A lean project management framework for additive manufacturing

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Dissertation submitted in fulfilment of the requirements for the degree *Master of Engineering in Development and Management Engineering* at the North-West University

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Graduation ceremony: May 2019

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Contents

Abstract

This study aims to present a lean project management framework for the additive manufacturing industry (AM). This framework will contain critical elements of project management (PM) and will intend to add value to an organisation by outlining a body of knowledge, processes, skills, tools, and techniques. The PM framework will further aim to improve the efficiency and performance within an AM organisation.

The PM framework will be developed from a lean perspective and focusses on the core idea of maximising customer value while minimising waste. The fundamental purpose is to improve productivity, improve the quality of products, to make production more flexible and to substantially reduce waste within an AM environment. The aforementioned will be defined within the main constraints of time, cost, scope, quality and good customer relationships.

The study will focus on the primary question, that if AM is identified as a lean manufacturing technology, how do AM organisations manage their design and development projects. The research will focus on the development of a framework, using the Delphi method, for the implementation of lean principles to AM project management.

Keywords: Lean manufacturing, project management, additive manufacturing.

Chapter One

1.1. Introduction

The aim of this study is to present a lean project management (PM) framework for the additive manufacturing (AM) industry. The PM framework is developed from a lean perspective and focusses on the core idea of maximising customer value while minimising waste. It is frequently suggested that lean should be understood on a strategic level of how to understand value; and on an operational level (tools) of how to eliminate waste (Hines, Holweg & Rich, 2004:995).

Part of this study will aim to prove that if lean's goal is to produce utilising fewer resources with an emphasis on waste elimination, then AM as a manufacturing technique can be classified as lean. AM has the advantage of using less waste production methods since they are additive methods rather than subtractive methods. AM is not only about reducing materials but also elements such as energy, production space and equipment, some stages of assembly, part consolidation, fewer set-up times, less human effort, less transportation, less packaging process and less delivery time and a reduced number of suppliers.

The developed framework concentrates on the basic project management processes and principles as prescribed in the Project Management Book of Knowledge (Kerzner, 2012:02). These processes will advocate the principles of a lean approach, and it will recognise these crucial dynamics in the AM environment.

Many authors portray a framework through diagrams and graphical representations. A framework is referred to as a prescriptive set of things to do (Anand & Kodali, 2008:207). There is a general acknowledgement that the researcher must develop a prior view of the general constructs or categories that are to be studied, and their relationships. The aforementioned prior view is often supported in the shape of a conceptual framework (Mellor, 2014:77).

This study will aim to present a lean project management framework which will outline the efficient project management practices, required to repeat the process in additive manufacturing. This conceptual framework will refer to the PM processes, activities and tools, lean principles and AM process, requirements, and benefits. This conceptual framework will accomplish the objectives of project management and lean in additive manufacturing; identify the fundamental, critical and value-added elements of project management in AM; and propose an appropriate set of approaches, methods, and tools to repeat in an AM environment. The conceptual framework will be defined within the main constraints of time, cost, scope, quality and excellent customer relationships and five process groups as identified in the PMBOK Guide, namely: project initiation, project planning, project execution, project monitoring and control and project closure (Kerzner, 2012:02).

In a study on implementation guidelines, based on the topology of AM business models by Lutter-Gunther, a recommendation is made that a paradigm shift is required on an operational and strategic level, to adjust processes and structures. Limited research is done on the implementation of AM, and this study has found insufficient evidence of specific project management in current AM environments. AM business models can be characterised by the way customer value is increased and how the effort to create this value is reduced using AM (Lutter-Gunther, Seidel, Kamps & Reinhart, 2015:549).

The proposed lean management framework will aim to offer a consolidated project management method to help project managers to plan and manage project efforts in an AM environment effectively.

1.2. Problem statement

Additive manufacturing and mass customisation are two of the most important identified processes to guarantee high value manufacturing in developed countries, such as the UK and Germany. (Deradjat, 2015:2079).

A lack of research in the implementation of AM and the specific focus of a lean approach to project management in additive manufacturing, is evident from the literature review.

(Deradjat, 2015:2081), (Lutter-Gunther, 2015:798), (Mellor, 2014:05). Despite all the contributing reviews of AM in different sciences and research areas, limited available research covers the management of AM and proposes research directions focused on its strategic and operational dimensions. (Niaki, 2016:1419).

This study will aim to emphasise the impact that both lean and PM have on AM and will attempt to gain a better understanding of how these two processes can be aligned to the advantage of AM. As required from lean, a clearly identified and appropriate framework should aim to aid this process of continuous improvement.

This literature review, as done according to the researchers' ability, has produced no conclusive evidence of a standard lean PM approach in AM. The researcher is thus of the opinion that each organisation or industry should develop its own approach, including AM.

If we want a lean approach to PM to be successful in an additive manufacturing environment, we need to apply it to a specific problem. It can therefore be deduced that the specific problem identified from the literature review is the development of a lean project management framework for additive manufacturing.

1.3. Literature review

This section presents the literature review, and it aims is to introduce the primary research subject and questions from which the study will proceed. To create a beneficial relationship between AM and PM, the fundamental principles of lean should be outlined, PM and AM and why a lean approach to PM could be a possible method of managing an additive manufacturing/production process or environment.

1.3.1. Lean

The definition of Lean according to the Lean Enterprise Institute is: "The core idea is to maximise customer value while minimising waste. Simply, lean means creating more value for customers with fewer resources" (2004:995). It is frequently suggested that lean should be understood on a strategic level of how to recognise value; and on an operational level (tools) of how to eliminate waste (Hines *et al*., 2004:995).

The concept of lean manufacturing was introduced in Japan, and the Toyota production system was the first to use lean practices. The idea of lean in production dates to the 1950's and has been discussed and propagated thoroughly in many publications. The purpose was to make the American auto industry as competitive as the Japanese production system, as developed at Toyota (Hasle, Bojesen, Jensen & Bramming, 2011:830). Typical features of this system include short storage times, small batch sizes, teamwork, and close relationships with suppliers. The fundamental purpose is to improve productivity, improve the quality of products, to make production more flexible and to reduce waste substantially. This formed the basis of a system called the Toyota production system (TPS). The basic principles of lean production are based on the TPS (Smith, 2011:03).

