GE Global Innovation Barometer (a survey of nearly 2,100 business executives worldwide). Global executives are excited about the potential of additive; 63% say it will have a positive impact on businesses, 91% believe it will increase creativity, and 89% believe it will help deliver goods to the market faster. This will help to power the emergence of a global manufacturing movement that will disrupt how the world thinks about product development, design, production, supply chain, and lifecycle management. A combined 41% of these executives claimed AM has had an impact on their organisations; with 27% reporting "additive has become a reality that is impacting businesses," and a further 14% saying "additive has already had an impact on businesses." At the same time, the study noted that just over half of the business executives believe additive has yet to reach its full potential, requiring more education and reassurance. AM is now reshaping the product design process, entire supply chains, and the vast landscape of manufacturing. Engineers are embracing new design freedoms to create valuable product performance improvements and cost efficiencies with lighter weight, better thermal management capability, better fluid mixing, customisation, and/or the ability to make different structures and textures that yield better part integration. Many companies are investing and scaling the technology in order to reap the benefits of AM."*

Figure 2.10: GE Additive *(new division presently established).*

The manufacturing industry operates in a fast-changing world where more than $700 billion is invested in the inventory of slow-moving parts and products (EY's Global 3D Printing Report, 2016). The appropriate application of AM will empower the manufacturing industry to release this vast amount of money into product development and innovation. To achieve this, the supply chain will have to be reassessed. The design and use of end-user technology to manufacture should also be decentralised at the point where the product, part, or service is required. To change the minds of industry leaders, one will have to develop a new view on how to cost the benefits of AM from one manufacturing setup to another.

The interest of industry regarding the progress of AM is growing. The more creative the role players in this sector become, the more effective their efforts become to integrate this technology into the South African manufacturing domain. In 2016, mention of AM was made in the "next industrial revolution – INDUSTRY 4.0" (De Beer et al., 2016). In 2016, for the first time, South Africa has been seen to quantify the number of industrialists that are investigating the augmentation of existing industrial setup with one form of layer-based technology or another, such as Voxeljet technology. The truth about AM and the smooth incorporation into the general industrial ambit is that there are still significant hurdles in the way of successful commercialisation of these technologies. The Collaborative Programme for Additive Manufacturing (CPAM) and support programmes have the vision of bringing all role players in the affected industrial, research, and commercial ambits to the table, to promote this high-potential disruptive technology. How to make this technology more accessible for the industry is a problem that needs to be solved. This AM technology platform accommodates a variety of AM methodologies with varying benefits, disadvantages, and potential. Any analysis of the sector must differentiate between the kinds of technologies used and the value they can create. This thesis aims to deliberate the elements affecting the industry, with an appreciation of the diverse benefits and challenges that AM platforms present. Owing to AM technology process improvements, a functional part can be manufactured directly by means of AM. AM processes can increase productivity while enabling mass and cost reduction, and an increase in part functionality. To take full advantage of the advantages of AM, new management methods must be developed to consider the nature of these processes. In this setting, developing a costing algorithm to obtain an optimal ERP methodology for AM platforms was proposed, with consideration of both design requirements and manufacturing constraints. During the past 20 to 30 years, researchers and engineers paid most of their attention to the quality, technological, and mechanical aspects of AM. Today, these aspects of AM are linked to good performance, and it is easy to benchmark with results obtained from conventional manufacturing technologies. AM technologies are now mature with a high level of market readiness. In many industries, the smooth incorporation of AM technologies is achieved with excellent results; therefore, the focus is on elaborating on the managerial aspects of AM. Thus, the focus shifts to accurate costing and quoting systems to be incorporated with an ERP system of a future business unit. Although this approach offers exciting possibilities, limited existing work has been carried out in applying this new line of thought in comparison with technical aspects (Fera et al., 2017a).

A possible reason for the above is that these processes are relatively new, still little known in existing industries, and different from conventional manufacturing processes. Industrial resistance to change may inhibit role players in production from utilising AM in the best way to enhance their capabilities and enhance international competitiveness. This timeline lays out past, present, and a potential future for development and application (Ford & Despeisse, 2016).

Like most international industrial rejuvenation or revitalisation programmes, the South African sector is making plans to integrate AM technologies with the manufacturing end-use technology mix. The unique feature of AM technology is the layer-by-layer manufacturing method, unlike most conventional manufacturing applications such as subtractive machining or multi-part manufacturing. The real strength of this technology is realised when it is combined with advanced CAD software packages. In South Africa is a conscious drive to connect AM technology with an emerging new generation of sophisticated software packages that offer design and analytical tools to foster an entirely new approach to problem solving in the manufacturing industry. With the above-mentioned in mind, it becomes evident that although AM is viewed as an instrumental part of the next industrial revolution, there is still work to be done concerning the industrial implementation of AM technologies. There is a need for a significant shift in the existing manufacturing industry, as well as those operating in the AM environment. The author of this thesis is aware of the myriad technologies accommodated under the AM heading.

The AM capabilities at a South African University of Technology (UOT) incorporate polymer-based technologies such as laser sintering (LS), fused deposition modelling (FDM$^{\text{TM}}$) and polymer powder-based binder jetting, as well as the silica sand-based binder jetting technology. The scope of the specific programme at the UOT is to explore and manage the many advantages AM can offer the South African industry sustainably and to advance the AM technologies mentioned towards the next stage of application and development. The final objective is to develop and support local companies and communities by making industrial AM technologies available to them. In this thesis, the author aims to report on the benefits, disadvantages, and potential of the different technologies under the umbrella of an all-encompassing management and operational tool.

Qualified AM technology for final part manufacturing for the medical and aerospace markets; AM technology for impact in the traditional manufacturing sectors; New AM material and technology development; and SMME development and support programmes. (De Beer et al., 2016).

Hopkinson and Dickens (2003) refer to the research that was done by Costabile, who is among the initial researchers to understand the intricacies of the analysis required to express an opinion on AM cost. Their research indicates that it is advantageous to use AM when limited demand does not warrant the investment in moulds and dies. Furthermore, it is suggested that for complex geometries, it is more economical to use layered manufacturing (Alexander, Allen & Dutta, 1998) methods than it is to use conventional approaches for manufacturing lower volumes. Hopkinson and Dickens based their model on the following:

D	Machine depreciation per year (Euros).
E	Initial investment in Euros.
FDM	Fuse deposition modelling.
PC	Polycarbonate material.
SC	Support material cost.
H Y	Hours per year.

PM Part mass

“E: machine purchase cost (Euros).

FDM PC: model material cost for FDM (Euros/kg).

FDM PM: mass of model material per part for FDM (kg).

FDM SC: support material cost for FDM (Euros/kg).

FDM SM: mass of support material per part for FDM (kg) H Y: hours per year in operation (h)”.

This thesis focuses on laser sintering as methodology although the approach will be similar to deriving an algorithm (Levy, Schindel & Kruth, 2003).

2.2 Business Models

Gausemeier et al. (2012) are of the opinion that the disruptive aspects of AM are overemphasised, and caution is advised (Klahn, Leutenecker & Meboldt, 2015). In practice, their research has shown that this takes place only in a randomised format. The nature of the industry is in line with the traditional method. The business models of these participants are entirely predictable: Material producers produce the required materials, machine manufacturers need feedback on requirements but build ranges of machines, and material suppliers provide innovative new materials. The findings seem to be as follows:

The inflection point (Figure 2.11) is indicative of the confluence of technologies that range from a variety of digital technologies, including additive manufacturing; the internet of things (IOT); advanced robotics; to new materials and processes of data-driven production. At the inflection point, the conversion to the current industrial revolution was ignited, and the key to all of this is AM (Gartner, 2016).

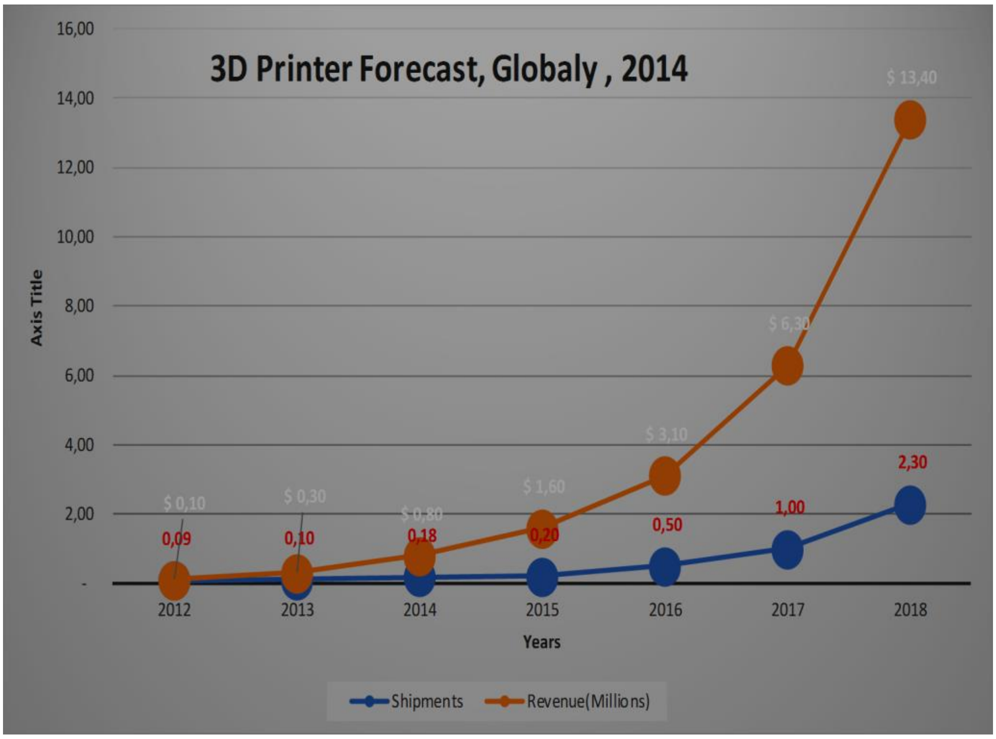


Figure 2.11: ***3D printer market inflection point*** *(Gartner, 2016).*

In the 2018 Wohlers Report (Wohlers, 2018), Wohlers Associates, Inc. predicted that an estimated 14 736 platforms were sold (only platforms > $5000 were considered). Consequently, the forecasted figures predicted by Gartner are below the factual figures as referenced from the 2018 Wohlers Report.

2.2.1 Use of established business model patterns

A specific feature that has emerged in the AM industry, compared to conventional manufacturing, is that machine manufacturers have added materials and process parameters to the products that they market. Many suppliers use the consultants of the operators of the consumer goods industry.

The business model is based on controlling the materials and machine-setting parameters. This seems to be a lucrative business model – for example, the razor blade model (Gillette blades that fit only in Gillette razors.). New aspects are that specialised materials, parameters, and design services are now part of the machine builder's standard offering. This can motivate the emerging success factors (Gausemeier, Jürgen & Schmidt, 2017). These success factors are explained next.

2.2.2 Success factors

The literature research identified the following nine critical success factors important for consideration (Gausemeier, Jürgen & Schmidt, 2012):

- The availability of durable machinery with uniform reproducible output.
- Technology needs to fit seamlessly into existing production systems with acceptable productivity and comply with the automation of the process chain.

- Availability of specialised materials.
- Identification and tested design and engineering guidelines.
- International norms and standards.
- Machine productivity.
- Norms and standards.
- Qualified personnel.
- Data security.

Other important aspects are the following(Gausemeier, Jürgen & Schmidt, 2017):

- Integration into existing manufacturing processes.
- The existence of a research road map.
- Enablers of AM implementation (research institutes, etc.).
- Engineering/design guidelines for automation of the process chain.
- The position regarding basic research.
- Legal clarity regarding product liability.

Balanced success factors imply factors where there is a balance between their importance and the current position of the industry. The five factors in this category are the following:

1. The existence of a research road map.
2. Legal clarity regarding product liability.
3. Data security.
4. The existence of enablers for implementing AM.
5. The position of the RSA in basic research and the support and endeavours of the current government to integrate this aspect with the first four points.

Factors such as legal clarity regarding product liability and data security in digital process chains will become more critical to success once manufacturing technologies become faster and more reliable, and once AM becomes more widespread in industrial applications and the range of additive manufactured products increases (Kearny, 2018).

Basic research is one of the main strengths of the RSA, and action should be taken to ensure that this continues to be the case in the future. At present, there are also enough enablers of AM, primarily service providers, research institutes, and business consultants, with expertise in this field. "Studies on additive manufacturing and its impact on business models are thus scarce, and there is a need to further explore the area and its many different aspects. Specifically, more empirical work is needed, moving knowledge away from scenarios and into how 3D printing in fact affects current businesses on the company level" (Öberg, Shams & Asnafi, 2018, pp. 15-33)

Owing to advancing digitalisation, production is merging increasingly with the IT world. Production is taking form at a more rapid pace, and customers' requests are becoming more distinct (mass customisation). This development requires intelligent factories with digitally networked systems in which people, IT systems, automation components, and machinery communicate with one another. The goal is to produce customised products fast, flexibly, and cost efficiently. AM platforms, plants, and machinery must be able to adapt to rapidly changing requirements.

The new reality of the INDUSTRY 4.0 is the requirement of real-time feedback, and the localisation of production. To develop a costing tool that can integrate the entire factory value chain seems to be the necessary tool to ensure fast decision-making and response times. INDUSTRY 4.0 faces a volatile, fast-moving, customer-driven market.

2.2.3 Costing tool recognising: Optimisation to reinvention – possible AM benefits

In the costing analysis, one of the key aspects that need consideration is that AM can add considerable value when developing new products. EY's Global Survey identified three principles by which AM can benefit from product innovation:

<u>Quality and value added</u>: It can manufacture products with fewer parts to assemble and lower the risk of failure.

<u>Customisation</u>: AM is key in a market where personalised products are in demand.

<u>Complexity</u>: The AM process allows for complex structures and unique geometries, implying that new products that were not economical with other systems can be developed (EY's Global 3D Printing Report, 2016).

2.2.4 Costing tool recognising: Mass customisation

The combination of costing tool recognising and mass customisation is a cross-industry reality. This trend is driving customer demand for personalised products. The supply chain has adapted to enable the cost-effective delivery of diverse products.

In the past, the major cost drivers for bespoke products were expensive tooling, inefficient production lines, many tool changes, and methods of fast delivery. AM requires firstly no tooling and facilitates low volume production and with the major advantage of in-process assembly, or can be used to produce hybrid tooling where AM inserts are fitted into pre-machined bolsters. AM is ideal for producing any order of different products, in line with customers' needs. Manufacturers can now involve customers in developing personalised products. Many of these markets, for instance markets involving hearing aids, orthotics for footwear, specialist wear for athletes, and medical and orthodontic applications are not cost sensitive.

2.2.5 Costing tool recognising: Creating high-quality, more complex, products

How does one consider costing when AM enables an industrial product that was technically impossible before? A few examples of disruptive technology enabled through AM, which do not fit current costing structures or project planning strategies, are the following:

- AM technology has created the possibility to manufacture internal structures and external product geometries unique to the technology. An example is “conformal cooling” for injection moulding tools. It is impossible to machine mould-cooling channels that provide an optimum solution, such as a cooling channel that follows the geometry of the cavity, spaced evenly throughout the mould.
- Freedom of design (or design for AM) allows products where assembly of parts are avoided. A multi-part component can form part of an integrated design, and multiple parts can be manufactured as a single unit. Combining the production and assembly phases into one single operation can save cost and time and prevent costly mistakes. This is a further consideration in the costing model of operation. Engineers can apply the freedom of design that enables the design of more lightweight structures so designed that they can also be adjusted to prerequisites of specific needs. In this case, the multiplier effect warrants the cost for lower material requirements, lighter aerospace equipment, and fuel savings.

2.2.6 Costing tool recognising: Market

The historic question of “What can be manufactured?” now changes to “What is required, what should the product perform, and what does the customer want?” From an engineering perspective, it becomes “What would the optimal functioning DFAM look like?” The agility offered by AM is what the customers expect. The industry standard is the hearing aid industry that converted to 100% AM within fewer than 500 days (Steenhuis & Pretorius, 2015). In South Africa, the technology has advanced beyond prototyping, and production of end-use components is a reality. The market and the cost factor of end-use technology will determine the utilisation of AM. It is also clear from the literature that point-of-use aspects will play a major role in future decision-making processes (EY’s Global 3D Printing Report, 2016). From the literature research, it is clear that the world’s resources and the circular economy will dictate market demands. Concerning the technologies, most of the platforms or AM is on a high market and technology readiness level. Thus, the utilisation of this technology depends on the willingness of the manufacturing paternity to adapt current practices to include AM technology. When one interrogates early adopters of the technology, it is clear that they are satisfied with the outcome of the platforms incorporated in the production facility.

Table 2.3 contains a testimony of how the incorporation of AM in the production setup has changed in the manufacturing world; a setup that tick all the boxes, of time, cost, and quality aspects of assembly. This was a watershed decision at the company.

Table 2.3: ***Testimony of how AM has changed the manufacturing world*** *(Retrieved from https://www.geglobalresearch.com/blog/3d-printing-creates-new-parts-aircraft-engines)*

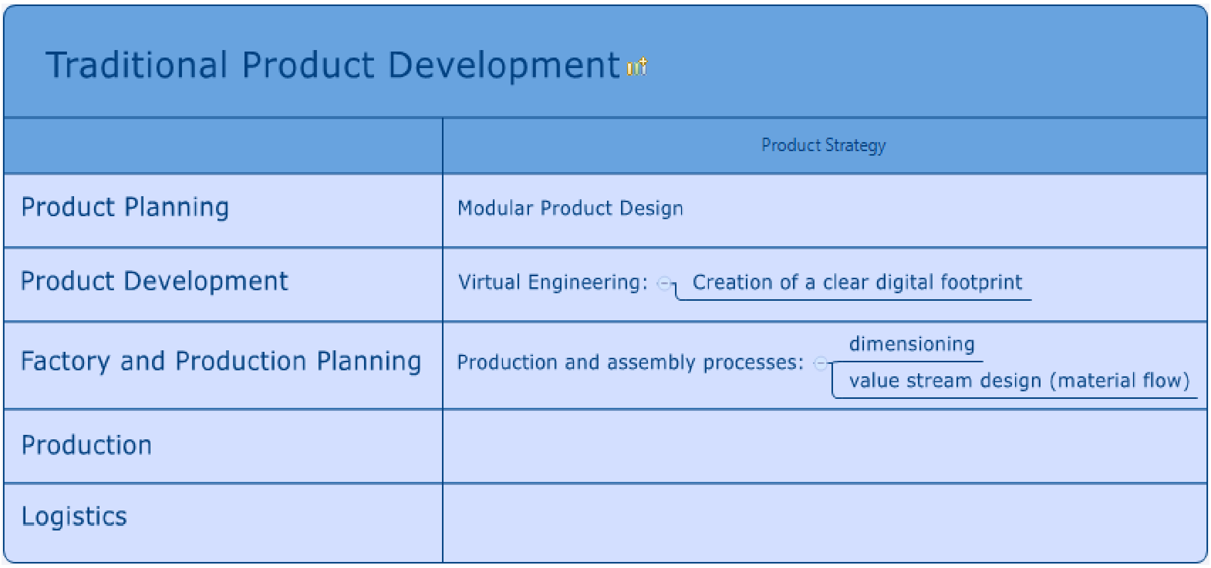
> *"In 2016, GE Aviation will introduce the first 3D-printed parts in an aircraft engine platform. Each of the new CFM LEAP engines, produced jointly by GE and its long-time partner, Snecma (SAFRAN) of France, will have 19 3D-printed fuel nozzles in the combustion system that could not be made any other way. The benefits of printing these parts are numerous.*
>
> *Lighter in weight – the weight of these nozzles will be 25% lighter than its predecessor part.*
>
> *Simpler design – the number of parts used to make the nozzle will be reduced from 18 to 1.*
>
> *New design features – more intricate cooling pathways and support ligaments will result in 5X higher durability vs. conventional manufacturing.*
>
> *These benefits all will lead to higher performance from our engines. With several thousand orders for the new CFM LEAP, GE Aviation will produce more than 100,000 3D-printed parts by the close of this decade. Today, GE is the world's largest user of additive technologies in metals.*
>
> *The production of 3D-printed parts in GE aircraft engines signals a paradigm shift that is happening with the emergence of additive manufacturing. Additive not only offers the opportunity to design parts never before possible; Scientists in GE's Additive Manufacturing Lab also see new possibilities for designing entirely new materials.*
>
> *New advances in laser technology and 3D-printing machines are allowing scientists to experiment with new material configurations by mixing and combining metal powders in more innovative ways".*

If one observes the quoted information disseminated by GE, the question is how many other components have the same challenges and complexities that can be solved by AM processes. The reality is that manufacturers need to deal with the fact that similar platforms can manufacture products with zero defects in future. If zero-defect manufacturing can be supported with the reality of freedom of material, freedom of platform, and freedom of design, it redefines the term "disruptive technology".