Crute, Ward, Brown and Graves (2003:919) mention specific terms for the current era of production as mass customisation, flexible specialisation, lean production, agile and strategic, time-to-market and importantly product customisation. The most popular term to describe the current era of production is that of lean. The essential characteristics of lean include integrated production, emphasis on prevention, pulled production, organised teamwork and close vertical relationships (Crute *et al*., 2003:917-928).

Womack (1990:12-15) claimed that lean practices would spread to all manufacturing. "The adoption of Lean production, as it inevitably spreads beyond the auto industry, will change everything in almost every industry—choices for consumers, the nature of work, the fortune of companies, and, ultimately, the fate of nations. (Womack, 1990:12). Womack (1990:278) also claims that lean production will supplant both mass production and the remaining outposts of craft production in all areas of industrial endeavour to become the standard global production system. Womack's predictions were correct, as lean practices have crossed from the automotive sector into other industries successfully.

Authors such as Marodin and Saurin (2013:6674), disagrees on the success of lean and states that the general adaptation of lean in sectors outside the automotive sector is limited and characterised by a partial use of these lean principles and practices. (Marodin, 2013:6673). This may well indicate that lean is not as commonly adapted as some studies have claimed. Marodin and Saurin (2013:6674) also mention some lean drawbacks. These drawbacks include the difficulty of using lean production in sectors other than manufacturing; the lack of in-depth knowledge on why companies fail or succeed in their lean efforts, and the lack of understanding on the complex dynamics involving the use of lean production in all areas of a company. Furthermore, the lack of effective theories and practices to manage the systemic, human and organisational dimensions of lean is also considered to be a drawback.

A further review of the literature on lean manufacturing revealed certain benefits and barriers. Typical gains are reductions in reworking, lower inventory levels and lead time reduction. Hidden interests include the reduction of fatigue and stress, culture change and reduced time for traceability, whereas waste elimination is a financial benefit. Lack of planning, lack of top management commitment, lack of methodology, unwillingness to learn and see and human aspects are the main barriers or problems which can be faced while implementing the lean manufacturing. (Shaman & Jain, 2013: 243). The author concludes that to remain in business it has now become a necessity for all industries to adopt the tools of lean principles.

Hasle's *et al.* (2012:832) literature review on Lean and the working environment quoted Womack and Jones's framework for the lean leap which defines a "one best way". It was concluded that a standard lean model which can be tested for more than one industry does not exist. It is thus a question of each organisation developing its lean practice based on its technical and organisational context, emphasising the positive aspects of lean while trying to reduce the negative ones.

Crute *et al.* (2003:917-928) highlights some important findings in a study which investigated the implementation of lean in the aerospace industry. He concluded that lean capabilities are not firm-specific, but plant specific. To achieve quick implementation results, an organisations' approach needs to be targeted and holistic. Creating a lean system was important, rather than just simply applying unique lean techniques. The eradication of waste and the implementation of efficient flow is achieved through the removal of non-value adding activities from processes; reducing lead times and inventory; and introducing pull systems. These findings indicate that it is possible that lean implementation can be achieved more rapidly in plants and processes where the culture supports autonomous working and learning through experimentation. (Crute *et al*., 2003:917-928).

In a literature review of contemporary lean thinking, Hines *et al.* (2004:1007) concluded that the distinction of lean thinking at the strategic level and lean production at the operational level is crucial to understanding lean as a whole to apply the right tools and strategies to provide customer value.

1.3.2. Project management

Project management is described by Kerzner (2009:03) as "the art of creating the illusion that any outcome is the result of a series of predetermined, deliberate acts when, in fact, it was dumb luck".

Project management is any series of tasks and activities, required to finish projects within certain specifications, deadlines and cost limits, through the utilisation of resources. This process includes the planning, organising, directing, and controlling of an organisations' resources to achieve specific goals and objectives. (Kerzner, 2009:01-03). Projects will be declared successful, if completed within the project constraints of the scope, time, cost and quality. (Kerzner, 2009:07).

The six driving forces that lead executives to recognise the need for PM, includes capital projects, customer expectations, competitiveness, executive understanding, new product development and efficiency and effectiveness (Kerzner, 2009:46).

Kerzner (2009:47) states that project management becomes an absolute necessity for new product development (NDP) where companies heavily invest in research and development activities. NDP is recognised as the driving force behind these companies and often project management could be used as an early warning system, on whether a project should proceed or be cancelled.

Howell (2014:08) concludes that lean is the best project management approach is to production, since lean deals with quick delivery, products that meets customer's unique specifications and with having no inventory. In project management the product that needs to be delivered is the project, therefore the basis of lean production fit with the need to address quickly complex and uncertain projects. This has been proven successfully in the construction industry.

Morris (cited by Howell, 2014:06) and describes project management in conventional or traditional manufacturing as the following: "first, what needs to be done; second, who is going to do what; third, when actions are to be performed; fourth, how much is required to be spent in total, how much has been spent so far, and how much has still to be spent."

Howell (2014:07) claims that projects are easier to manage with techniques, as prescribed by PMBOK, when they are uncomplicated, and when sufficient time is available. The modern project environment demands significantly less time to complete projects, thus pressuring project managers to innovatively combine activities, using tools to manage production.

1.3.3. Framework

The definition of a framework according to the online English Oxford Living Dictionaries (2018) is a basic structure underlying a system, concept or text. A set of beliefs, ideas or rules that is used as the basis for making judgements, decisions, etc.

Many authors portray a framework through diagrams and graphical representations. A framework is referred to as a prescriptive set of things to do. Anand and Kodali (2008:207-208) quoted a framework as being "a clear picture of the leading goal for the organisation and should present key characteristics of the to-be style of business operations". This means that one should design and develop a framework representing the current operation, the systems to be developed, the activities to be carried out and the ultimate vision of the modern style of management in the organisation. A framework helps to translate theory into practice through some systematic means (Anand & Kodali, 2008:207-208). There is a general acceptance that the researcher must develop a prior view of the general constructs or categories that are to be studied, and their relationships. This is often provided in the form of a conceptual framework (Mellor, 2014:77).