2.3 Purpose of the Study

It is paramount to develop accurate costing to ensure accurate quotations, job cards, and invoices. Like in any conventional manufacturing business, the integration and introduction of an information system such as an ERP system in an organisation imply change in how sales engineers work. It is logical that the ERP system will bring together the different operative divisions of a business. The different streams of research on ERP systems have focussed mainly on ERP adoption, success measurement, and critical success factors (CSFs). At present, there seems to be a shortage of research on user participation and the contribution of users towards the successful implementation of ERP systems. The objective of this thesis is to focus on the elements that incorporate the decision making with reference to the costing/pricing aspect of laser sintering.

If one negates the effect of design of external factors on additive manufacturing, skill requirements for complex design, customer expectations, and affordability issues, one can accomplish the all-encompassing solution only with complete digitalisation. Figure 2.11 below shows what could be termed the traditional steps for product development.



Traditional Product Development

	Product Strategy
Product Planning	Modular Product Design
Product Development	Virtual Engineering: Creation of a clear digital footprint
Factory and Production Planning	Production and assembly processes: dimensioning value stream design (material flow)
Production	
Logistics	

Figure 2.11: The traditional steps of product development.

To create the data capturing, manipulations, calculation and validation for the design follow this up with the implementation of a costing algorithm incorporated within the enterprise resource management, control, and planning system. Develop the plan to target AM production management specifically, integrated with the quality management system and other management and accounting systems. This scope explicitly excludes the development or integration of the algorithm into a script for online purposes.

Characteristics of the algorithm to fulfil the short- and long-term goals of the enterprise are the following:

Incorporate a unique data architecture to manage all customer orders, parts, and build platforms seamlessly.

It is a highly interactive and intuitive tool for AM planning, suited for full integration, automation, and control of AM machines

The following is envisaged for the future:

A fully interactable AM suite, with central data storage, and integration of an application programming interface (API) with IT systems. The envisaged future enterprise resource planning for the AM suite will encompass consolidation of planning, manufacturing, readiness for sales, and marketing efforts into one management system, and combine all databases across departments in a single accessible database. All tasks should be automated to perform an AM business process.

Wong and Hernandez (2012) say the following:

> "additive manufacturing processes use the information from a Solid Model computer-aided design (CAD) file, converted it to a format called stereolithography (STL) file. In the STL process, the CAD file is approximated by triangles and sliced containing the information of each layer that is going to be AM. The relevant additive manufacturing processes/platforms and their applications need to be considered. The technology application has unique relevance in the aerospace industry where it is used increasingly, because of the possibility of manufacturing lighter structures to reduce weight. Additive manufacturing is transforming the practice of medicine and making work easier for architects. In 2004, the Society of Manufacturing Engineers did a classification of the various technologies and there are at least four additional significant technologies in Figure 1.12 below."

The delineation of the thesis research and objectives considered the costing activities in the AM enterprise. If one analyses the information in Figure 1.12 below, it becomes clear that engineers and scientists have investigated and analysed AM technologies over the years, with the resultant reality that this technology can yield products and components successfully in a range of materials. However, few considered the economic aspects of AM. This reference is not made with the existing costing models in mind but consider the full supply chain benefits that are possible. The elements reflected in Figure 1.12 pertaining to an AM enterprise indicate only some of what needs to be considered in the overall economics of AM.

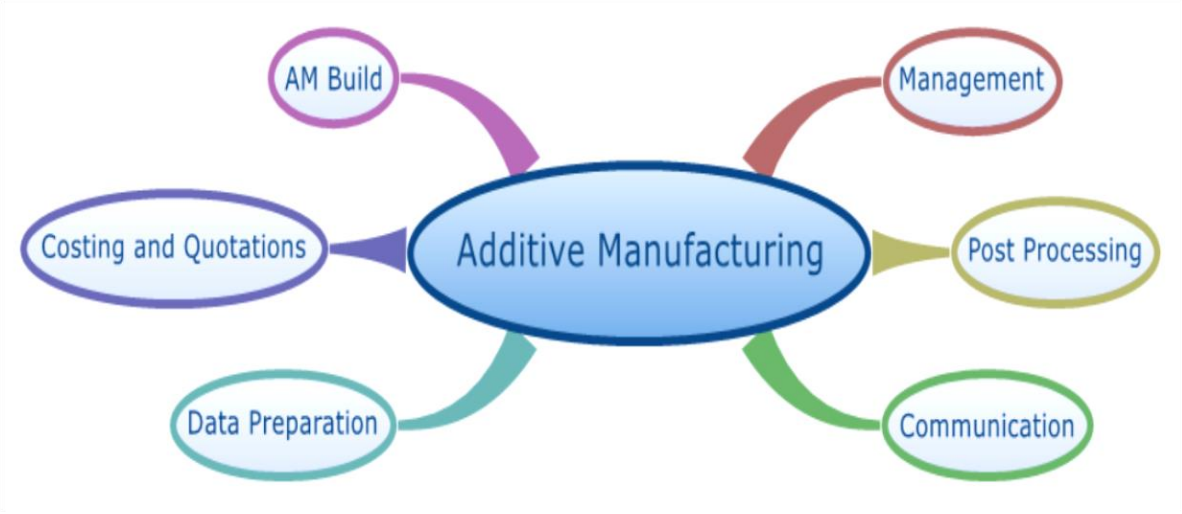


Figure 2.12: Elements of an AM enterprise.

2.4 Conclusion

The thesis was developed to create a tool for engineers to master the key costing aspects of AM when it comes to developing a holistic costing model approach. It aims to:

- understand the costing mechanisms behind AM;
- endeavour incorporating and understanding the benefits and limitations of each model;
- create a decision-making tool integrated into the ERP system;
- provide right actionable costing advice and guidelines; and
- embrace the INDUSTRY 4.0 objective.

3. METHODOLOGY AND ANALYSES

Internationally, INDUSTRY 4.0 forms part of the development programme of companies operating within the advanced manufacturing ambit. Unfortunately, many South African industry leaders still have not come to terms with the challenges and opportunities of digital transformation or with the conceptual leap it represents. Only now, the South African science and technology community is emphasising the importance of implementing the technology governing the trends in automation and data exchange. The challenge in the AM ambit is to offer the customer the freedom of enquiry, to receive a reliable quotation, and subsequently, to place an order for products and services in the digital realm. In the AM world, the technological opportunities are not in question, but to understand the underlying cost drivers, they need to be investigated. A fundamental understanding of the economics underpins the application of this technology, which is a fundamental precursor to converting the interface for this application to utilise the advantages of the digital aspects encapsulated in all facets of INDUSTRY 4.0. This thesis focuses on information obtained from the AM body of knowledge and from an empirical research project aiming to develop a holistic understanding of the underlying economics of AM. The result could be an algorithm that assists in capturing all the cost drivers, enabling the end user to present a full cost model for laser sintering AM technology (Baumers, Holweg & Rowley, 2016).

3D printing has grown beyond expectations in the past number of years. The rapid growth has led to new challenges in managing the technology sustainably. AM, commonly referred to as 3D printing, has evolved into an accepted manufacturing technology. The current understanding in consultation with AM specialists is that this advanced manufacturing process has two distinct advantages over conventional manufacturing techniques. First, it avoids many of the tooling-related constraints on the geometries limiting conventional manufacturing processes. Second, AM allows the efficient creation of products in small quantities, down to a single unit, enabling the manufacture of customised or highly differentiated products. The ability is a typical AM versus conventional manufacturing consideration, and the design flexibility needs further consideration.

The new understanding is that AM must not be regarded as a manufacturing process in isolation, but rather as part of the advanced manufacturing and mass manufacturing processes. The major driver for this research was to create the tools to link industrial AM to the INDUSTRY 4.0 principles, and then encourage users to review, redesign, and optimise existing designs to take full advantage of the benefits that AM can offer. The economics of AM are linked fundamentally to the distinct advantages it offers when it comes to design freedom (Baumers, Holweg & Rowley, 2016).

The cost of a model is only one aspect of the decision-making process. This new way of thinking brings several economic factors into play – the structural design and geometry optimisation aspects, and the full advantage of optimising topology – which negate the non-stressed areas within specific geometry. The advantages are all possible by collecting pre-defined information and design criteria from the end user. In the past, analysis of the economics of AM in principle focussed on the capital investment and material cost; in this research, all the calculations are referenced to the Model: EOS Formiga P 100 machine (see Table 3.1).

Table 3.1: Model EOS Formiga P 100 information

Model: EOS Formiga P 100 Selective laser sintering machine	Notes: Machine build size: W240 x D190 x H300 mm 3D print model shrinks. Tolerance is 0.1-0.2 mm. Min thickness 0.6 (x-y), 0.1 (z). Printing on an X-Y plane makes for higher strength output.
System manufacturer	EOS GmbH
Process type	Laser sintering
Energy deposition	CO_2 laser, 30W
Usable build volume size (X / Y / Z)	W240 x D190 x H300 mm
Process atmosphere	N_2
N_2 source	N_2 generator, internal power supply
Heater type	IR and resistance
Melting temperature	~173 ºC
Build material	PA2200, polyamide 12-type thermoplastic
Used layer thickness	100 µm
Support structures	Not required

Linking the AM technology to a conventional ERP system requires a more traditional approach. The principle used was to analyse the body of knowledge at the VUT for the laser sintering of products.

For an ERP system to work properly, a series of builds were identified to determine the actual cost; these data form part of the thesis. Three of the builds were at maximum build height, around a 282 mm useful capacity. The Materialise Magics™ software was used to prepare the builds (Su & Yang, 2010).

The objective of the costing model is to analyse the entire process, beginning with the receipt of the customer's specification, 3D model, or EBOM (engineering bill of materials), including the AM selective sintering process on the EOS platform EOSINT P100 (Table 3.1, and ending with the delivery to the customer (despatch). Analysing the activities ultimately led to the identification and understanding of the complete list of cost drivers. Information captured in the financial system and from the quoting and technical departments was used to determine the effect of each cost driver on the product cost. Based on this, an adaptive costing model was developed. The research grouped cost elements into material, electricity, machine, and labour cost. the analysis of these groups is discussed in the rest of the thesis. In any AM analysis, the following always needs consideration:

AM technologies offer significant scope to develop unique products that were previously impossible or difficult to manufacture.

AM technologies offer an elegant solution to mass customisation in several industries.

Making AM part of a sustainable endeavour requires an accurate and predictable understanding of the economics involved. (Su & Yang, 2010)

The aim was to use the body of knowledge in the AM Department at the VUT to develop a holistic, all-encompassing, predictive cost model for the selective laser sintering AM process. The control would be to test the costing algorithm empirically with a series of results.

3.1 Literature Review and Relevant Research Work

In the recent past, there was rapid development in the AM field. Table 3.2 gives a summary of developed cost models, which, according to the findings in the literature review, were developed independently for the different platforms.

Table 3.2: Existing cost models *(Costabile et al., 2017).*

No.	Model Development	AM Platforms	Cost Breakdown	Short - comings	Overhead Cost
1	Model by Hopkins and Dickens	SLA; FDM; SLS	Machine; Personnel; Material.	Negate recycling and finishing	Not accounted for in this model.
2	Model by Ruffo, Tuck and Hague	SLS	The identified cost-related activities are the material, software, hardware, personnel expenses, equipment purchase and maintenance, as well as production and management.	The machine, production costs, material costs, and labour costs.	
3	Gibson, Rosen and Stucker	Not restricted to any single platform. All kinds of processes that build products in single layer can be modelled.	Designed the calculation of material cost applicable for several AM processes.		

The information obtained from the literature review identifies some definite cost elements in the AM process, and it seems that the cost element has a considerable variation in contribution to the total cost.

The 2018 report (Wohlers, 2018) indicates that 20% of AM technology is used in the sector industrial/business machines, and equipment such as CNC machines and robots are included in this category. The aerospace sector grew by 1.2%, and the consumer/electronics have been the leading factor for much of the past 10 years.

The consumer products and electronic categories include a broad range of products, including mobile phones, home electronics, kitchen appliances, hand tools, and toys. These manufacturers typically produce parts in large volumes, and the life cycles of products are relatively short. AM accelerates product development by enabling rapid design integration and optimisation for companies in these markets. The aforementioned is definitely a category that needs serious consideration when it comes to determining the cost of AM supporting the relatively synoptic life cycle of these products.

It is extremely difficult to incorporate the above-mentioned advantages in the current costing structure of a manufacturing company that is considering AM. The next part of the document provides a synoptic overview of the current costing model, which is applied widely in the AM community. Using a process-based approach, all job-related activities are collected and expressed in monetary terms. From the different models, all the elements concerning the layer-by-layer laser sintering need consideration.

Table 3.3: SLS cost model for the evaluation of cost structures (Baumers et al., 2016; Fera et al., 2017).

- Integration of recycling and the use of waste material.
- Calculation of the manufacturing time.
- Maximum possible number of products that can be printed simultaneously in the building space.
- Specific manufacturing requirements of the product.
- Duration of the post-processing.
- Integration of modern quality management methods for the protection and monitoring of product and process quality.

In Chapter 4, this approach is negated as not successful to determine the full advantage of AM in any industry.

3.1.1 Costing model

Any conventional costing model will be regulated by a conventional industrial engineering process, which normally considers a bill of materials (BOM) that is linked to a master file for each product. The master file is normally incorporated in the ERP system and linked to the cost of components and materials. In practice, this whole process is initiated in the design office with the so-called EBOM. Normally, the empirical determination of the BOM is a process that occurs once the first products are assessed properly on the production line.

The objective of the costing model is to analyse the whole process, starting from receiving the customer's specification (3D model or EBOM), including the AM sintering process on the EOS platform EOSINT P100, until the delivery to the customer. Ultimately, the envisaged approach led to the identification and understanding of the complete, activity-based cost drivers. Information captured in the financial system, the quoting, and the technical departments was used to develop an empirical costing model. The objective with all this information was to divide the cost into four groups: material, electricity, machine, and labour cost. The interrogation of the suggested analysis of these groups is executed in what follows in the costing model (Baumers, Holweg & Rowley, 2016; Fera et al., 2017).

3.1.2 Comparison of costing models

Table 3.4: Cost of material and activities (2017 figures)

	Elements in manufacturing process	**Description**	**Cost indicator**
1	Material cost	The full cost of feedstock.	1370 R/kg*
2	Machine cost	Real machine usage extrapolated to a 5-year period (See Appendix A).	85 R/h
3	Labour cost	A process of allocating real labour cost to the sequence of activities.	80 R/h
4	Electrical cost	(2 hours * 3.55 kW + net running time * 2.6 kW) * 0.83 ZAR/kWh.	0.83 R/kWh

** Calculated by DA Mauchline as the delivered cost at Sebokeng AM Precinct.*

The literature research makes mention of all the different AM platforms and pays attention to the range of activities involved, as well as the unique aspects of the various technologies (Fera et al., 2017). The obvious shortcoming of all approaches is that there are no specific recommendations for actions about the different models to support further development.

4. OBJECTIVE 1: Empirical verification of existing algorithm

The invincible presence of connectivity coupled with technologies like robotics, artificial intelligence, and AM led to the fourth industrial revolution. Presently, most industries are going through change, but none as traumatic as the $12 trillion international manufacturing sector (Kearney, 2018). Analysis of the Wohlers Report 2018 (Wohlers, 2018) makes it clear that additive manufacturing advanced more in the last year more than in the previous 20 years combined; innovation in this field is growing exponentially.

One recognises the difficulty to express an opinion about what is required with reference to AM costing aspects, while considering the objective to take the AM industry to the next level of integration in current and future manufacturing industries, since it is clear that conventional comparisons of existing parts and components with the optimised components that make AM competitive are not enough. The answer is probably in reinventing the supply chain and answering the questions from this angle.

4.1.1 Product compatibility

Components need to perform at a higher level and advance beyond traditional or conventional solutions.

4.1.2 Material price

It was critical in this investigation to understand the importance to reduce the cost of advanced AM materials.

4.1.3 Selection of material

for participants in AM, proper selection of materials is the basis of successful manufacturing. Companies like EOS is offering a range of 50 materials, which supports the quotation freedom of materials.

4.1.4 Design for additive manufacturing (DFAM)

Conventional part, product, or assembly design methods based on technology that is currently in use in the manufacturing industry will no longer suffice and should not be copied without a proper redesign.

4.1.5 Supply chain considerations

The shipment of tangible goods will and needs to be replaced by the transfer of digital designs and raw material. Shortening and localisation of the supply chain will ensure manufacturing closer to the end user.

4.1.6 Standard and policies

Specialists in the industry need to re-evaluate existing policies and procedures. The manufacturing industry needs to establish a set of regulations and standards to help guarantee AM materials and processes are reliable and safe.

To complete objectives 1 to 3 for this thesis successfully, various aspects needed qualification.

The existing algorithm was used to calculate the quotation for the Easter Egg Wrapper:

Step 1: Is the Geometry available in the parametric format, for conversion to STL format?

- If yes: No cost.
- If no: Hourly cost at the predetermined rate of R300/h.

Step 2: Quantity – Follow the stacking process to determine the number of builds (select the machine ideally suited for the project).

Step 3: Select the specified material and enter the height of the build into the algorithm.

4.2 Methodologies

In Objective 1 (Table 4.2), the methodology was to compare the results of the existing costing algorithm with the results from data obtained empirically. The goal here was to validate the existing process and standard operating procedure used in operations.

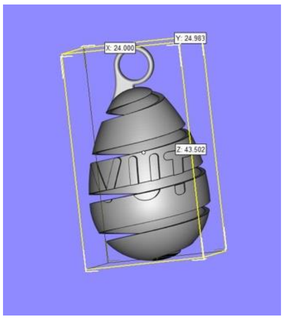
In Objective 2 (Tables 5.1 and 5.2), the activity-based costing model to obtain full cost was applied, and calculations were based on the model developed in the so-called unit cost model (Baumers et al., 2016).

In Objective 3 (Table 6.2), the reasoning in this calculation methodology was simple. The cost of a full build is the same for any product configuration. The average build density of 9% is applied to all calculations. The concept of build density is illustrated in Figure 5.1. For all practical purposes, the cost for the collective (total build volume) is the same for all full builds. This reasoning is applied, and cost of the individual component is calculated easily based on the fraction of the component of the collective;

hence, the cost is directly proportionate to the volume. The standard operating procedure in Figure 4.1 is applied in all objectives.

Recieve an email from client

- Client will send file in either STL, STEP or X.T format with the preferred quantity of the part



Open file in Magics™ Software

- Load the file into Magics™
- Choose the type of machine (P100, P110, P395. or P760)
- Fix the file and duplicate if necessary
- Nest the parts

Open costing spreadsheet

- Enter the following details into the spreadsheet: number of parts, part name, machine name, material name, height of build
- Cost of build depends on the height of build in SLS and height and volume in Binder Jetting

Send client a cost estimate

- Send the client a cost estimate with the different time leads (7 and 14 day lead time)
- Cient will send a signed copy of the cost estimate upon approval

Start a build

- Ensure that the machine is cleaned and prepared
- Prepare a build in Magics™
- (Assume that we are printing with the P100)

Open PSW for P100

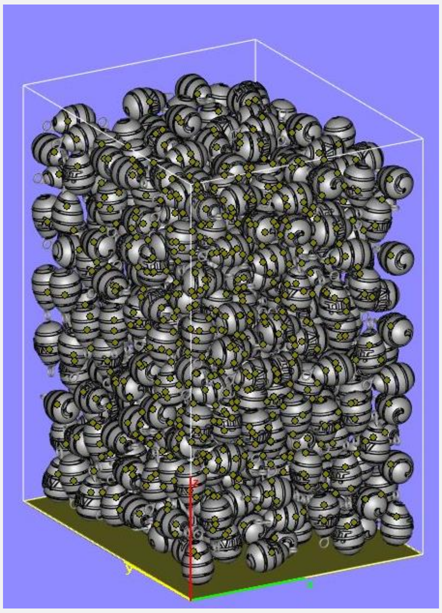
- Slice all the parts to be printed
- Load the sliced parts into PSW
- Ceck that the exposure parameters are correct
- Save the build in .jz format

Send build to machine via wifi

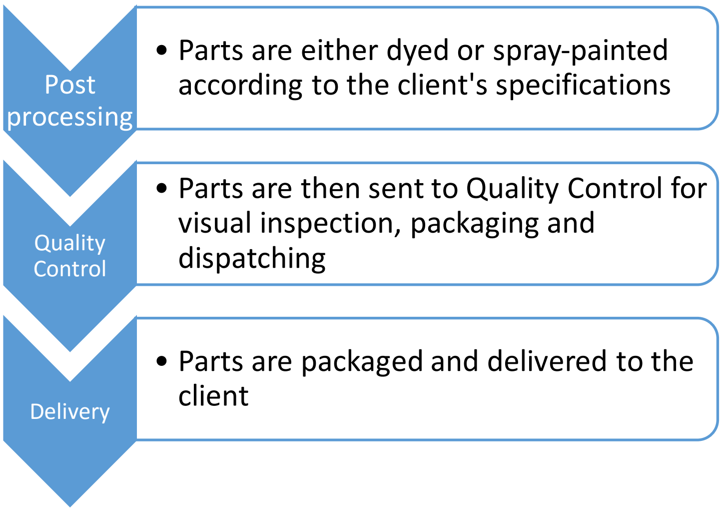
- Export the build to the machine
- Once the exportng is complete, press PLAYon the P100 machine

Post printing

- Once printing is done, record the build time
- Allow the machine to cool for two hours
- Take the build box out from the machine, place it in the unpacking station, and remove excess powder
- Clean the parts using compressed air in the blasting cabinet



Example of nesting in Magics



- Parts are either dyed or spray-painted according to the client's specifications
- Parts are then sent to Quality Control for visual inspection, packaging and dispatching
- Parts are packaged and delivered to the client

Figure 4.1: Standard operating procedure from BOK.

4.3 Results

The results are portrayed conclusively in Tables 4.2, 5.2 and 6.2. The deviation in final price is insignificant.

Table 4.1: Build properties: 400 Easter eggs.

Item/Aspect	Specifications
File name	20180315 P100 Internal PR
Machine	P100
Material	PA2200
Build time	33:31:00
Number of parts	401
Build height	282
Nesting density	4,39%
Layer thickness	0.10 mm
Post processing	Bead blasting
Total volume	580376,82

* Information in Table 4.1 was generated by the AM software.

*(**Materialise Magics™** is a versatile data-preparation and STL-editing software for AM that allows the technician to convert files to STL, repair errors, edit the design, and prepare the build platform).*

Figure 4.2: Selective laser sintering (SLS) and 3D printing at Materialise (https://www.materialise.com/en/manufacturing/3d-printing-technology/laser-sintering)

The Additive Manufacturing Department has developed a comprehensive costing process for the SLS process that is called a standard operating procedure (SOP). Dr PJM van Tonder has introduced this process flow for the department to depict the activities graphically. The methodology illustrated in Figure 4.2 was applied directly in the reasoning in Objectives 1 to 3.

It is also essential to understand that all the data used in the calculations were based on the information obtained from the body of knowledge in the AM Department accumulated over the last five years.

Part (File (s), STL; Parasolid, Step Print Information (Platform, Scaling, Post Processing)	Job report, cost estimate, AM master sheet				Job report, cost estimate, AM master sheet	Cost estimate acceptance or rejection document
Request for Quotation	Convert to STL	File quality and fixing	Part(s) scaling (process application)	Nesting of parts with Magics™ and save file	Create a Cost Estimate	Cost Estimate
Part + Build Information					Reject	Accept
					Terminate process	Generate quotation
						Trigger Production

***Figure 4.3: Standard operating procedure for a powder bed costing operation from BOK diagram designed by Dr PJM van Tonder*.**

Table 4.2: Objective 1 – Verification table.

#	Algorithm	Existing Costing (Table 4.3)	Empirical Verification (Table 4.8)see Addendum 2
1	Total height: build height + 11 mm base and 5 mm top layer Total height = build height + 16	282 mm + 16 mm	282 mm + 16 mm
2	Material specific cost = (feedstock cost/1000)/2*1.15 (R/g) (incl. VAT)	R2005/kg	R1 368,23/kg* (*Table 3.4*)
3	Volume = area x total height	61909 mm^2 x (282+16) mm	
4	Material cost = volume x density x material-specific cost x loss factor	18 448 882 mm^3 x 0.00045 x 1.152875=9571.16 x 1.2= R11 485-39	Component mass kg *(derived from Table 4.8)* Feedstock)* Material Cost R/kg *(0,0066kg*R1368,23/kg) =R9,079*
	Build time = build height/14 (BOK) 282 mm/14 mm/h	20,1429 h	
5	Machine cost = Build time x hourly rate	20,142 h x 300 (Table 4.3) R 6042,85	R6042,85**
6	Total cost incl. VAT = (machine cost + material cost) x mark-up	R18 930,51	R15 129,83 (60% margin) R15 328,83 (include R199 labour per build) Table 4.3
7	4 x Builds with Labour cost included.		R61 315,29 (R15 328,83 x 4 builds)
	Unit price	R41,15 ………………(A)	R40,88***………………..(B)(line 7 dived by 1500 Table 4.8 total qty)
	Unit price		
	VAT incl.	R47,32	R47,01

Unit Price=(((Material Cost +Machine Cost)/(1-0,60) + Labour cost) * 4)/Total Units

Please consult Addendum 2

* *Delivered cost.*

** *Amount for four builds (1500 products).*

*** *Nett sales price/price with labour.*

Table 4.3: Summary of cost drivers (AM BOK)

Cost	Existing Algorithm (Rand)
Powder cost	2005/2
Machine cost/h	*300*
Energy cost	*14.40*
Labour cost	*199.06 per build*
Operating cost	1,007.74
Total cost	2,375.97

The information contained in this thesis is part of a verification process analysing laser sintering information over a period of 4 years. Over this period, a costing algorithm was developed and refined. In the past 18 months, this algorithm was analysed and refined. Verification of cost drivers includes analysis of material (bulk density of the material and sintered components), labour, machine investment cost, and utilisation. The component geometry and preferred orientation determine quantity products (product density) per build (logically dependent on the job box volume, as is shown in Table 3.3). In the document, the relevant methodology regarding the mentioned cost drivers is referenced with the required detail. The algorithm can incorporate aspects like heating time, cooling time, and scanning time. In this analysis, the following rule of thumb was applied: On average, the P100 can build at a speed of 14 mm per hour. Source documentation formed the core of all other cost aspects.

The cost per part is disappointingly expensive, even when all the mitigating factors are being considered, which emphasises the importance of an accurate and trustworthy costing algorithm. Literature quoting experts predicts that the cost of future parts, in comparison with the cost today, will drop as much as 90%. The implication of this is based on the fact that the machine rate cost will improve meaningfully, and notable improvement in material prices will support this. All of this is augmented by faster production and better quality. Considering this information with advanced knowledge in the field of design for AM, more and more components become candidates for this form of manufacturing (Baumers, Holweg & Rowley, 2016).

4.4 Interpretation of Results

Product density, maximum product per layer, and maximum products per build equate to cost savings. If full builds are not possible when the customer demands small quantities, operators need to combine different jobs to improve product density and fully utilise work volume (Fera et al., 2017) (Baumers, Holweg & Rowley, 2016). Besides investment cost, load factor, and component geometry, orientation and product density are the main considerations regarding sensitivity aspects of the costing algorithm. Also, the post-processing cost that cannot be optimised need to be considered. Big components do not offer economies of scale that exist for small components. The existing algorithm employed by the AM Department is inherently cumbersome and potentially is not functioning as intended. The full cost model of the AM unit dictates that a high gross margin be sustainable, as evident from the variance between the algorithm and empirical verification.

Equation 2: The deviation calculation.

$S = \left(\frac{A-B}{A}\right)$ x 100 *(A and B from Table 4.2: Objective 1 – Verification table.)*

$$S = \left(\frac{41.15-40.88}{41.15}\right) \text{ x } 100$$

$$S = 1\%$$

The algorithm was also compared with the scripts available to generate quotations (see Tables 1.3 to 3.4 for information).

Table 4.4: Quotations for 999 Easter egg holders

Outfit	**Quotation QTY**	**Quotation in ZAR**	**Unit Price (R)**
TIRG's Hub	999 Easter egg holders	R424 449	N/A
3Dream's Hub	999 Easter egg holders	R27 496	N/A
My3DParts Hub	999 Easter egg holders	R178 555	N/A
Ara's Hub	999 Easter egg holders	R150 387	N/A
Materialise	999 Easter egg holders	R61538	R61.54
Shapeways	999 Easter egg holders	R61 827	R61.83
VUT AMP	999 Easter egg holders	R51 256	R51.83

Figure 4.3: Easter egg wrappers (Photo by courtesy of J. Bressler VUT quality system photos)).

4.4.1 Process-based cost

4.4.1.1 Material cost

The Wohlers Report (Wohlers, 2018) refers to two major categories of AM materials, namely polymers and metals. A variety of modified materials are also available, as well as ceramic materials. Beyond composition categories, it is helpful to group materials into functional categories, such as materials that are intended specifically for use as patterns for investment casting and sandcasting applications.

The material under discussion in this thesis is called polyamide 2200. This material is selected based on properties such as colour, tensile strength, and the sintering capability. Polyamide is the most commonly used polymer used in laser-sintering processes. The major shortcoming of the PA material is that it needs to be refreshed often because the properties of the material are altered during the sintering process. When the sintering process is completed, and the products are removed from the material matrix, the leftover material needs to be sieved and refreshed with virgin material; in the case of P2200, the recommended refreshment rate is 50%. The properties and subsequent refreshment rate contribute significantly to the cost of the final product.

When AM technology is considered in any production process, it is necessary to take cognisance of the fact that the prices of AM polymers are normally several times higher than those of the equivalent materials used in conventional manufacturing processes. The principal reason for the high material prices is the size of the industry that is many times smaller than the conventional manufacturing industry is. On the other hand, the material sales represent a significant portion of any AM system manufacturer's revenue, and they are quite reluctant to give up this recurring revenue.

The accurate costing of the build depends on the real cost of the raw material. The foundation of the calculation will be the build height, which governs the volume of the build. In the current calculation model, raw material (PA 2200 powder) usage is calculated by volume x powder density (unsintered). As can be expected, the sintered PA 2200 powder has a higher bulk density than the unsintered powder, and an unacceptable margin of error in the costing is the obvious implication. In the algorithm, the powder usage calculations will be based on the following:

Equation 3: Total powder mass calculation.

$$\text{Total powder mass} = \text{Build volume mass} + (\text{Sintered part mass} - \text{Unsintered part mass})$$

Equation 4: Powder usage calculation.

$$\text{Powder usage} = \text{Total powder mass x k} - 0.5 \text{ x (Unsintered mass)}$$

k = Loss factor

Equation 5: Unsintered mass calculation.

$$\text{Unsintered mass} = \text{Total powder mass} - \text{Sintered part mass}$$

The new costing model used a loss factor of k = 1.2 in all calculations to calculate powder usage.

Previous research indicates that material cost contributes 55% to 74% of the total cost; thus, it is the biggest cost driver in AM. The empirical analysis, as well as the model, has shown that this is also the case with current builds on the P100 (Baumers, et al., 2016).

4.4.1.2 Machine cost

The EOS P100 platform is manufactured by EOS, an international company based in Germany. EOS manufactures a range of metal and polymer powder bed fusion systems. EOS is a privately-owned company with an estimated revenue of €362 million per annum. Its sales of polymer-based technology declined slightly with 6% in the year 2017 (Wohlers, 2018)

The EOS P100 machine-acquisition cost, converted to cost per hour, forms the basis of calculating machine cost. The hourly cost of 84.56 R/h is calculated by dividing acquisition cost by the number of hours.

4.4.1.3 Labour cost

To calculate labour cost/h accurately, an analysis of the AM labour-to-machine ration needs proper consideration. The AM Department employs 6 employees interfacing with the manufacturing platforms:

Table 4.5: Operational HR cost.

Number	Position	Remuneration
1	HOD	R 22 000
2	Operator	R 8 000
3	JNR Technicians x 4	R 16 000

The labour cost calculation is based on the normal 160-hour work month (40-hour week). The information in Tables 1.3 to 4.2 was used in the labour-costing model. The average person-hour rate would be R97.92/h. The HOD spends less time interfacing the AM platforms than the average operator does. The AM specialist employed at the precinct gave empirical data pertaining to the time each worker spent interfacing with the AM platform. Based on this information, a weighted average cost of R78.63/h (including the HOD) and 79.89 ZAR (including the AM specialist) was suggested. In calculations, a rate of R80/h will be used. (The hourly rate for the AM specialist is R300/h).

4.4.1.4 Energy/electricity cost

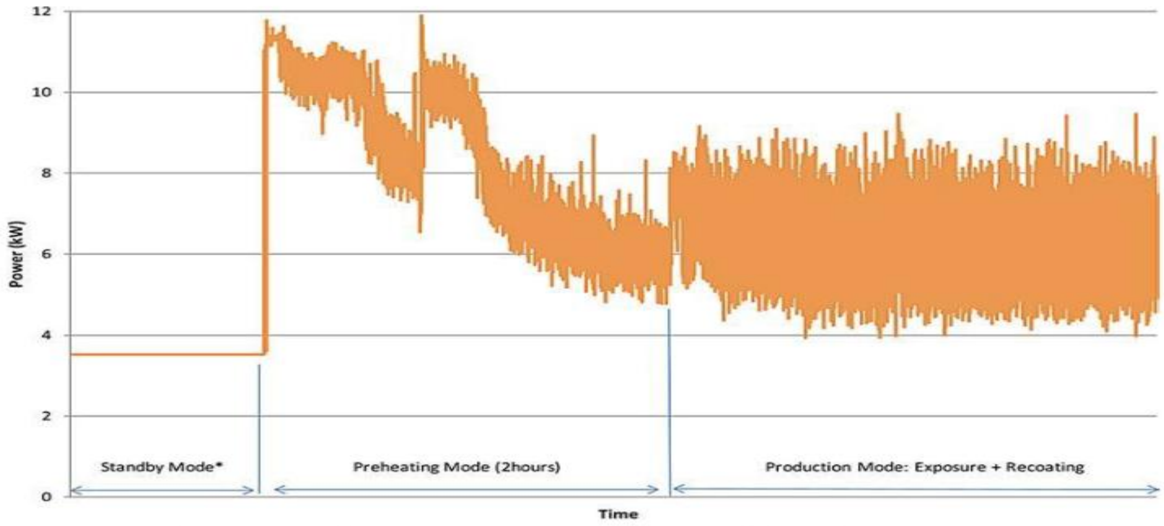
The Formiga P100 has a scan speed of 5 m/s and on average consumes 25,23 MJ of energy per full build. Average power levels from the system use a CO_2, 30 W laser source.

Table 4.6 shows the average power levels:

Table 4.6: Average machine power level (Kellens *et al.*, 2010)

Average power levels	Mode	Rating (kW)
	Standby	0,34
	Heating mode	2,96
	Recoating mode and exposure mode	1,30

Calculation of energy consumption is based on the research of Kellens et al. (2010) on the environmental impacts of selective laser sintering. Their study investigated the power consumption of an EOS P760 machine during a sample build, as shown in Figure 4.4.



Notes: * Standby mode (3.52 kW): power consumption level of the machine tool cleaning and preparing mode (25 minutes/build) as well as the cooling down mode (2 hours/build)

Figure 4.4: Power consumption of a sample built on an EOSINT P760 machine.

The graph shows that during the two hours "warm-up time", the machine consumes on average of about 8.5 kW, and during the production mode on average about 6.25 kW. According to the data sheet, the machine has a maximal power consumption of 12 kW and a typical consumption of 3.1 kW. (Baumers, Holweg & Rowley, 2016.) The average consumption during the warm-up time is 71% of the maximum, and during the print, it is 52% of the maximum.

Unfortunately, there is no maximal power consumption on the data sheet of the EOS P100, so the P110 machine is used as a reference. Its maximal power consumption is 5 kW. Presumed the P110 has the same course of power consumption during a build, it uses 3.55 kW during the warm-up (71% of 5 kW) and 2.6 kW during the production mode (52% of 5 kW).

The warm-up time always takes two hours, and during the cool-down time, no energy is required. Thus, the total cost of electricity is calculated as follows:

(2 hours * 3.55 kW + net running time * 2.6 kW) * 0.83 ZAR/kWh

The electricity price of 0.83 ZAR/kWh is the average price the VUT paid for electricity on the Sebokeng campus between 26 March and 25 April 2016 (76,727.63 ZAR for 92,275.93 kWh). At this low price, the energy cost is only a relatively small part of the operating cost.

4.4.1.5 Other cost drivers

Usually, overhead cost like rent or software licences should also be considered for an accurate cost calculation. The Vaal University of Technology owns the Science Park; the overhead costs are covered by the main financial office of the university. It is difficult to break down the cost for one lab, or even per machine (Mellor, Hao & Zhang, 2014).

4.4.2 Build information

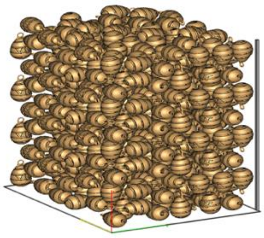
The build information in Table 4.7 was generated by the Materialise Magics™ Software, which prepares data and edits STL software for AM. All the build platforms were prepared using Magics. The results of the empirical work are in Table 4.8. Magics™ is only one of the commercial packages on the market, and the accuracy and functionally was not the objective of this thesis. In Figure 1.2, the process is explained step by step.

Table 4.7: Build information for the Easter egg wrapper.

PLATFORM PROPERTIES	***BUILD 1***	***BUILD 2***	***BUILD 3***	***BUILD 4***
File name	20180315 P100 Internal PR	20180316 P100 Internal PR	20180327 P100 Internal PR	201803129 P100 Internal PR
Machine	P100	P100	P100	P100
Material	PA2200	PA2200	PA2200	PA2200
Build time	33:31:00	33:31:00	33:31 h	23:25 h
Number of parts	401	401	401	300
Build height (mm)	282	282	282	209,269
Nesting density	4,39%	4,39%	4,39%	4,40%
Layer thickness	0.10 mm	0.10 mm	0.10 mm	0.10 mm
Post processing	Bead blasting	Bead blasting	Bead blasting	Bead blasting
Total volume (mm^3)	580376,82	580376,82	580376,82	433324,028

Table 4.8: Empirical work done

Job no.	Total mass (kg)	Mass of build box (kg)	Mass of powder + parts (kg)	Mass powder only (kg)	Mass of parts before cleaning (kg)	Mass of parts after cleaning (kg)	Mass of powder lost with cleaning (kg)	Total number of parts	The average mass of one part (kg)
1	17,50	6,55	10,60	9,27	1,33	0,73	0,60	400	0,001825
2	17,50	6,55	10,60	9,27	1,33	0,73	0,60	400	0,001825
3	17,50	6,55	10,60	9,27	1,33	0,73	0,60	400	0,001825
4	14,50	6,55	7,95	6,95	1,00	0,55	0,45	300	0,001833
Total Mass (kg)	67		39,75	34,76	4,99	2,74	2,25	1500	



The unit weight inclusive of 16.67%/ total units per build = 0,0066kg used in Table 4.2

***Figure 4.5. View of the stacking in a build*.**

4.4.2.1 Online Quoting

Online quoting can be done in four simple steps:

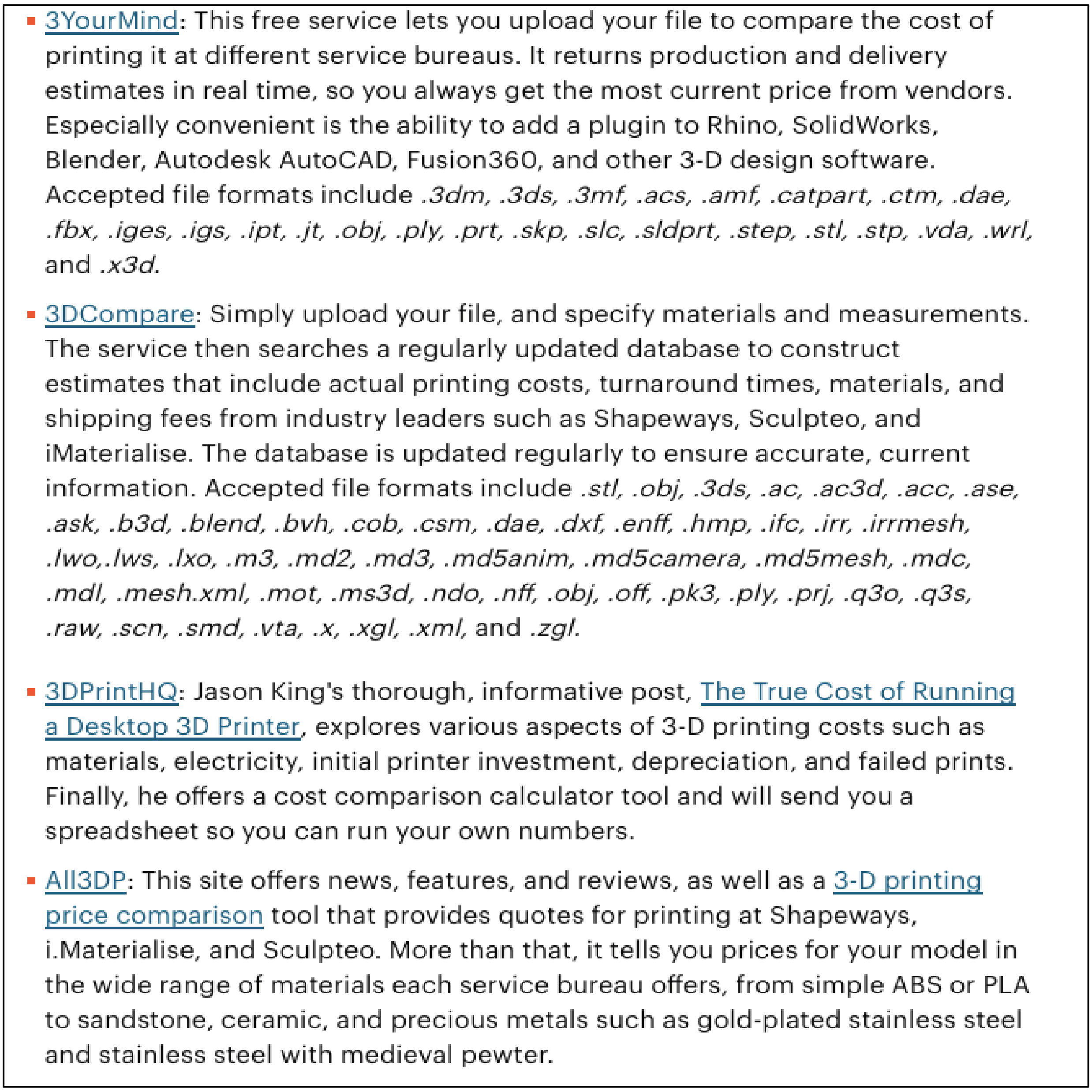
Step 1: Upload a 3-D model or get help from a professional designer.