A study concluded on the implementation of additive manufacturing technology for mass customisation by Deradjat and Minshall (2015:2079), highlighted some managerial and technical implementation challenges. The study confirms that traditional manufacturing systems are more cost efficient for large-scale manufacturing volumes, and in certain instances, additive manufacturing adopts the role of a mass production technique. Significant challenges were found relating to the tolerance levels of mistakes, time demands on order processing, technical restrictions in raw material supply and machine modifiability (Deradjat, 2015:2088-2090). The same study points out that the technology and operational questions associated with the production up-scaling of additive manufacturing, are not being addressed (Deradjat & Minshall, 2015:2091).

1.3.4. Additive manufacturing

AM creates new objects with unique material properties. It builds up products layer by layer, rather than removing it. Although this technology is hailed as "the next industrial revolution", significant hurdles are present in the successful commercialisation of the technologies. (RAEng, 2013:02). Numerous studies have been concluded in the field of AM, with most notably in the new material, mechanical properties, material quality and microstructure manipulation fields (Gausemeier, Wall & Peter, 2013:14).

AM technology is not near perfect and as a disruptive technology it can transform new ideas and methodologies. This according to ISO (2013:06) is not just another technology to replace the conventional but might require a new way of thinking regarding entire business models. "Ignoring that and pushing AM too hard into traditional rules at this early stage may inflict damage on the technology and also ruin the market reputation." (ISO, 2013:27).

It is critical to expand our understanding of the benefits of AM to include considerations not just at the part level but considerations at the organisation level as well. A better understanding of the total impact of AM can provide the researcher with more informed and effective decisions when selecting a manufacturing method during product development. (Stern, 2015:77).

Holmström, Partanen, Tuomi and Walter (2009:04) suggest the unique characteristics of AM production lead to the following benefits:

- No tooling is required, therefore lowering production time and cost.
- Small production batches are attainable and cost-effective.
- Quick design changes are possible.
- Allows product optimisation for functional usage.
- Allows product customisation.
- Reduction of waste

- Simplified supply chains; shorter lead times, lower inventories.
- Design customisation

If this study accepts lean's goal, to produce by using fewer resources with the emphasis on waste elimination, then AM as a manufacturing technique can then be classified as having the advantage of using less waste production methods, since they are additive methods rather than subtractive methods. Thus, AM is not only about reducing materials, but also about elements such as energy, production space and equipment, some stages of assembly, part consolidation, fewer set-up times, less human effort, less transportation, less packaging process and less delivery time and a reduced number of suppliers.

Flowing from the literature review, the problem statement and the 'gap' to be closed in the AM manufacturing industry as reflected in the research title, the objectives to be reached with this research are stipulated below.

1.4. Research objectives

The global manufacturing scene is changing, and more industries are looking at future alternative manufacturing methods to become more competitive. There are various known and future unknown technologies which will play a significant role. From the literature review, AM is seen as a significant role player in future manufacturing technologies. Apart from the technology itself, which requires more research into material quality, functional materials and new materials, etc., careful and specific management of the technology might be required. A study of literature by Niaki and Nonino (2016:1420) on AM in different sciences and research areas has shown that no available research covers the management of AM and proposes research focused on its strategic and operational dimensions. Bianchi and Ahlstrom (2014:02) are of the rationale that, to amount to a new industrial revolution, technological changes should go side by side with managerial changes.

This study poses the following research question: As described in this study, if AM is identified as a lean manufacturing technology, how do AM organisations manage their projects?
From this central question the following sub-questions are posed:

- What is and why choose Lean and PM as a research subject within an AM?
- Is there a specific approach used by AM organisations for PM and are they lean?
- Can we draw parallels between lean and PM in AM?
- What are the key principles in developing a lean AM management framework?

Upon presentation of these research questions posed above, the following specific research objectives are:

- To define and analyse to what degree, AM can be described as a lean manufacturing technology.
- To define what PM processes and knowledge areas, influences the identified lean management principles, to create a framework for future project management in AM.

The product of this research study is a framework, and it is important to note that it could be applied in various manufacturing environments. Focus will be placed on the theory behind the framework, and not just one specific application, as the detail for each project and its environment can differ rapidly.

1.5. Research methodology

The research methodology discusses the foundation of the study, the research design concerning the research framework, constructs and questions, outlining of the data collection and analysing strategies. A qualitative approach will be followed, and a combined effort applying case studies and background theory of lean, project management and AM will be used to develop a conceptual framework. Research regarding both the lean and traditional project management frameworks will include technical and managerial practices, current/future research, principles, benefits, barriers, techniques and tools. Findings will result in a combined framework, within an AM environment. This is designed from the initial stages of the research study, based on a theory-building perspective.

From the review of the literature, along with informal data collection, the research questions and objectives were defined. The study poses the central research question: if AM is identified as a lean manufacturing technology, how do AM organisations manage their design and development projects?

1.6. Scope

Chapter Two presents the literature review used in the formulation of the research questions, and it brings together the fundamental areas of research, as formulated in the research study and include the fields of PM, Lean and AM. Literature reviews from previous studies are highlighted, and the focus is on current and future research, principles, benefits, barriers, techniques and tools in AM environments.
Chapter Three focuses on the research methodology. The researcher discusses the foundation of the study, the research design concerning the research framework, constructs and questions, outlining of the data collection and analysing strategies.
Chapter Four focuses on the results from the Delphi study.
Chapter Five focuses on the presentation and analysis of the gathered data and formulation of framework.
In Chapter Six the researcher concludes by discussing the main findings, conclusions, recommendations and contributions of the research.

1.7. Exclusions and assumptions

The assumption will be made that findings will limit the generalisation to all AM firms. The aim of this work is to support future work in the AM project management fields partly. The research study will essentially focus on the development of a lean project management framework for additive manufacturing, and the following assumptions will be limited to:

- This research will exclude information linked to design and development projects that are not compatible, or where the introduction or uses of lean principles and project management are not of valuable interest.
- This study will aim through the development of a lean project management framework to contribute to the management of projects in current and future AM manufacturing environments. It will focus on the concept of lean and be limited to its principles, as well as the processes of project management and all of their related tools and techniques. This will exclude other extensive investigations such as marketing models or methodologies and software models. Software models will only be developed, if required, if there are not any software models already available on the market to incorporate in the research study. Development, if needed, will only focus on the specifics of lean, project management and AM.
- The management of AM technology is a specialist field and is not included in this study. This study focusses on the project management of AM in a lean manner.