Step 2: Material and required finish.

Step 3: AM process and post processing of the model.

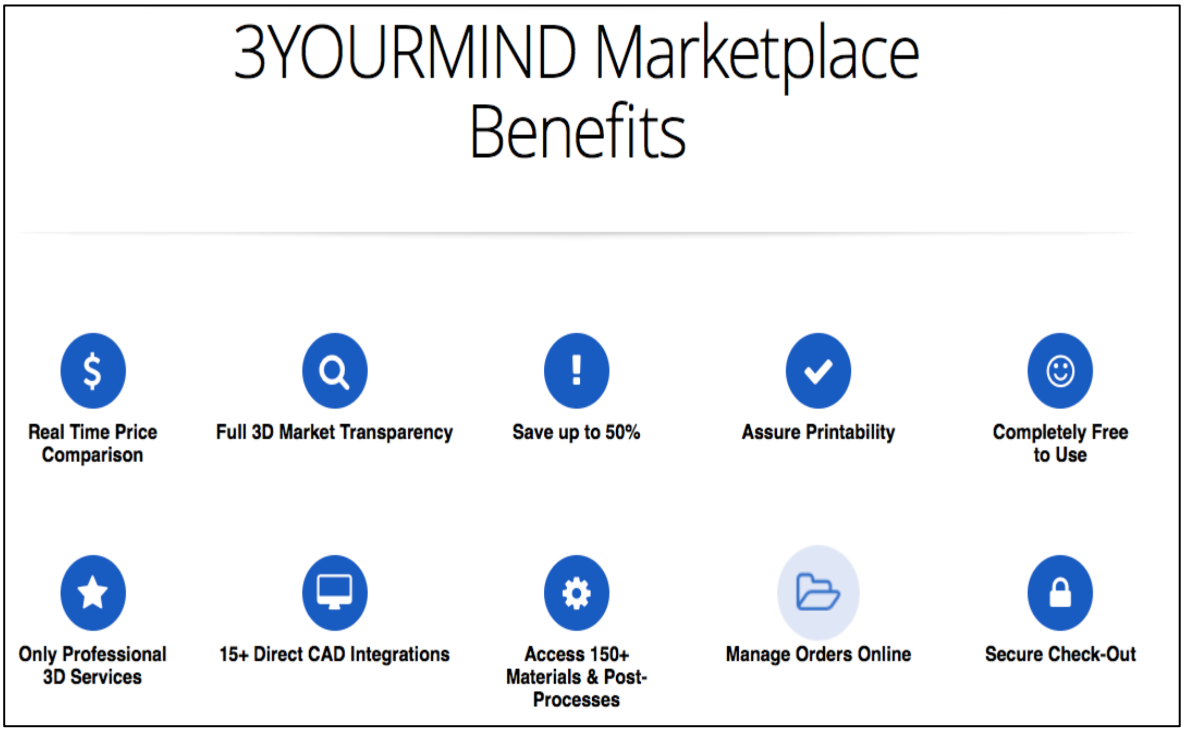
Step 4: Delivery of the complete 3D printed component.

In Figure 4.6 is a more elaborate explanation of the online quoting process.



- 3YourMind: This free service lets you upload your file to compare the cost of printing it at different service bureaus. It returns production and delivery estimates in real time, so you always get the most current price from vendors. Especially convenient is the ability to add a plugin to Rhino, SolidWorks, Blender, Autodesk AutoCAD, Fusion360, and other 3-D design software. Accepted file formats include *.3dm, .3ds, .3mf, .acs, .amf, .catpart, .ctm, .dae, .fbx, .iges, .igs, .ipt, .jt, .obj, .ply, .prt, .skp, .slc, .sldprt, .step, .stl, .stp, .vda, .wrl,* and *.x3d*.
- 3DCompare: Simply upload your file, and specify materials and measurements. The service then searches a regularly updated database to construct estimates that include actual printing costs, turnaround times, materials, and shipping fees from industry leaders such as Shapeways, Sculpteo, and iMaterialise. The database is updated regularly to ensure accurate, current information. Accepted file formats include *.stl, .obj, .3ds, .ac, .ac3d, .acc, .ase, .ask, .b3d, .blend, .bvh, .cob, .csm, .dae, .dxf, .enff, .hmp, .ifc, .irr, .irrmesh, .lwo,.lws, .lxo, .m3, .md2, .md3, .md5anim, .md5camera, .md5mesh, .mdc, .mdl, .mesh.xml, .mot, .ms3d, .ndo, .nff, .obj, .off, .pk3, .ply, .prj, .q3o, .q3s, .raw, .scn, .smd, .vta, .x, .xgl, .xml,* and *.zgl*.
- 3DPrintHQ: Jason King's thorough, informative post, The True Cost of Running a Desktop 3D Printer, explores various aspects of 3-D printing costs such as materials, electricity, initial printer investment, depreciation, and failed prints. Finally, he offers a cost comparison calculator tool and will send you a spreadsheet so you can run your own numbers.
- All3DP: This site offers news, features, and reviews, as well as a 3-D printing price comparison tool that provides quotes for printing at Shapeways, i.Materialise, and Sculpteo. More than that, it tells you prices for your model in the wide range of materials each service bureau offers, from simple ABS or PLA to sandstone, ceramic, and precious metals such as gold-plated stainless steel and stainless steel with medieval pewter.

***Figure 4.6: This is a screenshot of self-help quoting and order-placing technology for AM*.**



3YOURMIND Marketplace Benefits

Real Time Price Comparison

Full 3D Market Transparency

Save up to 50%

Assure Printability

Completely Free to Use

Only Professional 3D Services

15+ Direct CAD Integrations

Access 150+ Materials & Post-Processes

Manage Orders Online

Secure Check-Out

***Figure 4.7: Screenshot of the online menu of options of a quoting and order-placing web page*.** (By courtesy of https://www.3yourmind.com/marketplace)

Compare and Save on your next 3D Printed Model for FREE!

Are you looking for the best price from 3D print services around the world?
Want to ensure that your model is optimized for printing in over 150 materials and post processing methods?

- Submit your 3D model from **15+ CAD integrations**
- Analyze your 3D model to **guarantee printability** of your order
- Choose from over **150+ materials and post-processes**
- Order from **professional 3D print services**
- **Compare cost** and delivery in real time
- Manage and **track orders online**
- **Secure data handling**, every step of the way

Solutions for Professional 3D Manufacturing with One Click

Access over 150 materials and finishes from professional service providers with a single click. Upload 3D models from over 15 leading CAD software solutions. The platform will provide an instant analysis of printability, pricing and delivery time to guarantee a quality 3D print, every time. Hundreds of companies are already benefiting from 3YOURMIND's platform. All service providers are tested for quality and reliability. Experienced 3D printing consultants assist businesses in developing 3D printing solutions, including the setup and implementation of 3D printing technologies and profit maximization.

3YOURMIND provides complete solutions for access and management of 3D print processes.

***Figure 4.8: Online service offering for quoting and ordering of AM parts*.** (By courtesy of https://www.3yourmind.com/marketplace)

Looking at Figure 4.8 the reality of the freedom factors pertaining to AM becomes a reality:

- Freedom of material - 150 materials;

- Freedom of design - 15 software solutions; and
- Freedom of platform (quoted in the INDUSTRY 4.0 realm).

4.5 Conclusion

The outcome of the work to verify the accuracy of the existing quoting algorithm will also provide the author with the information to progress to Objective 2. Objective 1 was completed with the intention to generate an elegant solution for a future customer interface executing the Objective 2 process and subsequently Objective 3, conforming to the digital freedom that is potentially possible and striving to conform to the INDUSTRY 4.0 criteria. This research is well delineated, focussing only on the laser-sintering platforms with specific reference to the P100 machine. The literature review highlighted the complexity of the analysis and portrayed a plethora of complex challenges and elements that need to be considered. The research also raises concerns regarding the current costing model employed in the AM Department.

The positive aspects of the research are that a dependable algorithm was developed following a reliable method, where all cost-relevant activities, subprocesses and main process steps are incorporated in a simplified algorithm that can calculate the full cost of manufacturing accurately. Further attention is required to determine the sensitivity of the proposed algorithm.

5. OBJECTIVE 2: DEVELOPING AN ACTIVITY--BASED COSTING MODEL

5.1 Introduction

The principle range of builds that govern the empirical verification on the P100 platform comprises four builds that conform to the unique capabilities of AM. The other aspect to note is that the objective of the builds was to pursue maximum capacity. The P100 laser-sintering system permits operation capacity using the entire build volume (with a usable Z-height of 330 mm). The reason for running these extensive builds and the generation of four builds was to have the cost reflected per part under the ideal conditions, which is required to pursue Objective 3. Detailed information pertaining the build quantities, build height, and material usage was captured from the Magics™ output files. The information and build statistics can be perused in Tables 4.7 and 4.8 respectively. The Magics™ Software was used. The main purpose of the Magics™ software is to optimise the computational build volume and the optimum build height of 282 mm with 401 units per build.

Table 5.1 contains all the activities and elements in the costing model. Table 5.2 shows how the full cost model for the Formiga P100 was used to calculate the full cost of the part (Easter egg wrapper). All the cost was still derived from the information obtained from the Objective 1 verification process.

Method (see Figure 1.13):

1. File preparation: Convert the 3D CAD data into STL files, and knit corrupt surfaces. Slice and stack the build.
2. Digitally set up the build on the control system.
3. Prepare the machine and check material melt flow and hopper material holding.
4. Initiate the build checking by initiating the standard operation procedure (SOP);
5. Monitor the build process based on requirement and experience, and initiate machine supervision concurrently.
6. Cool-down period and remove build volume.
7. Quality control and post-build SOP.
8. Unpack and handle powder.
9. Pack and despatch after the process.

Consult Figure 1.20 Direct cost + Indirect cost. This is a succinct overview of all the cost drivers.

The costing model in Table 5.1 is populated with the information and build statistics gathered and measured in Objective 1. The tried and tested algorithm developed at the University of Nottingham in the UK was used (Baumers, Holweg & Rowley, 2016).

Table 5.1: Elements of the unit cost model (Baumers, Holweg & Rowley, 2016).

Indirect cost			Labour cost		
Production overhead rate	R 35	/ h	Full annual labour costs	R134 400	/ year
Admin overhead rate	R 0,15	/ h	Working days net of holiday	210	days
			Total hours worked per year	1680	h
Machine purchase	R 2 581 713		Labour cost rate ($\dot{C}_{Labour}$)	R80.00	/ h
Depreciation period	8	years			
Annual operating time	5 000	h	Direct cost data		
Estimated maintenance and consumables	R 105 000	/ year	Raw material price *(Table 4.3)*	R1 370	/ kg
Total machine cost rate	R85.54	/ h	Material density, as deposited	0.93 g/cm³	
			Energy price (Table 3.4)	R 0.83/kWh or R0.23/MJ	
Total indirect cost rate ($\dot{C}_{Indirect}$)	R120,69	/ h	Fixed energy consumption per build	25.23 MJ	
R35/h + R0,15/h +R85,54h			Energy consumption rate	1,407.50	J / s

Table 5.2: Full cost model for Formiga P100

Elements	Unit (A)	Factor	Unit allocation (B)	Cost (A*B)
($\dot{C}_{Indirect}$)Total indirect cost rate (Indirect) R/h	120,69	1	33,5	R 4 043,12
($\dot{C}_{Labour}$)Labour cost rate (Labour) R/h	80,00	1	33,5	R2 680,00
Energy Cost (Rand/ build)	0,25	1	25,23	R 6,31
Total Fixed				R 6 729,42
Material Cost R/kg (M)	1368,23	1		
Material (kg)		1		(M*A)
Overflow (Table 4.8)	1,000	1		R 1 368,23
Recycle component (Table 4.8)	0,815	1	34,76	R 1115,11
Cleaning (Table 4.8)	0,600	1		R 820,94
Product (401 parts) (Table 4.8)	0,730	1		R 998,81
Reject factor 2,5 % (Table 4.8)	0,018	1		R 24,97
Quality Control				(A*B)
Small parts (Tier 3)	450	1	1	R450,00
Finishing(R/h)	300	1	8	R2400,00
Total (Direct)				R7 178,05
Unit Cost				R 34,68
Unit price (include 10% margin)				R38,54

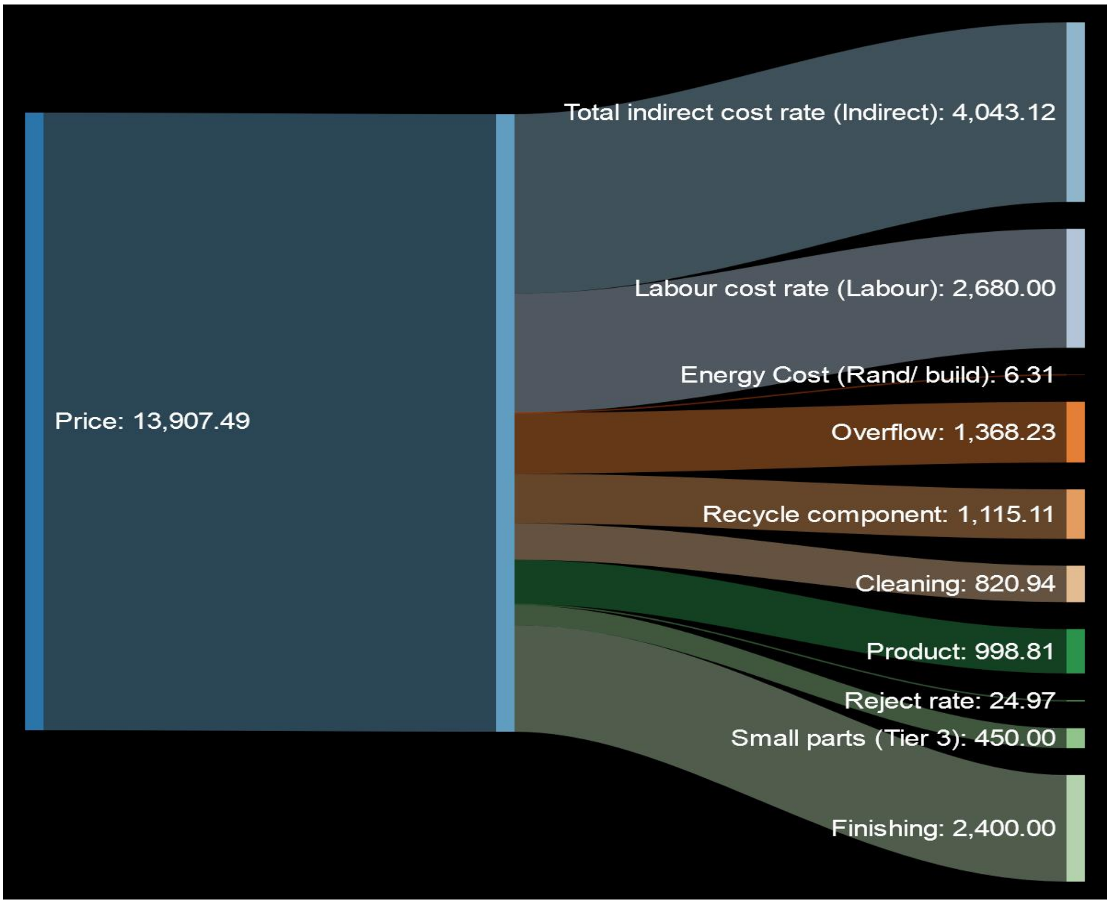


Figure 5.1: Sankey diagram depicting the cost streams.

5.2 Conclusion

AM technologies represent a new opportunity to develop products that previously could not be manufactured and the opportunity to make existing products better and to customise products to specific needs. The economic case for adopting AM technologies, however, was over complicated and the work under Objective three will point this out.

6. OBJECTIVE 3: SIMPLIFIED COSTING MODEL

The results from the costing models used in Objectives 1 and 2 led to an opportunity that was identified to simplify the costing model. Based on the simple assumption that using an average build density in a full build scenario offers one the opportunity to do volume-based costing.

Table 6.1: Average build density P100

P100 build density 1) 18.36%; 2) 17.56%; 3) 17.27%; 4) 16.64%; 5) 15.05%; 6) 13.98%; 7) 12.39%; 8) 12.09%; 9) 11.75%; 10) 11.67%; 11) 11.66%; 12) 11.63%; 13) 11.44%; 14) 11.29%;

15) 10.38%; 16) 10.22%; 17) 10.21%; 18) 8.89%; 19) 8.57%; 20) 8.08%; 21) 8%; 22) 7.55%;

23) 6.06%; 24) 6.02%; 25) 5.73%; 26) 5.07%; 27) 4.70%; 28) 4.40%; 29) 4.39%; 30) 4.39%;

31) 4.39%; 32) 3.94%; 33) 3.78%; 34) 1.68%; 35) 1.65%; 36) 1.40% AVERAGE 8.95%

This could be useful when calculating the amount of material to be considered, having 0.97 density, as opposed to the 0.45 density of the powder bed.

The total build volume is 580376,82 mm^3, of which approximately 9% is product.

Comparing the results of the costing models in Table 7.1 indicates that this simpler approach yields an accurate enough cost.

Table 6.2: Build information

240*190*282 Build volume mm^3	**Build Density 1/100**	**Product Volume mm^3(C)**	**Product g/cm^3**	**Matrix g/cm^3**
12 859 200	0,09	580376,82	0,97	0,45
Element	**Rand Cost (R)**			
Build fixed cost	7000,00	Table 5.2 rounded to nearest 1000		
Material	4238,71	(Material 1368,23 R/kg * used material 3,10 kg) see Addendum 3		
QC	450	See Table 6.3 Tier 3		
Finishing	2400	See Table 5.2		
Total	14 088,71			
Product Cost	35,22 (Total/400 units)			
Profit (10%)	39,13			

kg (Addendum 3)					
Used (1/6)	Used (Overflow)	Product	Cleaning	Reject	Material (kg)
(BV-PV)*0,001/6		PV*ρ*1E-6			
0,92	1,00	0,56	0,60	0,01	3,10

The element of building density is indeed a way to determine cost calculation simply but accurately. The estimate is based on the fact that we have empirical data related to the matrix and building density. All the other costs in the platform-based calculations remain the same for all practical purposes.