1.8. Knowledge gap to be closed

The developed framework concentrates on the basic project management processes and these processes will advocate the principles of a lean approach and it will recognise these important dynamics in the AM environment. The following knowledge gap opportunities can be fulfilled by this research study:

- The study highlights an opportunity in the management of AM technologies, as identified through literature studies.
- Potential research focus areas in AM, with a specific interest in lean project management.
- This study will aim through the development of a lean project management framework to contribute to the management of projects in current and future AM manufacturing environments.

The abovementioned knowledge gap opportunities will aim to provide the researcher with the following deliverables as stated in the next section below.

1.9. Deliverables

Following from the above knowledge gap opportunities, the objective of the study is supported by the literature review facts, that no specific studies explicitly targeted lean project management for additive manufacturing. The targeted outputs or deliverables for this research will aim to provide the following:

- Classify additive manufacturing (AM) as Lean.
- Identify and construct a PM framework within AM.
- Identify and construct a lean framework within an AM environment.
- Compare common factors between lean and PM to create a single lean PM framework within an AM environment.

1.10. Conclusion

This study will conclude in an attempt to present a lean project management framework for the additive manufacturing industry (AM). The framework will aim to contain critical elements of project management (PM) and lean; and will intend to add value to an organisation by outlining a body of knowledge, processes, skills, tools, and techniques. This could be proven in a model to improve the efficiency and performance and reduce waste within the main constraints of an AM organisation. The objective of this research, therefore, requires the development of a lean project management framework for AM.

Chapter Two: Literature review

2.1. Introduction

This chapter presents the literature review performed in the research study and the aim was to define the primary research question from which the study would proceed. The study focuses on project management within AM and attempts to distinguish between traditional and lean forms of project management methodologies.

This chapter will focus on the various properties of traditional and additive project management approaches to support a lean PM framework within AM organisations. Various study literature covers project management within a traditional manufacturing environment, and it is therefore necessary to narrow down the focus to lean project management in additive manufacturing. Only the relevant areas in traditional project management will be discussed and used towards the formulation of the intended framework.

The foundation of the literature review is based on project management (PM), lean project management (LPM), traditional project management (TPM), lean versus traditional methodologies and lean projects. These foundations were used as keywords in search of information from several on-line sources, academic and research databases and journals, such as Elsevier, Science Direct, ProQuest, GoogleScholar, NWU library, books, working papers and conference papers. These searches provided the necessary background information to review the literature on traditional project management, lean methodologies and AM.

This chapter is structured into four sections. The first section reviews the additive manufacturing environment, the technologies, the industry, applications, characteristics and research. The second section provides a review of project management research in the traditional and additive manufacturing context. The third section provides a review of Lean project management in the context of traditional and additive manufacturing. Finally, a gap analysis is presented, and the chapter, therefore, summarises the conclusions of the review and how they have defined the study questions; namely, how we manage projects in a lean manner within an AM environment.

2.2. Advanced manufacturing

Manufacturing across the entire value chain is changing fast, and technology is transforming how what and where things are produced. Considerable progress has been made in the development of material and systems, and the future market leaders will be those that understand, embrace and apply the changes technology is bringing (Pinsent Masons, 2015:20). Additive manufacturing is one such key technology that will influence the way we manufacture and develop goods, and it is vital that we look at the management of this technology.

The factories of the future (FOF) will influence how we are going to manufacture and develop goods in the future. Future products are expected to be more complex (3D, nano-micro-meso-macro-scale, smart), therefore these manufacturing processes need to deal with these complexities and enhanced functionalities, while minimising any extra costs (FOF, 2012:45-46).

According to FOF (2012:44), advanced manufacturing is identified as one of the researches and innovation priorities of the future and is an emerging advanced manufacturing technology. Advanced manufacturing systems have a critical role in making key enabling technologies and new products competitive, affordable and accessible and need to be placed in the market in time to have a valuable contribution to society. As well as turning technological achievements into products and services, advanced manufacturing also enables a cost-effective, resource efficient and timely production and commercialisation, which steers it towards a lean approach.

FOF (2012:48-49) divides advanced manufacturing processes into three sub-domains. The first sub-domain involves the processing of novel materials and structures into products. The processing includes the manufacturing of custom-made parts, advanced joining technologies for advanced and multi-materials, automated production of thermoset and thermoplastic composite structures/products, manufacturing processes for non-exhaustible raw materials, biomaterials and cell-based products and the delivery of new functionalities through surface manufacturing processes. The second sub-domain involves complex structures, geometrics and scale. It includes material efficient manufacturing processes, high volume manufacturing at the micro- and nano-scale, robust micro- and nano-enabled production, integrated manufacturing processes, manufacturing of high-performance flexible structures. The third sub-domain involves business models and strategies for disruptive manufacturing processes. The business models and strategies include product lifecycle management for advanced materials, novel supply chain approaches for innovative products, new models for introducing disruptive processes and photonic process chains (FOF, 2012:43-47).

2.3. Additive Manufacturing

The Additive Manufacturing Strategic Research Agenda (AM SRA) defines AM as the process of joining materials to make objects from 3D model data. The joining is done through a layered process, as opposed to a subtractive manufacturing method, such as in traditional manufacturing (AM SRA, 2014:04).

The Royal Academy of Engineering (RAEng) employed AM as the umbrella term for the industrial use of the technology and 3D-printing as a reference to consumer-focused desktop-based AM, using plastics and other non-metal printing material (RAEng, 2013:2-3). The same report states that it is important to state the differences between 3D printing and AM so that it could attract new interest and private investment and to improve materials and processing at the top end of the market. The different benefits are highlighted as created by different versions of the technology and that basic 3D printers can support education and research through rapid prototyping. Sophisticated machines will promote industry savings in materials used, and the creation of more economical and lightweight products (RAEng, 2013:26). A large variety of consumer-grade 3D printers were made available through crowdfunding and the expiry of patents, thus putting hobbyist in position to design and manufacture personalised products (Ford & Despeisse, 2016:02). Piller, Weller and Kleer (2015:40) claim that although large conventional companies have been behind the development and innovation of the manufacturing chain, a growing community of so-called "makers" have been responsible for innovation in the digital value chain. They include people such as hobbyists, small start-up businesses and private consumers who are all using AM for local private manufacturing.

2.3.1. AM Technologies and Processes

AM technology provides us with distinct options regarding the material and required industry uses. The ASTM F42 committee (AM SRA, 2014:23) categorises the processes with its definition and required material and usages:

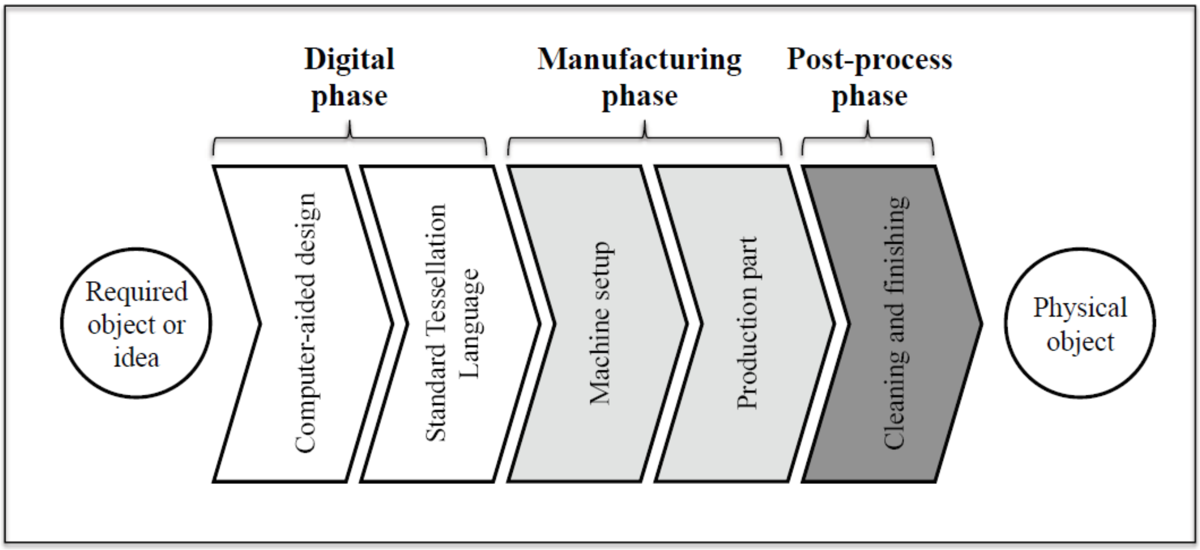
Table 2.1: Classification of AM processes (AM SRA, 2014: 23)

Process	Definition	Material	Example usage
Vat Photopolymerisation	Liquid photopolymer in a vat is selectively cured by light-activated polymerisation.	Photopolymer and Ceramic.	• Mostly prototypes for fit, form and functionality. • Consumer toys and electronics. • Some guides, jigs and fixtures.
Material Jetting	Droplets of build material are selectively deposited.	Photopolymer and Wax.	• Casting and non-structural metallic parts. • Some metal end-use parts. • Marketing prototypes with colour. • Tooling • Automotive covers/trim, kits/dashboards. • Consumer electronics.
Binder Jetting	Liquid bonding agent is selectively deposited to join powder materials.	Metal, Polymer and Ceramic.	
Material Extrusion	Material is selectively dispensed through a nozzle or orifice.	Polymer	• 3D objects with low structural property requirements. • Tooling • Light and modular structures (hollow spheres)

Power Bed Fusion	Thermal energy selectively fuses regions of a powder bed.	Metal, Polymer, Ceramic.	• 3D objects of polymers or metals. • Tooling • Secondary/tertiary structures. • Orthopedic and dental implants. • Mechanical joints/sub-components/ducting.
Sheet Lamination	A process in which sheets of material are bonded to form an object.	Hybrids, Metallic and Ceramic.	• Large parts. • Tooling • Non-structural parts.
Directed Energy Deposition	A process in which focussed thermal energy is used to fuse materials by melting as the material is being deposited.	Metal: Powder and wire.	• Re-work of articles. • 3D objects. • End-use parts with low structural property requirements.

AM can be divided into three distinct phases, namely the digital, manufacturing and the post-process phases, as illustrated in Figure 2.1 below. The digital phase includes two main activities, namely Computer-aided design (CAD) and Standard Tessellation Language (STL). The manufacturing phase includes machine setup and production parts, and the post-process phase consists of the final cleaning and finishing (Vieira & Romero-Torres, 2016:114).

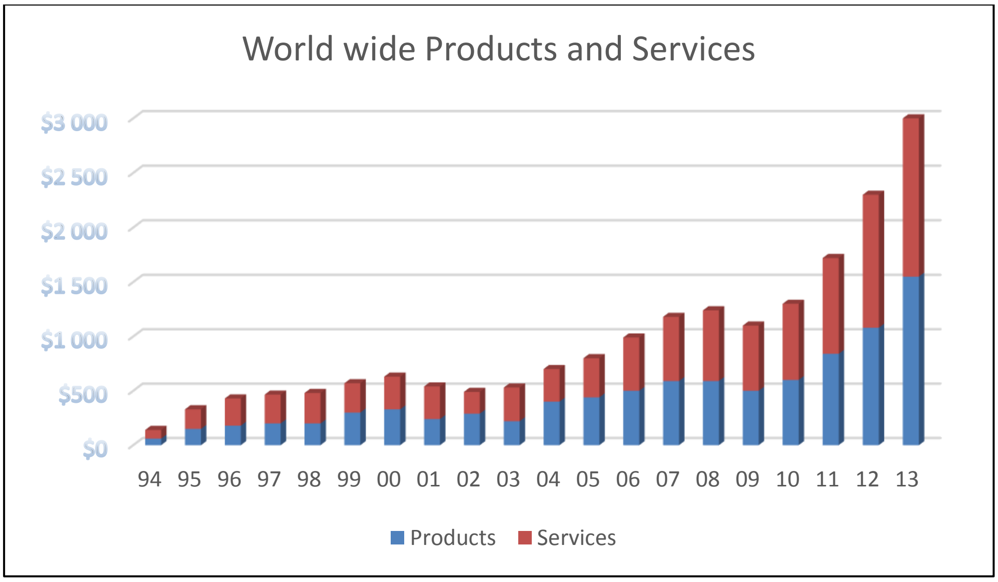
Figure 2.1. Additive Manufacturing Phases (Vieira & Romero-Torres, 2016:114)