Table 6.3: Powder density

Verified bulk density of virgin powder	**0.4349 g/cm³ – (use 0,45 g/cm³ in calculations)**

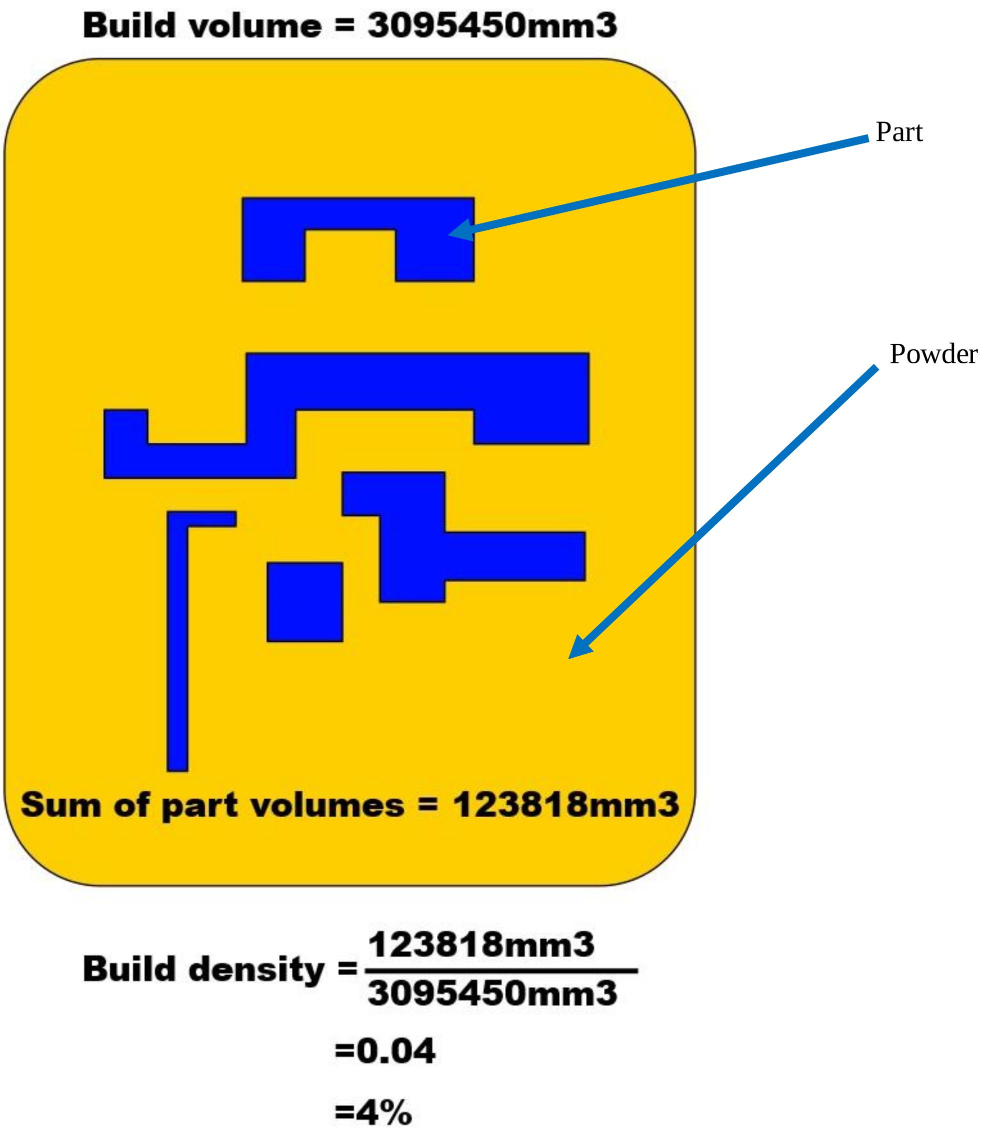


Figure 6.1: A graphic representation of build density the figures is just to illustrate the principle.

6.1 Additive Manufacturing Quality Control Rates

This is additional information used in Objectives 2 and 3.

For build size, see Figure 6.1. Depictions are based on the total volume of the EOS P100.

This model was designed to guide the quoting system, based on the number of parts in a specific build.

6.1.1 Method

The volume of Product A makes up 10% of the total build; therefore, 10% of the cost is allocated to product A.

6.1.2 Result

The calculations in Table 6.2 support this approach, and the cost and the selling price of a single component compares favourably with the control calculations in Objectives 1 and 2. The principle in Objective 3 makes it now possible to provide a simple but accurate method to determine the cost of a product. The obvious shortcoming is that methodology is only applicable to full builds. In Table 7.1, this argument is concluded by comparing this results with calculations in Objectives 1 and 2.

6.2 Conclusion

The method tested and compared with Objectives 1 and 2 led to a simplified method to determine cost on the P100, which will also work on **any other powder-based system.**

The variable cost in Objective 3 as depicted in Table 6.2 is supported in the range of cost indicated in Table 6.3.

Table 6.3: Quality control cost

Tier	Part Volume	Rate/ Build
1	Ranging between 15 000 000 mm^3 – 1 375 000 mm^3	R150
2	Ranging between 1 375 000 mm^3 – 229 143.75 mm^3	R300
3	Ranging between 229 143.75 mm^3 – 57 285.94 mm^3	R450
4	Ranging between 57 285.94 mm^3 – 28 642.97 mm^3	R600

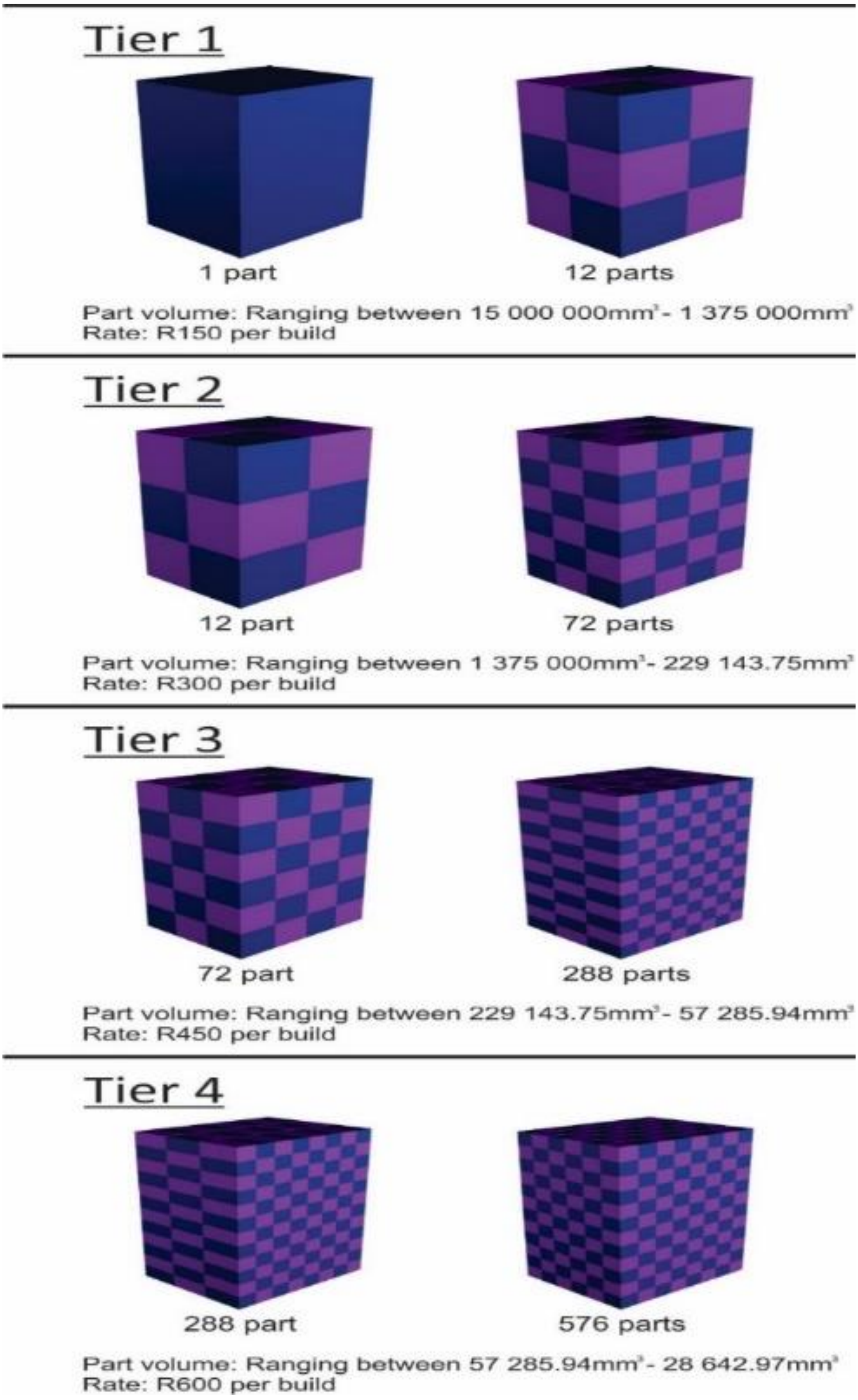


***Figure 6.2: Rates are calculated according to volume*.**

7. CONCLUSIVE PROOF OF ARGUMENT

The results of the work done in Objectives 1 to 3 are proof that the current costing algorithm is trustworthy and accurate. The full cost model in Objective 2 based on the cost elements in the activity-based costing model is also good enough. The desired outcome of this thesis has been reached with the calculations in Objective 3, and in Table 7.1 is conclusive proof.

Table 7.1: Conclusive proof of the thesis

Conclusive proof of the argument		
Model	**Cost per single Easter egg wrapper**	**Deviation from AM**
Existing AM Department	R41,15	
Empirical data	R40,88	1%
Activity-based model	R38,53	6,3%
Build-density model	R39,13	4,9%

8. RESULTS

8.1 Introduction

The manufacturing world is changing. AM not only is deemed suitable for rapid prototyping, but also promotes rapid (direct) manufacturing, AM or 3D printing, and its adoption (Steenhuis & Pretorius, 2015). Steenhuis and Pretorius (2015) compare the AM entry-level revolution, which seems to grow exponentially, with the heydays of the personal computer era when start-ups were the order of the day. This statement can be compared with the Wohlers Report of 2014: "*It is believed that more than 250 companies and teams are making personal 3D printers, with a few that generated revenues of $1 million or more within a year of launch*" (Wohlers, 2018, p. 100)

Fera et al. (2017) affirm the intensive research on material and component properties using technologies such as stereolithography, selective laser sintering and electron beam melting. They also introduce a holistic approach with their overall equipment effectiveness index to link evaluations to real production systems and potential issues (Fera et al., 2017).

Most literature begins with a thorough definition of AM, explaining in some detail the transformation of 3D model digital data in a layer-by-layer manufacturing fashion to form a solid object. The next aspect is the reality that this technology captured the imagination of manufacturing and the product development world. The next phase in academic literature is to focus on the quality and properties of the mechanical and other physical properties of the resultant component. Materials studied and components that are manufactured by means of AM vary from ceramic to carbon fibre reinforced material, special tooling steels, titanium for load-bearing applications to medical solutions. International companies like Deutsche Bahn have increased their component range from two to 15 000 different components using some form of AM technology.

Costabile et al. (2017) point out that a literature review by this team of researchers has discovered that only 4% of all academic papers deal with the business case issues about AM.

The papers dealing with the costing models for AM more or less agree on these advantages and disadvantages, as can be seen from Table 8.1 below.

Table 8.1: General advantages and disadvantages associated with AM as a manufacturing choice

Advantages	**Disadvantages**
• **More flexible development**	• Machine and material costs are high
• **Freedom of design and construction**	• The quality of parts needs improvement
• **Less assembly**	• Rework is often necessary (support structures)
• **No production tools necessary**	• Build time depends on the height of the part
• **Fewer spare parts in stock**	• Slow process speed
• **Reduce complexity in business**	• The high cost of special materials
• **Less time to market**	• Dimensional accuracy
• **Faster deployment of changes**	• Build failure and unpredictable performance
• **The creation of highly functional and complex products is possible**	• Not economically suited for medium to high production volumes
• **Products closely tailored to customer requirement**	
• **Higher utility through differentiation ensures new end users**	

The literature that deals with AM economics indicates the development of some guidelines for decision making. For example, the economic indications for a production requirement of fewer than 1000 components show that the most economic manufacturing option for the end users should be some form of a layer-by-layer technology or another (EY's Global 3D Printing Report, 2016).

8.2 Costing Models

Although it seems as if academics shy away from research and reporting on the costing and managerial aspects of AM, as reported in the previous section, the trend is changing slowly (Costabile et al., 2017).

The custom usage of injection moulding technologies, as the benchmark technology, is a general element in the research. Hopkinson and Dickens (2003) indicate in their research that some complex geometry is more economical when manufactured on an AM platform rather than the conventional approach.

Thomas and Gilbert (2014) took a bird's eye view in their research about cost and cost effectiveness of AM. When questioning the current supply chain, ill-structured cost due to the nature of conventional systems and practices to move products from supplier to end user comes to light. According to them, AM has the potential to have a significant effect on the structure and magnitude of this system. The nature of current businesses clearly inflates inventory and increases associated cost. A technology like

AM that can manufacture parts to demand can play a significant role to decrease associated supply chain costs. Low demand and infrequent orders render conventional technology inadequate, which can make an economic case for AM. More than $ 700 billion capital is locked up in inventory (Thomas & Gilbert, 2014).

The effect of transportation cost on a full cost model is clear; therefore, a point-of-use, low-volume production method makes more economic sense. If this philosophy takes root, it will be a significant opportunity for end users to consider point-of-use manufacturing. The increase in implementation of the technology will change the economic aspect around AM, with a potential knock-on effect that will lower the cost of technology and materials.

Conventional technology is driven by machine productivity as the main driver of per-unit manufacturing cost; however, this is possible only with high inventory numbers.

Future South African manufacturing companies need to implement advanced manufacturing engineering solutions and should give proper attention to the AM process and resources that are suitable for the variances of each manufacturing AM platform. Principally, for effective implementation of an ERP system in an AM environment, the digital integration of product data management (PDM) is one of the key aspects to consider for success. Integration of product data dictates that the engineering bill of materials (EBOM) should be adopted into a manufacturing bill of materials (MBOM); however, the transformation should be done in such a way that it will fit the uniqueness of each AM platform. In this process, a method suitable for the incorporation and transformation is required. The focus of the research was limited to the EOS Formiga P100 Selective Laser Sintering (SLS) machine.

ERP has justly become a trusted business application, and the relevance or not is not an objective; hence, it was not questioned in this paper. Small, medium, and large enterprises invest in information technology to ensure improved integration with stakeholders and partners, effect reduced costs, and establish a competitive advantage (Lee, Leem & Hwang, 2011).

Incorporating the AM road with the world of ERP might just be one of the most important aspects transforming this technology from a prototyping technology to a manufacturing business environment (Matende & Ogao, 2013). Wallace and Kremzar (2001, p. 4) say the following:

“ERP can be described as an enterprise-wide set of management tools that balances demand and supply, containing the ability to link customers and suppliers into a complete supply chain, employing proven business processes for decision-making, and providing high degrees of cross-functional integration among sales, marketing, manufacturing, operations, logistics, purchasing, finance, new product development, and human resources, thereby enabling people to run their business with high levels of customer service and productivity, and simultaneously lower costs and inventories; and providing the foundation for effective e-commerce.” .

When investigating the ERP requirements and digitisation of the different AM processes, it is prudent to understand the advantages of this disruptive manufacturing methodology over conventional manufacturing techniques. The most important advantage of AM is that no tooling requirement and product complexity constraints are associated with the manufacturing process. AM also offers low-volume production and mass customisation. The fact that AM is a real manufacturing method is not disputed anymore and is confirmed by the nature of business at the Advanced Manufacturing Precinct of the VUT (Gartner, 2015).

8.2.1 Digital Engineering

This thesis proposes that digital engineering should be used as the key data-accumulation tool between PDM and ERP. Digital manufacturing encompasses the physical and logical computer modelling and simulation techniques for actual manufacturing. This provides the methodology for transforming EBOM to MBOM that fits the uniqueness of each AM platform, based on the process and resource models that reflect the uniqueness of each AM platform (Matende & Ogao, 2013). The first step and the part on which this research focused was the digitisation of customer information, which would allow the customer to generate and accept a self-generated quotation on a website customer interface. To do this safely and accurately with reference to cost, the old debate of EBOM vs. MBOM becomes part of the thesis. This thesis focused on aspects of the manufacturing methodology as such; however, it is imperative to mention that the manufacturing entities have to implement AM engineering with the necessary attention given to the production process and resources that are suitable for the specific requirements of each production site. Particularly for effective execution of an ERP system under a universal production environment, the integration of product data management (PDM) for product data is one of the important keys to success (Lee, Leem & Hwang, 2011). Once the system is operational, it is also paramount that no unauthorised manipulation of this information is possible. Full data integration is possible only once the EBOM is fully integrated with MBOM, but the MBOM alteration must be done in such a way that it fits the specific requirements of each manufacturing site (some materials are hygroscopic; thus, humidity control is a requirement). This transformation and full integration require an appropriate method to implement it properly. In the INDUSTRY 4.0 philosophy, the digital manufacturing data propagate important elements for proper integration between PDM and ERP. As a technique, digital manufacturing possesses the physical and logical computer modelling and simulation methods for actual production. It provides the technique for transforming EBOM to MBOM that fits the requirement of each AM manufacturing platform, based on the process and other models that reflect the specific requirement of each manufacturing platform. It also provides the procedure for MBOM confirmation and the integration of the process and resource model. This is the single most important shortcoming of the present manual system running in the AM Department. Using such a system ensures that the data flow of each platform is incorporated properly with the ERP system (Lee, Leem & Hwang, 2011). The INDUSTRY 4.0 philosophy of starting and ending with the customer emphasises that the economics that underpin the application of this technology are a fundamental prerequisite to developing a business case for its application and need to be understood holistically before one can incorporate this as part of the ERP. In this research, the findings presented aim to promote better understanding of the underlying economics of AM. An ERP system affects the strategy, organisation, and culture of a firm. One should begin by recognising the importance of planning an ERP implementation at the strategic level. With all the platforms at the Advanced Manufacturing Precinct, the decision was made to use the EOS P100 for such an analysis. The machine specifications are shown in Table 8.2.

Table 8.2: Key processing information analysing batch manufacturing on the P100

Build no.	**Build height**	**The total volume of parts (mm^3)**	**Invoice**	**Monetary Density**
1	145,458	429946,88	R 9 540,83	2,22%
2	65,5	338803,24	R 4 263,42	1,26%
3	251	2001941,02	R17 505,62	0,87%
4	278	1226145,96	R23 122,31	1,89%
5	16,973	295719,37	R8 491,29	2,87%
6	181,5	545788,70	R11 943,05	2,19%
7	182,875	659358,22	R 7 756,23	1,18%

The data captured in Table 8.3 is an attempt to introduce the typical data from the AMP available in the AM body of knowledge (BOK). It also refers to the economic aspects of the different builds. This information offers the author the opportunity to evaluate the real information with findings in the literature that were perused for this thesis.

Table 8.3: Analysis of the first data group

Parts in cm^3	**Vol cm^3 using build height**	**Sales value R/kg**	**Over- or under recovering.**
429,9469	6632,8848	R2 386,10	19%
338,8032	2986,8	R1 353,09	-33%
2001,941	11445,6	R940,25	-53%
1226,146	12676,8	R2 027,71	1%
295,7194	773,9688	R3 087,53	54%
545,7887	8276,4	R2 352,92	17%
659,3582	8339,1	R1 264,87	-37%

Build height is an indicator of utilisation of the full capability of the platform with understandable implications for the economics of a particular build. The production facility should endeavour to keep the build density (proper stacking) and the build height in mind to ensure the most economical option. Data in Table 8.3 correlate with the graph in Figure 8.1 in dictating the utilisation of the capability of the platforms expressed in % build height. Table 8.3 also indicates that there is an underrecovery in cases of mixed builds below optimum build height (Baumers, Holweg & Rowley, 2016).

The information from the PDM (data from BOK) is not conclusive at all and was impossible to analyse. A clear mathematical relationship was expected.

The graph in Figure 8.1 below portrays the findings on PDM in decision making from a cross-section of builds in the AM Department on the P100, for private and in-house customers. The plan with the PDM was to test the validity of the EBOM using an equation modelling approach. Results suggest that PDM cannot contribute to the task. An unexpected result was that the PDM did not contribute to verify the comparison to any level of satisfaction, which in turn forced the author to implement a fresh empirical process to verify costs and other critical aspects.