2.3.2. AM Industry

The AM industry has shown double-digit growth in the last two decades. According to Wohlers and Caffrey (2014:109-110), sales of industrial AM systems increased, and growth sales for personal 3D printers in 2013 have gone into triple digits. The AM market industry grew 34.9% worldwide to $3.07 billion. The market consists of primary products and services. This figure increased from 32.7% to $2.275 billion in 2012. The secondary market increased to $1.36 billion by 14.3% in 2013, up from $1.19, in 2012 when it grew by 10%. The total overall additive manufacturing market was $4.428 billion. It led to an increase of 27.6%, $3.47billion, generated in 2012 (Wohlers & Caffrey, 2014:115). According to the Wohlers (Wohlers & Caffrey, 2014:110) the AM industry, grew by 25.9%, reaching $5.165 billion in 2015. The chart below provides revenues for AM products and services globally. These figures show a significant increase in the last four years and neither category includes secondary services, such as tooling, moulded parts or castings.

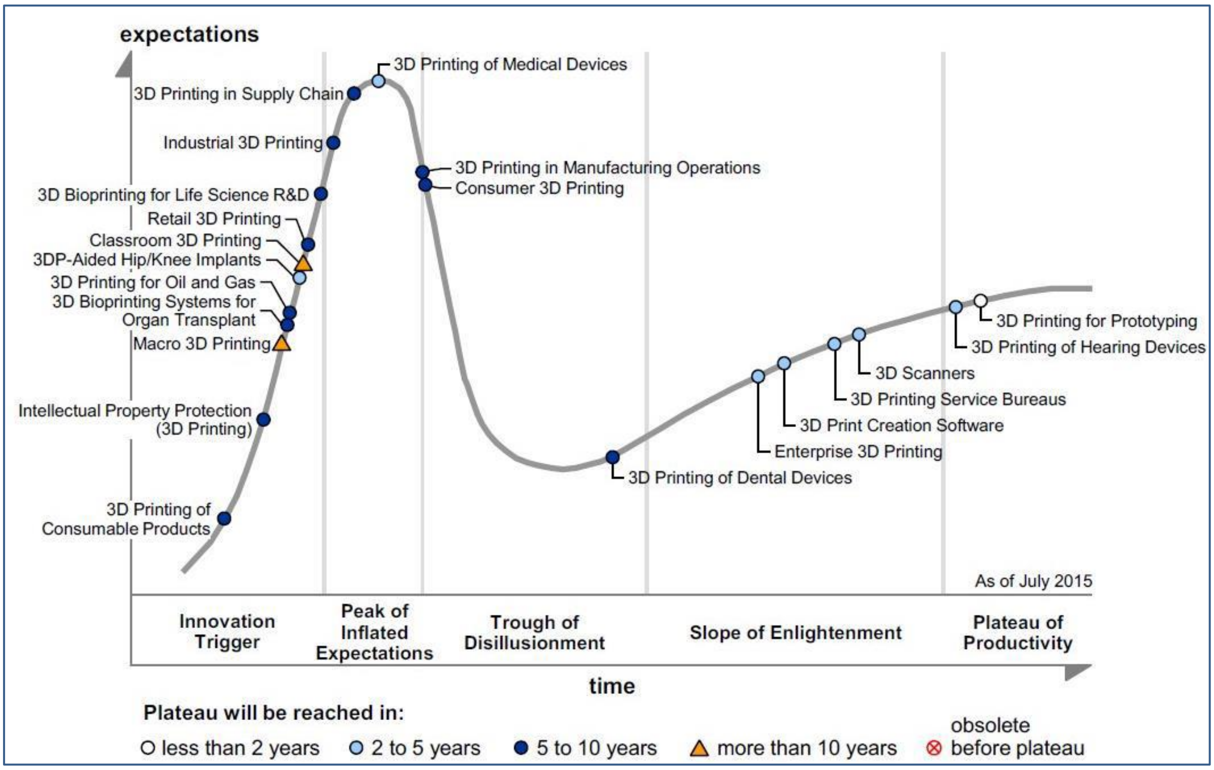
Figure 2.2: Global AM Revenues [adopted from Wohlers & Caffrey, 2014:110]



South Africa adopted a strategic AM roadmap development approach in early 2014. The aim was to identify opportunities in human capital development, job and enterprise creation, growth, resource and investment requirements and the investment in 2013 was more than $10 million (Wohlers & Caffrey, 2014:138). The initial investment was through active research participation from the Council for Scientific and Industrial Research (CSIR) and certain universities. According to De Beer (2011:02), the majority of the research performed in South Africa, addressed specific applications, rather than basic research. Research institutions became technology demonstration centres in parallel with process development and improvements, to produce models and components. This research also affected managerial aspects of the product development process, inclusive of rapid prototyping (RP) usage.

The benefits of AM as referred to by Ford (2016:12), are well documented in various literature reviews and is also seen as a differentiating technology. Gartner, cited by the European Commission's Executive Agency for Small and Medium-sized Enterprises (EASME) (2016:30), refers to AM as a victim of recent hype, and it is illustrated by his "Gartner Hype Cycle for 3D-printing", as shown in Figure 2.3 below. In Figure 2.3 Gartner illustrates the maturity of certain applications and the constant development of new "innovation triggers" as to counterbalance less realistic expectations (EASME, 2016:30).

Figure 2.3: "Hype Cycle for 3D-printing" (EASME, 2016:30)



2.3.3. AM Applications

'EASME identified current and future EU application areas for AM. The selected application areas were identified by looking at which significant current and future sectors and applications will be affected by 3D-printing. The main criteria as defined by EASME was to select the most essential and relevant applications and sectors where the "added value that Additive Manufacturing brings in", the "Maturity of the area", and sufficient presence of organisations, especially in the supply chain, to support potential and dynamic progress (EASME, 2016:34). These sectors include:

Aerospace: Compared to several traditional manufacturing methods in the aircraft industry, where large volumes of material ARE wasted through subtractive methods, this sector focuses on the optimisation of components through weight reduction. The manufacturing of these components through AM can focus on complex, demanding and low volume components.