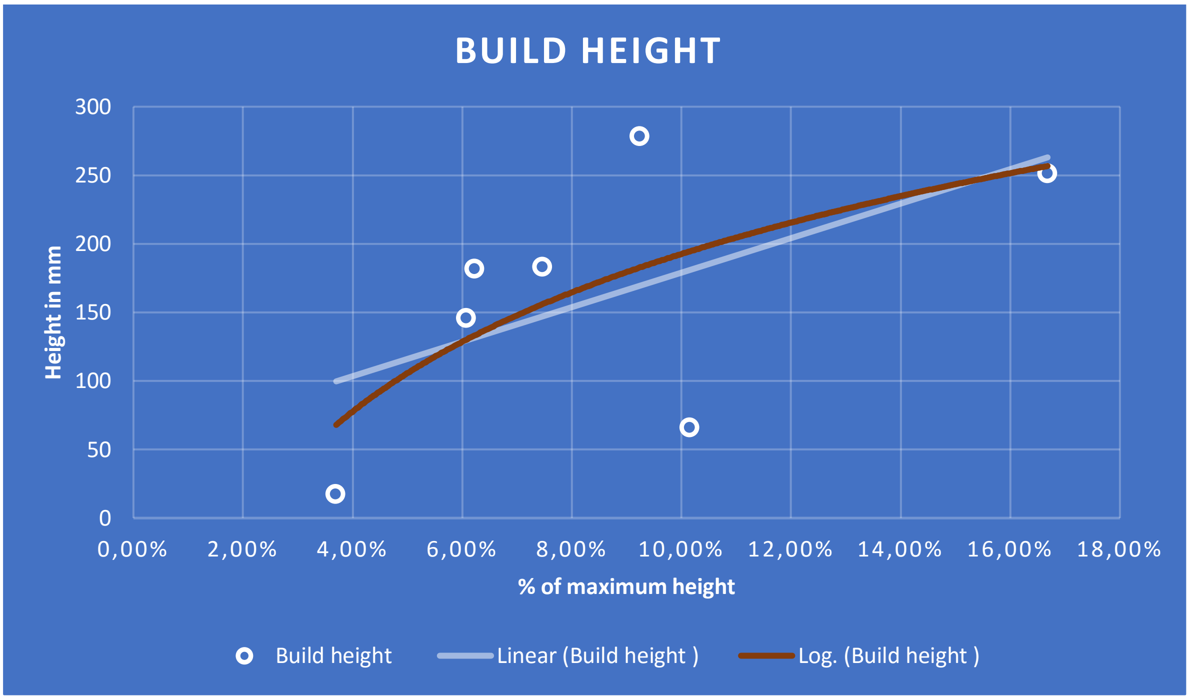


***Figure 8.1: Built height of first data group is from the AMBOK to analyse the information available in the PDM*.**

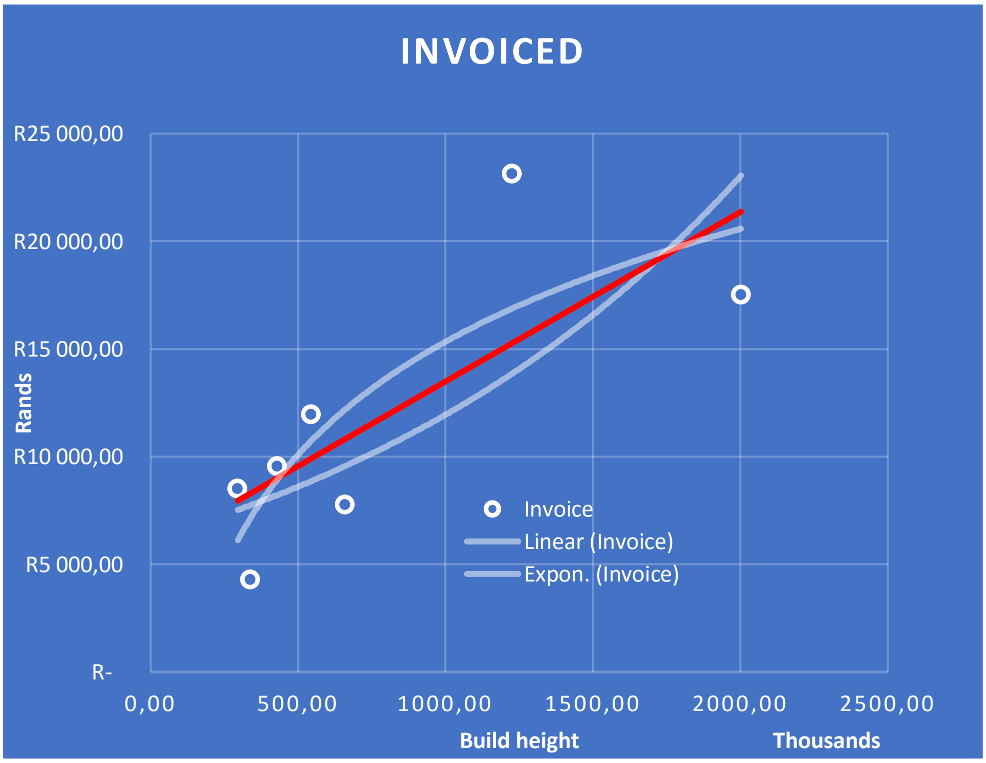


***Figure 8.2: Invoiced values. Interrogating the invoice values vs. the cumulative build height*.**

It is clear that the invoiced value per build improves with the better utilisation of the P100 platform.

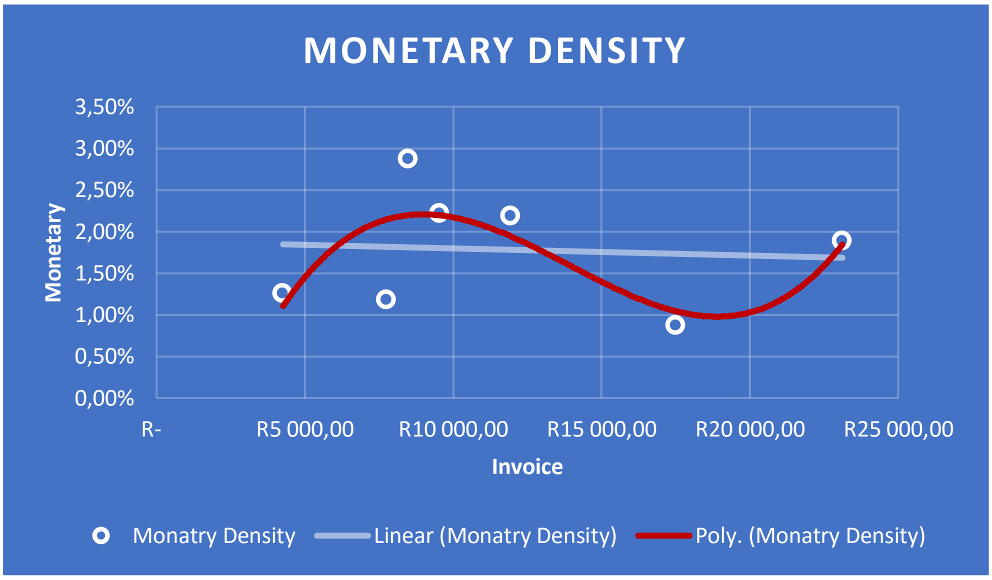


Figure 8.3: Attempt to display monetary density.

The results from the first data group are not conclusive; therefore, no assumptions can be based on them. The graph in Figure 8.3 supports this statement clearly. The R/kg values per build show no trend at all. This led to a decision to analyse empirical data from builds that were monitored more closely.

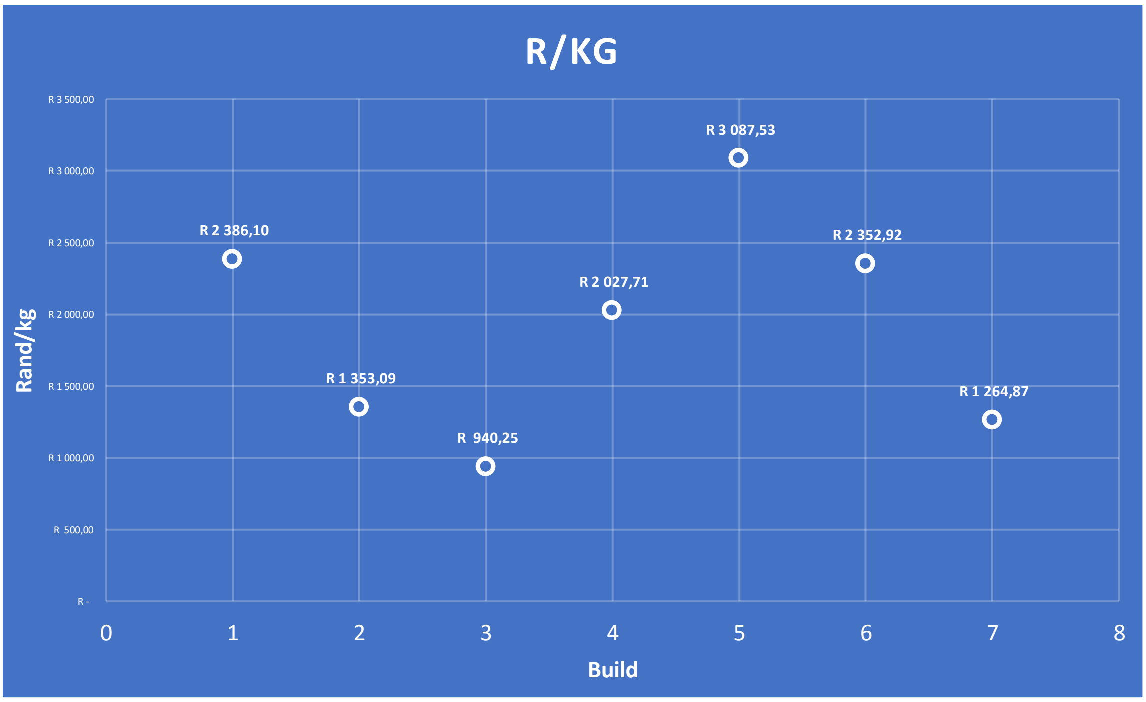


Figure 8.4: Build cost (R/kg) capricious and data not useable at all. A R/kg value of more than R2000/kg should be the norm.

In Table 8.4, it was established beyond any doubt that the data from the PDM for mix products were not going to assist in determining the objectives set in the thesis. The only reference in the literature was the fact that higher quantities of parts per build lower the cost per part (Rand/Part) (Baumers, Holweg & Rowley, 2016). In Table 8.4 and Figure 8.4, as expected from the literature, one can see the price per product decrease with an increase in the number of products per build (Baumers, Holweg & Rowley, 2016) The second data group also indicated less than optimum utilisation of the P100. The graph in Figure 8.5 also indicates that the effect of higher volumes of part per build lowers the Rand/part relationship.

Table 8.4: Info from the second set of information (second data group).

2nd Build	Build Height	Price R	Part Qty	Rand/Part
1	48,11	R 3 074,02	2	R 1 537,01
2	58,00	R 2 026,12	4	R 506,53
3	40,00	R 1 439,72	2	R 719,86
4	50,03	R 2 146,50	2	R 1 073,25
5	50,00	R 4 946,34	11	R 449,67
6	40,00	R 911,32	1	R 911,32
7	69,407	R 3 904,39	40	R 97,61

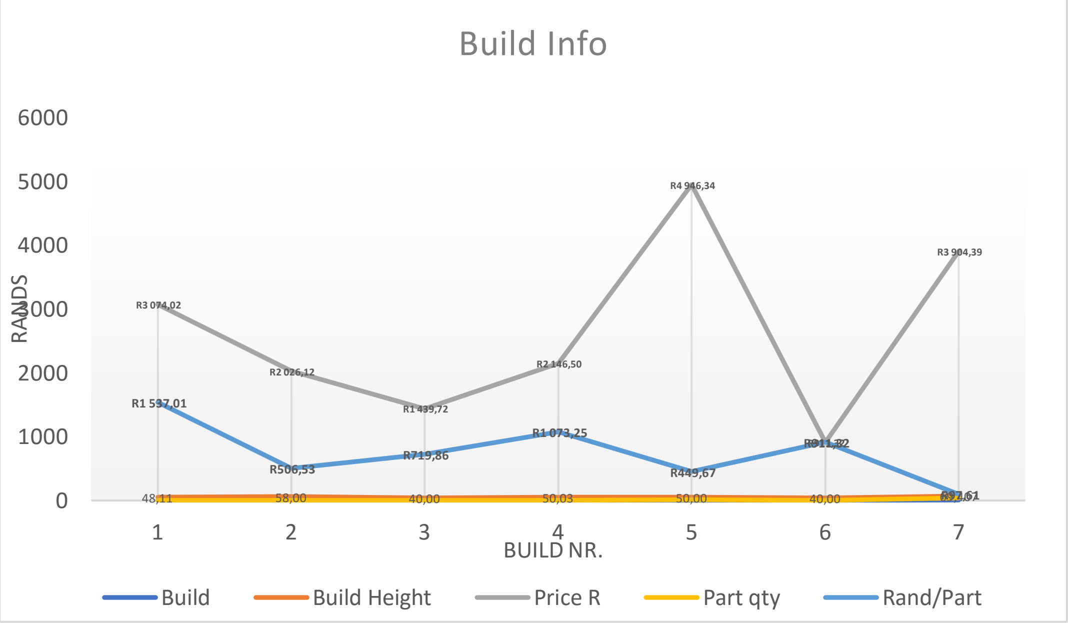


Figure 8.5: The graph shows how increasing part numbers lower the cost per part.

8.2.2 MBOM

The informed assumption was made that the full cost model methodology applied to accommodate the overhead structure at the science park for the MBOM verification is well integrated with the process and resource model. This method developed by the international company EOS to do a full costing model was related to the P100 platform. Thus, the MBOM and the process and resource data are deemed fully verified and appropriate for the specific AM platform, in the required format, these data should be suitable to send to the ERP system (Newswire, 2016).

The PDM data clearly indicated a relationship between the number of parts included in a build volume, the build height, and the nesting density. As expected, utilisation below the optimum leads to drastically higher cost. However, the problem was the R/kg deviation that could not be explained and put a question mark on the validity of the PDM in this instance, if this finding is compared with the findings in the literature research (Baumers, Holweg & Rowley, 2016).

The MBOM cost model was based on a total cost model that accommodates both manual process inputs and interventions including the risk of build failure. This is the basis of the VUT cost model.

With the above-mentioned declaration, one can be sure that the algorithm envisaged for the EBOM, tested with the information from the actual builds, will ensure a high probability of success with satisfactory deviation.

To augment and remedy the problems encountered, the plan was to implement an empirical verification process to investigate all cost drivers systematically and finally determine an accurate costing algorithm, gauge cost drivers, and finally determine the real cost.

After analysing the build and job information, it was realised that the data used in this research could be used to establish a customer interface using a web-based script. Utilising the EBOM to arrive at a quotation with little deviation from the cost quoted by using the MBOM is unrealistic at this stage due to unexpected variations in the Rand per kilogram (R/kg) factor. See figure 8.4 to support this claim.

The discrepancies in the data of the first and second build warrant the implementation of a full, empirically based exercise to support the MBOM calculations.

Several cost models and algorithms were identified in the literature research that can be handy in calculating the full cost. The algorithm in Equation 6 forms the basis of the cost calculations, considering the fixed cost and variable cost elements.

Equation 6: Basis of the cost calculations.

$$C_{Build} = P_{Material} \text{ x } V_{Build} + C_{SetupLabour} + (C_{Indirect} + C_{Energy}) \text{ x } T_{build}$$

$P_{material}$: Price R/kg

V_{Build} : Volume

$C_{setupLabour}$: Cost Rand

$C_{Indirect}$: Cost in Rand

C_{energy} : Cost of energy R/kWh

T_{Build} : Duration H

The general assumption around these models (Equation 6) is that all builds likely will be composed of multiple geometries. The reality is that existing AM-suitable ERP systems in the marketplace like the Materialise Streamics option do not make provision for the multiple geometry. To achieve the original objective, a digital customer interface was created that could convert the EBOM into digital data with an STL, which in this case was going to predict prices of between 35% and 45 % higher than expected; hence the need for a newly develop computational build volume packing and build time estimation tool. This would be developed to obtain multiple job-related quotations for a direct SLS unit like the P100.

The estimation tool should operate by filling the available machine capacity with components and additional reference parts algorithmically drawn from a basket of reference geometries.

Once this digital build has been composed in cyberspace and build time has been estimated with the aid of the tool, it is possible to calculate the cost and send a quotation.

In Figure 8.6, reference is made to the activity-based full cost model, an approach supported in the literature (Nottingham School & Oxford, n.d.)

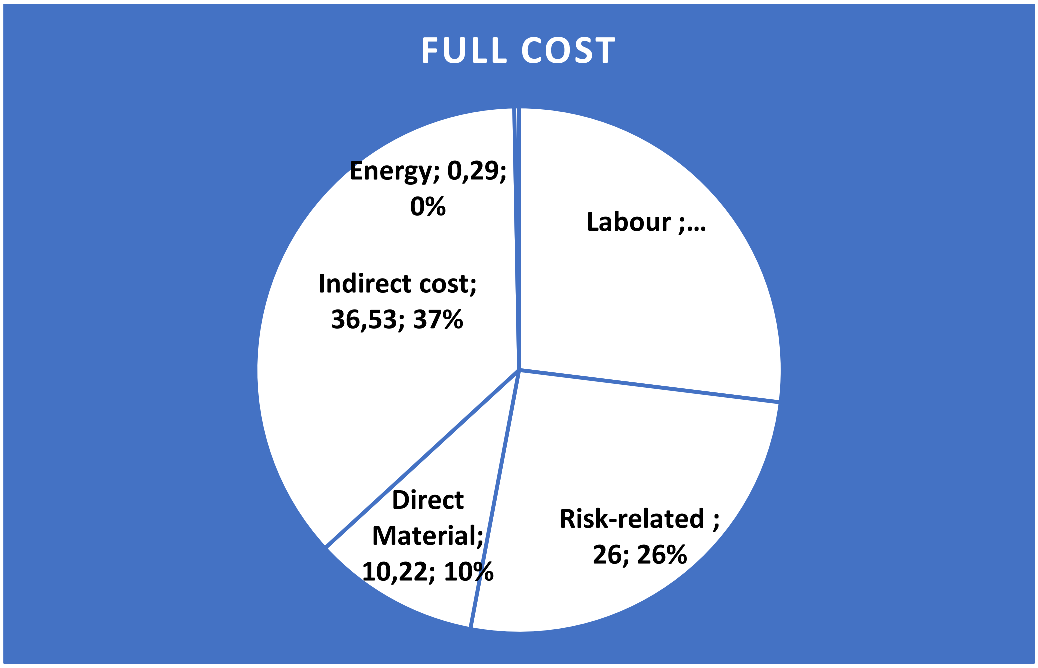


Figure 8.6: An indication of a full cost model.

8.2.3 Capabilities of AM

From the Wohlers Report 2018 (Wohlers, 2018), it is clear that industrial AM systems are used for a wide range of applications, such as:

- visual aids;
- presentation models;
- prototypes for fit and assembly;
- patterns for prototype tooling;
- patterns for metal castings;
- tooling components – functional part; and
- education/research.

Interesting facts captured in the Wohlers Report 2018 (Wohlers, 2018) are that 33,1% of AM technologies are used to produce functional parts and the mention of the I2P lab developed in South Africa to support education in AM. The cost of AM is intertwined with software platforms and design for AM abilities of these platforms. Some of these platforms have developed into generative design technologies that are now integrated with some solid modelling products. Generative design takes an evolutionary approach to design by applying materials, parameters, methods, and cost to the geometry.

Considering the nature of these processes, new management methods should be developed to take full advantage of the capabilities of AM. In this setting, the above-mentioned method used to obtain an optimal ERP method for AM platforms was proposed, considering both design requirements and manufacturing constraints.

The dilemma faced when investigating the digital interface with the customer as a website-based philosophy is the effect of build volume capacity utilisation, ancillary process steps, the effect of build failure, and design adaptation. In this instance, one also needs to realise the operator can assign unused volume (machine capacity) to another job. In most cases, this job will be unrelated with regard to geometries and customer. This puts forward a new basis of argument, namely how to predict the cost of a new inquiry via the script on the website utilising an STL drawing format as the input.

This aspect is integrated into the cost estimation framework utilising the latest stacking software for build volume packing, drawing on a basket of sample geometries. It was determined that the unit cost in mixed builds at full capacity is lower than in builds limited to a mono-geometry; in the study, this results in a mean unit cost overstatement of up to 157%, evident from the analysis in this chapter.

The magnitude of the problem is indicated clearly in the price range of 1000 R/kg to 2000 R/kg in the graph in Figure 8.7.

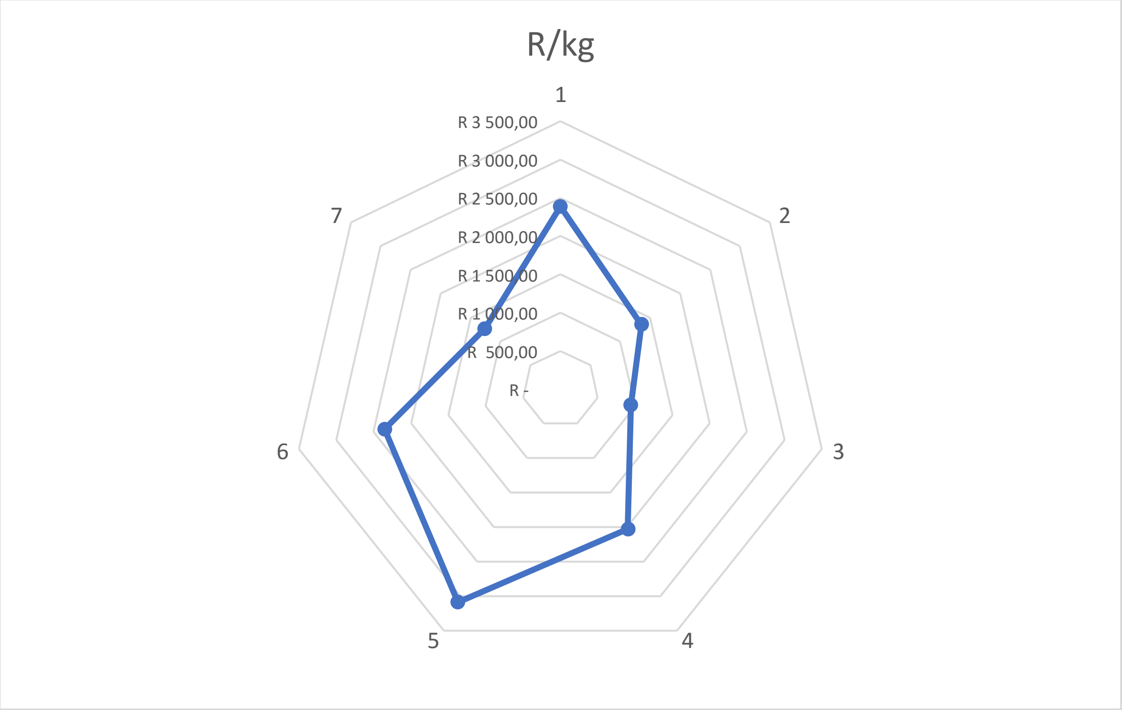


***Figure 8.7: Deviation from target price R/kg*.**

Although this approach offers interesting possibilities, existing work has been carried out in applying this new line of thought; however, it is still poorly understood. A possible reason is that these processes are still relatively new, little known in existing industries, and different from conventional manufacturing processes. The resistance to change may deter industry role players from utilising AM effectively to enhance their capabilities and international competitiveness (Baumers, Holweg & Rowley, 2016; De Beer et al., 2016).

The ultimate objective was to develop and advantage local companies by making industrial AM technologies available to them. In this research, the author aimed to report on the data analysis from the AM Department, focussing on information Available from: the PDM system. The thesis aimed to report on the benefits, disadvantages, and potential of the different platforms under the umbrella of devising and implementing all-encompassing management and operational tool (ERP for AM platforms). Unfortunately, because the PDM aspects could not provide the necessary information to address this gap, the team needed to review the current total cost model for AM processes and measured the key variables in a series of experiments. As machine technology improves and aspects such as process stability and material cost advance further, the economic case for AM is likely to progress. Thus, the value of the parameters in the model is likely to change over time; however, the model itself will remain valid.

One can make a case for DIGITAL interfaces with all the advantages that go with the implementation thereof. However, if the fundamentals are not properly in place, one needs to be careful to commence with implementing it. It is clear from the literature that a properly installed and managed ERP system is a great aid. However, the technical problems experienced with weak information from the PDM system have necessitated a new investigation to remedy the problems identified when researching this topic.

8.3 GRIPTECH Case Study: Volume-based Rapid Manufacturing

A significant development was undertaken with GRIPTECH – a past collaborator (and provider of equipment to the VUT). GRIPTECH develops machines; amongst others, educational and other small CNC apparatuses.

GRIPTECH approached VUT, as it needed guidance in the production planning to produce AM batch-manufactured parts (end-use, directly manufactured machine parts, which would be time consuming to do with injection moulding). A further aspect was the injection moulding cost and lead time to produce the parts. GRIPTECH needed a total of 80 sets of components, totalling 800 individual parts, which were planned in four batches and laser sintered in PA2221 on the EOS P760 and EOS P100. Certain parts were coloured red by means of an in-house-developed colouring process (developed at VUT).

The costing and overheads were broken down as follows:

Competitive pricing structure: R230 001.79

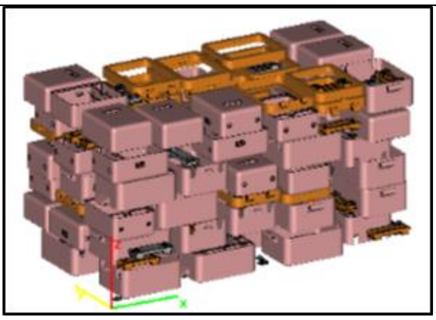
With the subsidy, the client paid R183 351.88 cost per part: R218.27 per part.

The short lead time of fewer than three weeks for manufacturing a mould excluded manufacturing these parts using conventional tooling; thus, large-batch laser sintering was the only option. In Tables 8.5 to 8.8 below, the job reports are explained in more detail.

Batches built: Job Report: 20160822 P760 VUT

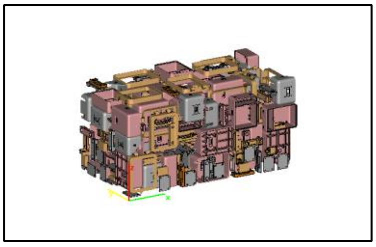
8.3.1 Platform properties

Table 8.5: 1. Job Report: 20160822 P760 VUT Grip

Build name	20160822 P760 VUT	
Machine	P760	
Material	PA2221	
Number of parts	180	
Build height	333.998	
Layer thickness	0.12 mm	

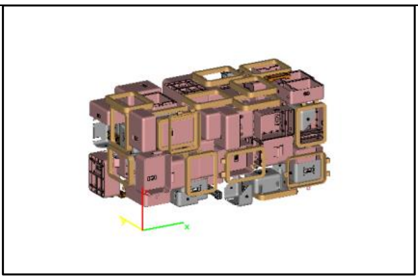
Job Report: 20160824 P760 VUT Grip

Table 8.6: 3. Job Report: 20160824 P760 VUT Grip

Build name	20160824 P760 VUT Grip	
Machine	P760	
Material	PA2221	
Number of parts	460	
Build height	345.598	
Layer thickness	0.12 mm	
Post processing	Bead blasting	

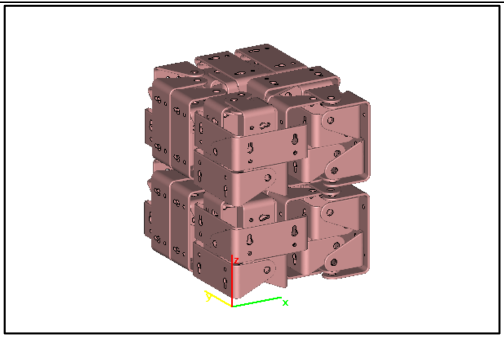
Job Report: 20160825 P760 VUT Grip

Table 8.7: 4. Job Report: 20160825 P760 VUT Grip

Build name	20160825 P760 VUT Grip	
Machine	P760	
Material	PA2221	
Number of parts	120	
Build height	361.498	
Layer thickness	0.12 mm	
Post processing	Bead Blasting	

Job Report: 20160825 P100 VUT Grip 80

Table 8.8: 5. Job Report: 20160826 P100 VUT Grip

Build name	20160826 P100 VUT Grip	
Machine	P100	
Material	PA2221	
Number of parts	80	
Build height	229.517	
Layer thickness	0.10 mm	
Post processing	Bead blasting	

Thus, a production batch of 840 parts was produced in four builds.

This was done competitively to injection-moulded options, due to the price and production time and negating a mould. The images in Figure 8.8 below show pictures of the parts and post processing:

Figure 8.8: Bead blasting of parts.

Figures 8.9 and 8.10 are an indication what happens with post processing: first, the excess material is removed from the components using the bead-blasting process, and afterwards the products are coloured with an industrial grade dye.

Figure 8.9: Finished parts.

Figure 8.10: Finished parts.

9. CONCLUSION

9.1 Effects on the Industry

AM will realise its disruptive pinnacle and achieve full economic effect with narrowing the focus to become a sequential manufacturing technology for end-use products, only when the assembly capability is fully realised. The maximum effect will be achieved only when manufacturers begin to produce their end products by means of AM and thus yield a contributing amount of their revenue from this share.

The new costing elements that require attention in the pricing space are linked to the following key aspects of AM: efficient production, low reject rates of components, and fast manufacturing of end-use technology with an element of customisation. Willing customers see the following aspects as worthwhile, and this is part of the costing philosophy that is not covered in a simple algorithm to determine cost. The author emphasises the following as important examples:

- “Development agile manufacturing which will reduce the lead time from conception to the production (Time-to-Market);
- AM platforms have a chance to revolutionise low-volume manufacturing of complex parts; and
- Usage in biomedical application, customized manufacturing and by the application in automobile and aerospace (EY Global 3DP Study, April 2016).
- Multiple technology approaches: great variety.

For this thesis, work was done on a single platform. In reality, the industrialist has a broader choice of technologies to consider his decision-making process. Figure 9.1 below provides an overview of this variety.

Dependence on application approaches and the selection of a technology best suited for this particular application is possible, with a range of materials that can be considered based on the capability of the technology.

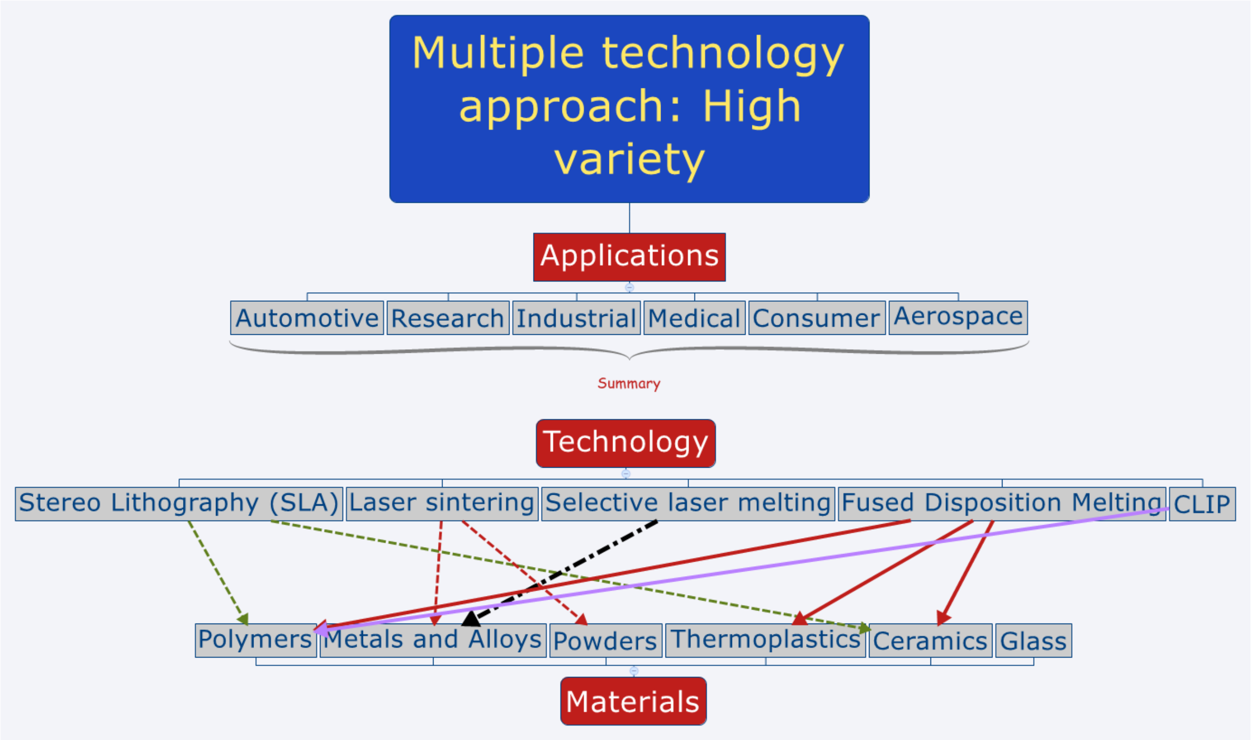


***Figure 9.1: Multiple technological approaches linked to technological applications and material options to indicate all the options that are available to the industrialist*.**

9.2 Global Perspective

The fact that the customer can interrogate the quoting system with solutions, such as seen in Objective 3, fits into the global perspective. The connection between the digital and physical world has been democratised to the level of individual makers and consumers improved by the influence of artificial intelligence, augmented reality, advanced robotics, smart devices, and AM creating a new revolution – INDUSTRY 4.0 (Costabile et al., 2017; Kearny, 2018).

3D printing has been available since 1967, although statistics indicate a significant effect by this technology since the early 1980s. In the last decade, AM became more prominent as the leading technology and therefore convinced business leaders that this option indeed proves to be a game changer (Costabile et al., 2017).

The scope of 3D printing has increased in the last decade. The latest AM offering offers solutions for many types of industries. The costing element, which was the critical objective of this thesis, can provide the insight for the industrial sector to make proper decisions. The thesis mentions the current levels of advancement for the technology, while linking it to future trends. Although the calculation was based on laser sintering, it provides a multi-stakeholder view of the industry.

To integrate the global perspective with the reality in a typical batch AM facility, the thesis had to integrate the opinion of several experts and incorporate the knowledge gathered over the past five years at the advanced manufacturing precinct at the Vaal University of Technology (VUT) in Gauteng. If one analyses the statistics Available from: the PDM at the VUT, it is clear that the technology matured to readiness level that engages with industry. The technology deals with sectors related to aerospace, automotive, consumer goods, electronics, energy, logistics and transportation, mechanical plant engineering, wholesale, retail, and kindred services (Thomas & Gilbert, 2014).

The local and global interest in AM has escalated beyond everybody's imagination in the past five years; both end users and manufacturers show significant interest in this technology. The new perspective is clear from the nature of the AM business, which has matured from a rapid prototyping endeavour to an industrial solution business.

Research by Ernest and Young's (2016) points out that component cost is still an issue, although captains of industry believe that much has been achieved in the last years. A group of people still believe that AM has no effect on their businesses or operations (Ernest & Young, 2016). The costing element drives new research into materials and technology to determine the success of individual competitors in the market, which is a clear indication that manufacturers are showing keen interest in this technology. Industries that have already adopted AM in their production setup believe that the technology is affecting their business strongly, and most leaders of industry indicate that AM is an important strategy or at least an important topic for their business. A survey conducted by Ernest and Young (2016) indicates that approximately 24% of companies included in the survey had already gained relevant experience of AM technologies, and a further 12% were considering adopting the technology. Companies that have already ventured into AM are at a different level of maturity. Other companies are just beginning to experiment with AM, while some of the companies have integrated AM with the operations of individual divisions. Most of the companies have a clear goal of how AM could bring them competitive advantages.

9.2.1 Value at play

The freedom of an online quoting system with the tools developed, as discussed in Objective 3, supports the fact that AM will change the fortunes of the economic world globally. It will have a significant effect globally concerning economic growth, higher-skilled jobs, and a more sustainable future for the manufacturing world.

9.2.2 Economic value

The following formation in the manufacturing sphere emphasises the magnitude of the costing relevance in the world economy: Kearney (2018) predicts that AM is ready to disrupt $4 to 6 trillion

(USD) of the current world economy within the next five to ten years. Furthermore, this segment of the economy has the highest potential to be re-distributed globally (Kearney, 2018).

The global manufacturing sector is estimated at approximately $12 trillion USD. In this calculation, the following sectors were considered: design, production, and logistic flow of universal goods. Kearney (2018) states that the following five key industries have the most significant potential to be transformed by AM: heavy industry, automotive, consumer products, healthcare and medical, and aerospace. The work in this thesis relate to identified industries that are jointly responsible for 76% of the global manufacturing sector. Surveys conducted by industry experts forecast that 23% to 40% of parts in these sectors will be converted to AM within the next 5 to 10 years (Kearney, 2018).

The thesis work in the ambit of industry that, according to Kearny (2018), will grow the USA economy with $600 billion to $900 billion per annum if the USA economy capitalises on the potential of AM. The report also points out that South Africa is a close follower in this scenario, which is mimicked in the PDM customer data in the VUT body of knowledge. The solution arrived at in Objective 3 is relevant to the increased access to tools that will compare manufacturing options.

AM products generate revenue share, and manufacturers that already have adopted AM state that AM contributes 2% of their revenue.

Ernest and Young (2016) indicate that 38% of the respondents in their study reported that they planned to convert some of their production to AM.

AM can become part of production in one of the following three ways:

- AM can be incorporated as a supplementary manufacturing technology in the existing manufacturing set up.
- AM can be combined with conventional manufacturing technologies as part of the production set up.
- Total conversion to AM to replace traditional method.

One of the apparent advantages of AM is the on-demand production capability. Furthermore, to be close to the customer, this implies an option to develop an operating model based on contract manufacturing, providing access to different technologies and specialised expertise (Thomas & Gilbert, 2014).

The use of AM has increased significantly in previous years. Multiple industry subsectors, including motor vehicles, aerospace, machinery, electronics, and medical products, use AM. Currently, however, additive manufactured products represent less than one per cent of all made products in the US. As the cost of AM systems improves, AM may change the way in which consumers respond to new products and the producers. AM technology unlocks new opportunities for the global economy and countries. AM can lead the customisation of new products and manufacturing of durable and functional light-weight products and accommodate designs that were not possible with conventional manufacturing systems and techniques. However, numerous stumbling blocks can prevent and impede the implementation of AM. In some instances, the cost of manufacturing a product using AM processes exceeds that of conventional methods. This thesis interrogated the expenses of AM and sought to identify instances where AM is the cost-effective solution and also identified potential means for reducing costs when using this technology.

9.2.3 Additive manufacturing costs and benefits (direct cost consideration)

In principle, the author considered cost of parts; however, the reality of the broader perspective equates to a bigger realisation, when assembly costing is considered in the calculation model. Overheads can be structured as labour, material, and machine costs; it can also be augmented to the involvement in build failure, machine setup, and inventory. The literature study conducted by Thomas and Gilbert (2014) indicates that the main cost drivers in an activity-based model are material and machine costs. The significant result of the many comparisons by Thomas and Gilbert in their research in this field is that the cost per assembly of SLS parts compared more than favourably with conventional injection moulding for volumes of fewer than 20 000 assemblies. The focus on the opportunity to use AM platforms to generate assemblies is the pinnacle of this technology. The simple reality is that, since complexity does not affect cost, the result of Objective 3 is a handy costing tool. The significance of assemblies is that this will absorb downstream cost in the costing algorithm of the specific platform, which needs to be part of an economic consideration.

9.2.4 Material cost (direct cost consideration)

The part that the author considered in the analysis is a good example to reference in geometric freedom aspects of AM, which allows products to be produced using less material without sacrificing component performance. With proper AM design protocol, production exceeds the performance levels embedded in traditional manufacturing. The current drawback around specific material is the fact that the specific elements required for AM exceed the cost prices of conventional materials (Thomas & Gilbert, 2014). Thomas and Gilbert (2014) indicate that material cost for laser sintering amounts to between 55% and 69 % of the value of the product. Thus, it is one of the key considerations in any economic analysis and a key consideration in the algorithm developed to capture cost.

9.2.5 Machine cost (indirect cost consideration)

The Wohlers Report 2018 (Wohlers, 2018) shows the cost of machines is trending downwards. The bottom line is that machine cost is the other significant driver of part cost, and it ranges from 59% to 66% of the cost of a typical plastic component. The machine cost is the other key cost driver in this technology arena. The machine cost drives the magnitude of depreciation as an indirect cost in the full cost model.

9.3 Build Envelope and Envelope Utilisation (Indirect Cost Consideration)

The size of the build envelope is affected by two aspects of the cost of an additive manufactured product. First, the build envelope determines the size/volume of the product that can be manufactured. Second, the effect of the build envelope relates to the utilisation of the available build volume.

9.3.1 Build time (direct cost)

Build time is related to machine cost, and the research was based on the utilisation of the P100 platform as recorded in the on-board parametric system. A build rate of 14 mm per hour was typical for the P100 platform.

9.3.2 Energy consumption (direct cost)

Thomas and Gilbert (2014) conclude, as concluded in Objective 2, that with the energy consumption analyses, one should also consider the energy required to manufacture the raw material as well as the energy consumed when manufacturing the component. The conclusion of this research was that approximately 60% of the energy was used in the polyamide production and 37% was consumed during the component manufacturing with SLS (Thomas & Gilbert, 2014).

9.3.3 Labour cost (direct cost)

In correlation with the findings in Objective 1, direct labour tends to be a small portion of the AM cost. Labour includes activities like removing the finished product or refilling the raw material, estimated at 2% to 3% of the total cost (Ruffo, Tuck & Hague, 2006). This corresponds with the PDM at the VUT.

9.3.4 Finishing cost (direct cost)

Owing to the AM process, finishing costs that improve the appearance of the component always need to be considered, depending on the end use of the element. The latest development is that designers incorporate the layer-by-layer appearance in the overall design of the element. At the VUT, extensive research was done on the aspects of finishing; for this thesis, it is enough to identify this cost. It is important to understand that this can be a significant cost driver based on customer requirements.