Automotive: The use of AM in this industry is limited to prototyping and tooling, as typical production volumes in the automotive industry are too high to produce final parts with AM economically.

Healthcare: The medical and dental sectors are the primary users of AM; however, regulation has a negative influence on the use of new technologies and materials. Hearing aids, dental braces and crowns, medical implants and bio-printing are the main utilisers of AM in this sector.

Machines and Tooling: The application of AM in this sector focusses mainly on the customisation and production of lightweight parts, internal channels/structures, reach functional integration and design surface structures. AM also lends itself to a hybrid approach, where it is combined with conventional technologies such as computer numerical controlled (CNC) milling. Typical products include mould insert, investment casting patterns and jigs and fixtures.

Electronics and Electronic Devices: The latest Direct Write technologies allows for the printing of several kinds of electronic circuitry directly onto flat or conformal surfaces. The printing can be done in complex shapes, without any tooling or masks. Such co-printing techniques are useful as it can co-print fused deposition modelling (FDM) filament and conductive ink, using only one printer.

Consumer Lifestyle and Fashion: 3D-printed industrial and consumer products are identified in this sector. New and innovative material and multi-materials are developed for the use in jewellery, clothing, shoes and sports equipment.

Oil and Gas: The use of AM apply mainly to the production of spare and wear parts in the petroleum industry, specifically in extreme environments and locations. Products include pumps, pipeline parts, valves and drills, as used in ultra-deep-water or arctic environments.

Energy: The development and use of renewable energy have become a significant energy driver around the world. The use of AM in the manufacturing of solar cells could bring savings of up to 50% on expensive materials, such as glass, polysilicon and indium.

Construction: The need for affordable housing not only in South Africa a great need, but also in the rest of the developing world. The use of AM in this sector focusses mainly on the printing of facilities and structures. The advantages of this technology will allow countries to build more, quick, affordable houses with increased architectural freedom.

Military: The application of AM in this sector overlaps with other sectors such as the medical field and aerospace. Spare parts for weapons and skin cells for skin and burn wound injuries can be printed in operational and conflict areas.

Transportation: Spare parts in the special transport and marine industry will be produced using AM. Several companies will join in research and development attempts to produce these parts for future use.

Food: According to the Institute of Food Technologists (IFT), 3D-printers will revolutionise the way we manufacture food. Food can be customised or personalised in various shapes and forms, using different nutritional ingredients. 3D-printers are currently researched for food such as sugar, ice-cream, pasta, pizza, etc. (EASME, 2016:34-36).

The 10 most essential and shortlisted applications are surgical planning, plastic-based car interior components, metallic structural parts for an aeroplane, Inert and hard implants, metal AM for injection moulding, spare parts for machines, lighting and other home decoration products, 3D-printed textiles, affordable houses and 3D-printed confectionery. This study looked at the scope of each application area, the key players and value chain components. Secondly, it looked at the critical factors, barriers to the deployment of AM and the policy implications of these applications (EASME, 2016:49).

The previous sections have focused on AM technology, the industry and applications. The following sections give a limited overview of project management, traditional project management (TPM) and it also highlights the limited literature on AM project management.

2.4. Project management overview

This research, as stated before, does not focus extensively on traditional project management, as the subject is well researched in many works. This study will focus on literature on lean and project management in the AM environment, which was found to be less common. It was found that most research focused on the development of AM processes and materials. As stated before, a study of literature by Niaki and Nonino (2017:1420) on AM in different sciences and research areas has shown that no available research covers the management and it is encouraged that future technological changes should go side by side with managerial changes (Bianchi & Ahlstrom, 2014:02). The literature review conducted in this study highlighted that there are limited literature resources available that may be used as a basis for the development of a lean framework for project management in AM. The Project Management Book of Knowledge (PMBOK) literature is used as the authority on project management in this study. Considering this, the review of additional PM literature applicable in AM, is encouraged for future research.

2.4.1. Definition

PMBOK (cited by Kerzner, 2009:4) describes project management as the planning, organising, directing, and controlling of company resources for a relatively short-term objective, necessary to complete specific goals and objectives. The theory of management consists of the theories for planning, execution and control. Koskela & Howell (2002:01) argued that a reform of project management will be driven by theories from production management which will include the management of workflow, the creation and delivery of value to activities. Howell & Koskela (2000:05) claims that of all the approaches to production management, the theory and principles drawn from Lean Production seem to be best suited for project management.

2.4.2. Stakeholders

Stakeholders needs to be identified early on in the project management process and it is important that they are identified by the project team; requirements determined, and it then managed to ensure that the project is successful. Project stakeholders according to the Project Management Institute (PMI), are individuals or organisations which are actively involved in the project. These members have solid interests in the project outcomes, as these interests may be affected or they themselves may exert influence on the project results. Key project stakeholders typically include: project manager, customer, performing organisation, project team members and sponsor. (PMI, 2000:16-17). There are many other potential stakeholders like shareholders, owners, family, contractors, government agencies, etc. Typical stakeholders in the AM industry includes some or all the above mentioned, but AM also provide the user or consumer the opportunity to develop, collaborate and manufacture products. It forms part of the "maker movement", which is a resurgence of DIY craft and hands-on production among everyone. It turned consumers into active participants and creators. (Deloitte, 2015:10). The availability of affordable printers and the active involvement from consumers could determine a different looking stakeholder composition in some AM organisations.

2.4.3. Planning

PMBOK's (Koskela, 2002:02) definition of planning is to determine what needs to be done, by whom, and by when, in order to fulfil one's assigned responsibility. There are nine major components of the planning phase:

Table 2.2: Components of the Planning phase (PMBOK, 2013:46-47)

Component	Description
Objective	Goal, target, or quota to be achieved by a certain time.
Program	Strategy to be followed and major actions to be taken in order to achieve or exceed objectives.
Schedule	Plan showing when individual or group activities or accomplishments will be started and/or completed.
Budget	Planned expenditures required to achieve or exceed objectives.
Forecast	Projection of what will happen by a certain time.
Organisation	Design of the number and kinds of positions, along with corresponding duties and responsibilities required to achieve or exceed objectives.
Policy	General guide for decision-making and individual actions.
Procedure	Detailed method for carrying out a policy.
Standard	Level of individual or group performance defined as adequate or acceptable.