9.3.5 Cost models and comparisons for cost modelling of additive manufacturing

The two models that requires mentioning in this thesis are those by Hopkinson and Dickens (2003) and Ruffo, Tuck and Hague (2006). The elements of the two models were considered in developing the cost models in Objectives 1 to 3, because both models involved true platform-based component cost. The first model that considered the manufacturing of a component was utilising maximum build volumes, and the machine was in operation for 90% of the time. This model also considered labour, material, and machine cost.

The second model calculated cost using an activity-based costing model similar to the model in Objective 2, where each cost is associated with a particular activity. Model 2 includes computing the direct and indirect cost represented in the cost of the build model in Figure 9.2. The majority of cost studies assume a scenario where a uniform part is produced repeatedly; however, the benefits of AM is the ability to create different components simultaneously.

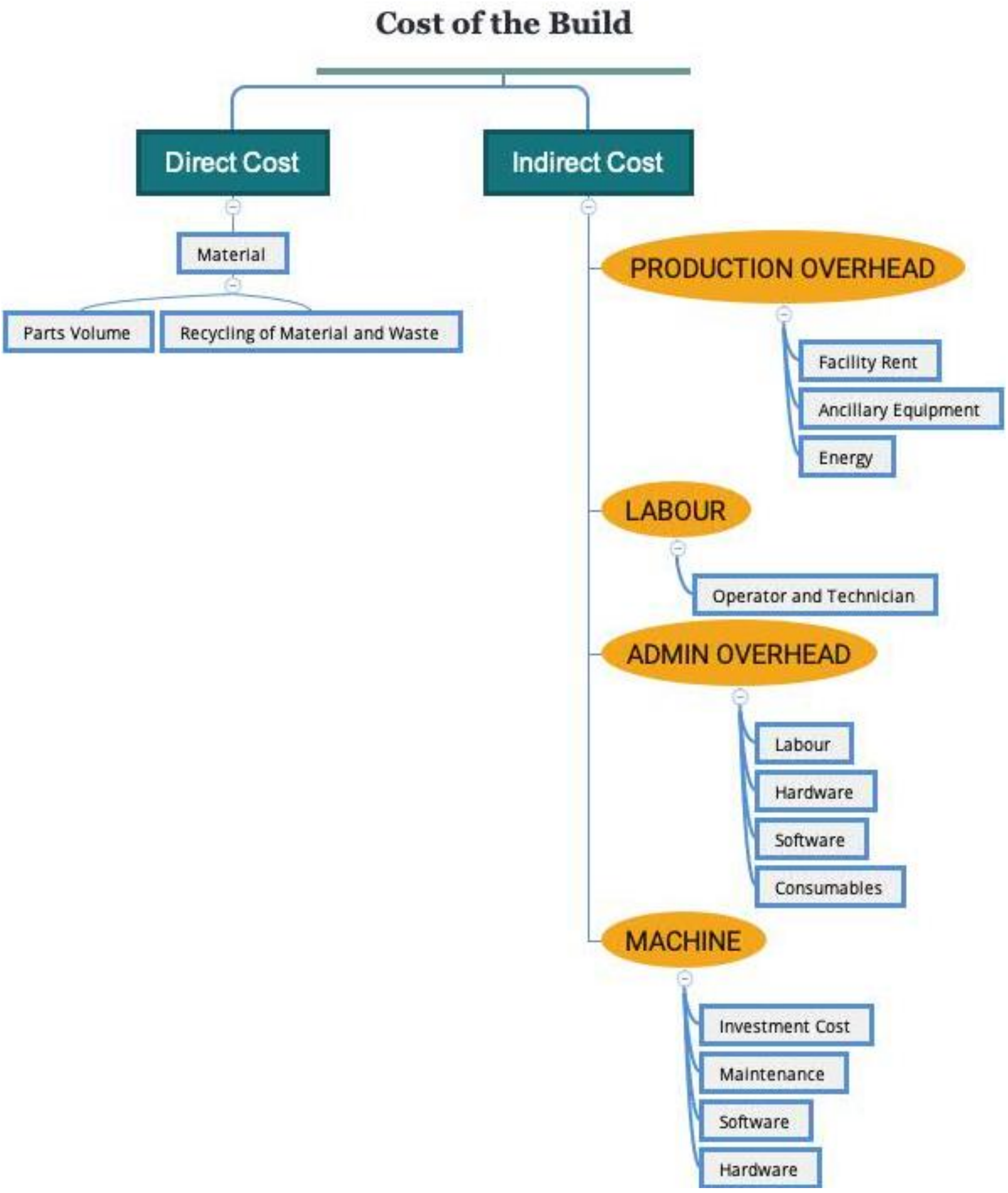


Figure 9.2: Diagram of the Ruffo, Tuck and Hague (2006) activity-based cost model.

9.3.6 Cost advantage of additive manufacturing

Most of the cost analyses in the literature studied derived from the cost of materials and machines. The reality that cost accountants deal with is different from the understanding of AM process cost. To benchmark AM cost against conventional manufacturing cost, one needs to investigate the total supply chain. In most cases, parts manufactured and shipped for assembly originate from different factories with their material inventory, finished goods inventory administrative staff, and transportation infrastructure, among other things. Using this holistic approach benefits AM, because the components utilising AM use less material, perform as required, and last longer because the design is not limited to the methodology practised in traditional manufacturing. Many of the benefits that should be included would not be captured in the conventional costing models, as research in the literature study in this thesis indicates.

Incorporating the findings in this thesis, according to the author, the current assumption that AM is cost effective for manufacturing small batches is based on inadequate research negating the influence of increased automation and mass customisation. AM has implications for the cost of production and the added value arrived at when one considers freedom of design, material, and platform. It is also essential to calculate the AM ability to produce an assembled final product, which makes AM competitive, although none of the cost models considered this advantage.

From the information above and the case studies presented in this research, it is evident that the use of AM technologies for production, as opposed to prototyping, has increased in companies like GE, Boeing, and Airbus.

The slow initial adoption of the technology is likely due to the caution and resistance to change evident in many well-established industrial fields (Gartner, 2016). The high current cost of producing patterns and moulds using AM tends to make cost-conscious companies more apprehensive about relying on AM. It may also be assumed from the rapid increase in AM usage after gaining the confidence of these industries that, once AM has been experimented with, it has proven viable for use in production.

It has been shown at the VUT with the Voxeljet technology that the ability to produce highly accurate and complex geometry in wax-infused PMMA and silica sand has allowed local companies to compete effectively in the global market. Both cost and time savings have been observed within the local foundry sector by implementing AM technologies. This sets the stage for a promising future for the local manufacturing industry.

Regarding design for AM, engineers in industry, once being familiarised with AM capabilities, have begun exploiting these innovative ways; thus, the diffusion of AM-centred design skills has begun to develop naturally, showing that even established industries, such as foundries, are willing to venture into the realm of design freedom that AM offers. This is an extremely encouraging development.

All the literature research and study done for this thesis, as well as the in-house body of knowledge, point out that AM is the way to go for small to medium batch manufacturing. The depreciation contribution to total cost is the major contributor to the total cost. Other processes affect the total cost marginally.

The cost analysis emphasises the pertinent contribution of machine cost per part as a significant cost element, as discussed in Chapters 3 and 4. The other components of the costing models are low in contribution. The high cost of feedstock (raw material) superimposed on the high platform cost is punitive towards the component cost.

The current drive to optimise inventory levels will accelerate the diffusion of AM platforms as ordinary production systems and manufacturing processes. The consequent logic is that higher demand will improve competition and reduce system prices. The break-even point will move towards larger production volumes as presently considered in the current price milieu.

The positive effect link to the advantages of additive thinking and applying the design for additive manufacturing (DFAM) principles are not evident in the current costing models. The DFAM principles will help to exploit the full benefit of the freedom factors that will swing the advantage in the favour of AM.

The other unique benefit with AM technologies is if one integrated assembly, which reduces or eliminates cost, time and quality issues resulting from assembling line operations. Correct design with proper part consolidation can negate assembly cost. Modern software with Topology optimisation and other design aids can ensure optimum strength to weight ratios.

9.3.7 Cost linked to how AM can benefit business

If the information that was considered in this thesis is applied to answering the question, the answers are as follows:

- The cost of entry is becoming more affordable:

  The cost to acquire AM equipment for manufacturing setups is becoming more affordable. Reliable industry-level machines can be procured at R10 000. The costing tools in Objective 3 are good to ensure sustainability and to help to increase production.

- The ease of revision:

  AM is not only about the physical product. It is about bringing design and innovation into the equation. Creative freedom without considering cost or time penalties is one of the principal advantages of additive manufacturing.

- Design for AM:

  The advantages to train people to design for additive manufacturing is still one of those questions that is not fully answered. The reality is that fundamental training is now available for those who have experience with tools of technology, which can aid companies with product development and design.

- AM minimises waste production:

AM technologies generate significantly less waste than conventional manufacturing technologies.

9.4 Future Research

AM technology demonstrated positive growth during the past eight years after the global market decline that was experienced in 2009. The average annual growth rate of international revenue produced by all products and services over the past 29 years is an impressive 26,6%. (Wohlers, 2018). If focus has to be placed on the past four years, from 2014 to 2017, Wohlers (2018) reports a phenomenal growth rate of 24.9% in 2018 (Greyling, 2016).

All the major industries like Boeing, Airbus, Adidas, Ford and Toyota are investing in AM technology. Future research should focus on skills training designed for AM and the management of an AM facility. To make a significant research contribution, it is recommended that institutions augment curriculums to foster understanding of these technologies and the management of these technologies in the maintenance required for the different platforms. The focus should be on applied research and how to utilise the technologies do ensure the best possible outcomes. The research done in this thesis has made it clear that AM should not be viewed in isolation but be included holistically as part of the bigger supply chain. Future research needs to be based on a holistic approach, to ensure accurate cost calculations. Future research needs to be based on multiple disciplines.

In view of international literature pertaining to AM, it is clear that AM has reached a point of influx. This has a significant effect on the road ahead for the South African manufacturing industry. It is notable to realise that many companies have adopted AM in one form or another, especially in the research and development department. The total investment in AM is difficult to estimate, since most of the figures quoted exclude significant investment by big companies like GE, Airbus, Boeing, and Ford (Thomas & Gilbert, 2014).

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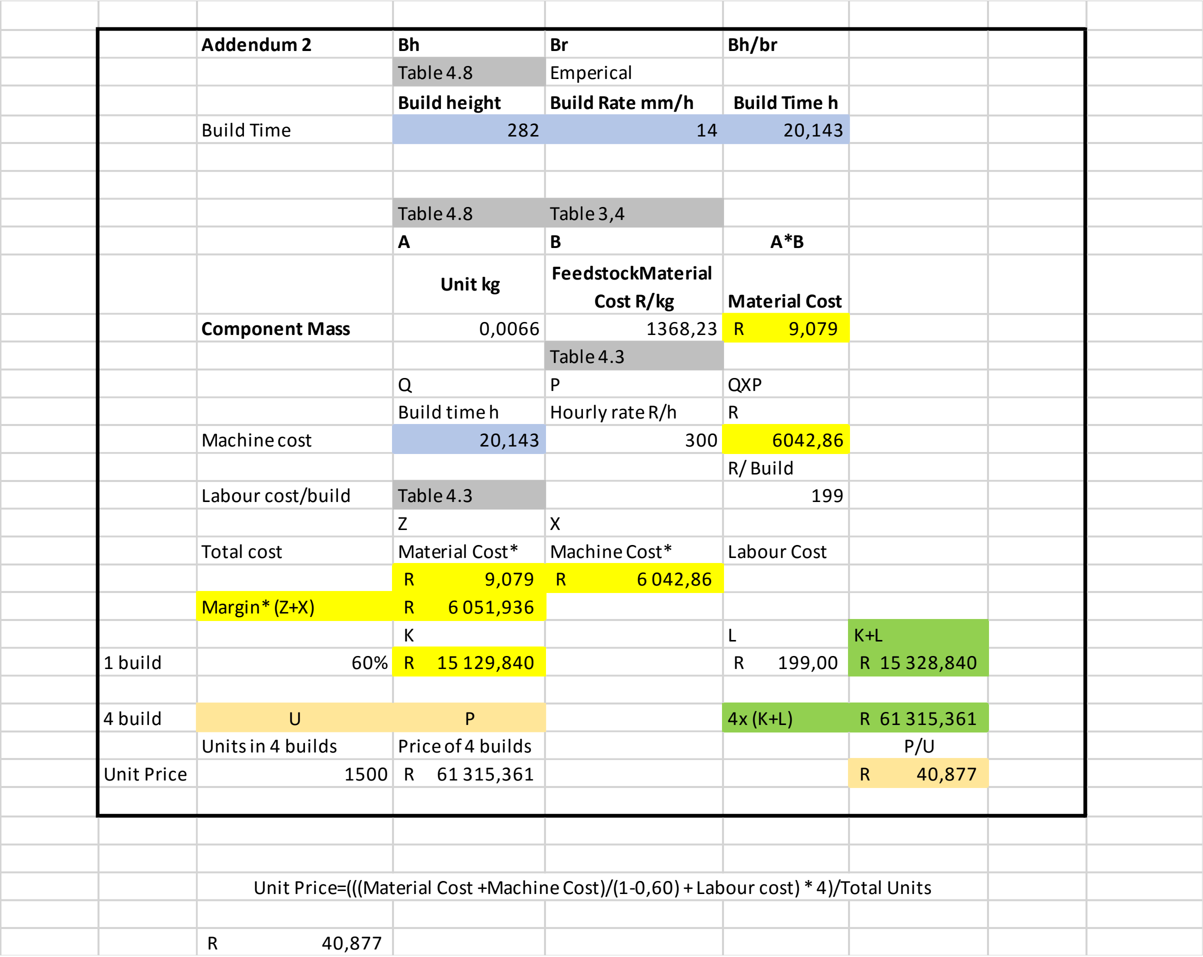
ADDENDUM 1 : POLICY FOR RESPONSIBLE RESEARCH CONDUCT AT STELLENBOSCH UNIVERSITY

POLICY FOR RESPONSIBLE RESEARCH CONDUCT AT STELLENBOSCH UNIVERSITY Document reference number	**BEL-001E-2013**
Purpose	**To promote and ensure research integrity and the ethical conduct of research**
Type of Document	**Policy**
Accessibility	**General (internal and external)**
Date of implementation	**June 2013**
Revision date	**Jan 2016**
Revision history	**V1 Approved March 2009**
Rewritten 2012/13	
Policy Owner	**Vice-Rector (Research and Innovation)**
Institutional curator of this policy	**Senior Director: Research and Innovation, Division for Research Development**
Entity responsible for policy development and revision	**Senate Research Ethics Committee**
Date of Approval	**SU Council: 24 June 2013**
Approval by	**Rector's Management Team, Stellenbosch University Council, Institutional Forum and Senate**
http://www.sun.ac.za/english/policy/Documents/Research%20Ethics%20Policy.pdf	
Key words	**research ethics, research integrity, accountability, stewardship, animal research ethics, human participant, environmental ethics, biosafety**

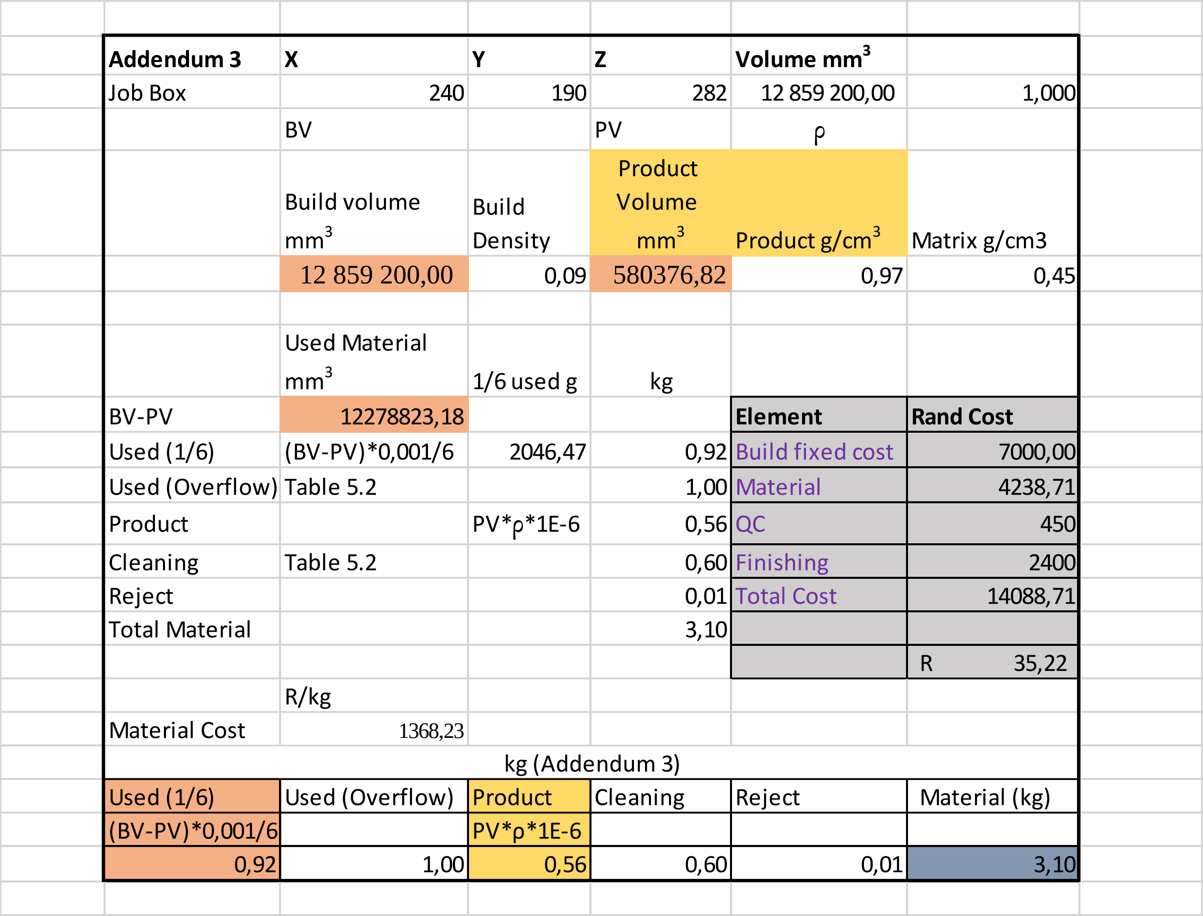
ADDENDUM 2 : REFERENCE TO TABLE 4.2



	Addendum 2	**Bh**	**Br**	**Bh/br**	
		Table 4.8	Emperical		
		Build height	**Build Rate mm/h**	**Build Time h**	
	Build Time	282	14	20,143	
		Table 4.8	Table 3,4		
		A	**B**	**A*B**	
		Unit kg	**FeedstockMaterial Cost R/kg**	**Material Cost**	
	Component Mass	0,0066	1368,23	R 9,079	
			Table 4.3		
		Q	P	QXP	
		Build time h	Hourly rate R/h	R	
	Machine cost	20,143	300	6042,86	
				R/ Build	
	Labour cost/build	Table 4.3		199	
		Z	X		
	Total cost	Material Cost*	Machine Cost*	Labour Cost	
		R 9,079	R 6 042,86		
	Margin* (Z+X)	R 6 051,936			
		K		L	K+L
1 build	60%	R 15 129,840		R 199,00	R 15 328,840
4 build	U	P		4x (K+L)	R 61 315,361
	Units in 4 builds	Price of 4 builds			P/U
Unit Price	1500	R 61 315,361			R 40,877
	Unit Price=(((Material Cost +Machine Cost)/(1-0,60) + Labour cost) * 4)/Total Units				
	R 40,877				

Addendum 2

ADDENDUM 3: REFERENCE TO TABLE 6.2



Addendum 3	**X**	**Y**	**Z**	**Volume mm^3**	
Job Box	240	190	282	12 859 200,00	1,000
	BV		PV	ρ	
	Build volume mm^3	Build Density	Product Volume mm^3	Product g/cm^3	Matrix g/cm3
	12 859 200,00	0,09	580376,82	0,97	0,45
	Used Material mm^3	1/6 used g	kg		
BV-PV	12278823,18			**Element**	**Rand Cost**
Used (1/6)	(BV-PV)*0,001/6	2046,47	0,92	Build fixed cost	7000,00
Used (Overflow)	Table 5.2		1,00	Material	4238,71
Product		PV*ρ*1E-6	0,56	QC	450
Cleaning	Table 5.2		0,60	Finishing	2400
Reject			0,01	Total Cost	14088,71
Total Material			3,10		
					R 35,22
	R/kg				
Material Cost	1368,23				
kg (Addendum 3)					
Used (1/6)	Used (Overflow)	Product	Cleaning	Reject	Material (kg)
(BV-PV)*0,001/6		PV*ρ*1E-6			
0,92	1,00	0,56	0,60	0,01	3,10

Addendum 3