Effective planning and management are needed so that specific time-phased, measurable goals, sub-goals and action steps can be set. The PMI divides the planning process into two different processes, namely the core planning process and a set of facilitating processes. The core planning process includes the steps of scope definition; activity definition, sequencing and duration estimation; resource planning; cost estimating and budgeting; and project plan development. The facilitating processes are done according to the need and are dependent on the complexity of the project and the type of organization. This facilitating process includes the steps of quality planning, organisational planning, staff acquisition, communications planning; risk identification, quantification and risk response development; procurement and solicitation planning.

2.5. Traditional project management

Traditional project management (TPM) is defined as "the application of knowledge, skills, tools, and techniques to project activities to meet project requirements." Thus, project management is the "completion of a full cycle involving the initiating, planning, executing, controlling, and closing phases under the guidance of the project team". (PMBOK, 2004:08).

The two models mainly used in traditional project management, are the "waterfall" and the "spiral models". The waterfall model is based on the principle that one phase cannot start until the previous phase is completed. The spiral phase requires an iterative process, and we repeat going through the phases until we have reached maturity. Both models are based on the fundamentals of project management, which includes the phases of define, planning, implementation and control.

2.5.1. Elements of traditional project management used in this study

This study employs inputs and recommendations from the PMI and the PMBOK guide as the basis for all traditional project management. As mentioned earlier in the literature study, work will only focus on relevant literature which will enhance the process of managing projects in AM. It is worth pointing out that the PMBOK Guide is not a project management methodology, but a framework for organising and executing a project. It is also worth pointing out that the guide is a foundational reference. Although the guide is used in this research as basis for PM, it is neither complete nor all-inclusive. It provides this research with a means to identify a methodology, tools and techniques to manage projects in an AM environment. The PMBOK Guide is used in many different industries, from information technology, banking, healthcare, product development, etc. The researcher is thus of the opinion that this framework can be successfully applied or adopted in an AM environment.

2.5.1.1. Project management knowledge areas

The PMBOK guide highlights ten project management knowledge areas and each area represents its own specialization and includes specific tools, concepts and tasks. To manage most projects successfully, the project manager needs to have sufficient knowledge of each area. These knowledge areas group the required theory and practical techniques together and the project manager should be able to work across these areas to get projects done. The ten knowledge areas include: integration management, scope management, time management, cost management, quality management, human resources management, communication management, risk management, procurement management and stakeholder management. (Salameh, 2014:59). The five process groups identified necessary to perform project management work, includes: initiating, planning, executing, monitoring and controlling and closing (Salameh, 2014:602). The following matrix in Table 2.3. describes the process groups and knowledge area mappings. (Salameh, 2014:61), (PMI, 2013:61).

Table 2.3. below explains the project management process groups and knowledge areas mapping. The knowledge areas are down the side, the process groups along the top and then maps the different processes in the relevant boxes where the two axes cross. For example, at the junction of Project Stakeholder Management and the Initiating Process Group you have the process to 'Identify Stakeholders'. Thus, by applying the five process groups to every knowledge area, a project can be managed efficiently and consistently. The right processes need to be identified for the required knowledge areas in AM, as there is no need to apply specific processes to areas we don't use.

There are huge benefits for an organisation if everyone is using the same processes for the same activities. PMI's 2017 Pulse of the Profession study reported that high-performing organisations are three times more likely to use standard processes across the organisation than low performers. Using project management processes does improve project success. The same report also states that the traditional measures of scope, time, and cost are no longer sufficient in today's competitive environment and the ability of projects to deliver what they set out to do, the expected benefits, is just as important (PMI, 2017:16-21).

PMI emphasises the value of project management and companies are re-evaluating their relevance and ability to meet current and future demands such as digital advancements, higher customer expectations, disruptive organisations (i.e. AM) and a changing workforce (PMI, 2017:13).

Table 2.3: Process Groups and Knowledge Area Mapping (PMI, 2013:61).

Knowledge Areas	Initiating Process Group	Planning Process Group	Executing Process Group	Monitoring and Controlling Process Group	Closing Process Group
Project Integration Management	Develop Project Charter.	Develop PM Plan	Direct and Manage Project Work.	- Monitor and Control Project Work. - Perform Integrated Change Control.	Close Project or Phase.
Project Scope Management		- Plan Scope Management. - Collect Requirements. - Define Scope. - Create WBS.		- Validate Scope. - Control Scope.	
Project Time Management		- Plan Schedule Management. - Define Activities - Sequence Activities - Estimate Activity Resources - Estimate Activity Durations -Develop Schedule		- Control Schedule	
Project Cost Management		- Plan Cost Management - Estimate Costs - Determine Budget		- Control Costs	
Project Quality Management		Plan Quality Management	Perform Quality Assurance	- Control Quality	
Project Human Resources Management		Plan Human Resource Management	- Acquire Project Team - Develop Project Team - Manage Project Team		
Project Communications Management		Plan Communications Management.	Manage Communications	Control Communications	
Project Risk Management		- Plan Risk Management - Identify Risks -Perform Qualitative Risk Analysis - Plan Risk Responses		Control Risks	
Project Procurement Management		Plan Procurement management	Conduct Procurements	Control Procurements	Close Procurements
Project Stakeholder Management	Identify Stakeholders	Plan Stakeholder Management	Manage Stakeholder Engagement	Control Stakeholder Engagement	

2.6. Lean

Lean is based on a philosophy of its understanding and motivation of people. It focusses heavily on providing the customer with what and when they exactly want products. Attempts will focus on the customer to provide them more, with less human effort, less equipment, less time, and less space. “Lean provides a way to specify value, line up value-creating actions in the best sequence, conduct these activities without interruption whenever someone requests them, and perform them more and more effectively”. (Womack & Jones, 2003:46).

2.6.1. Definition and origins of lean

Lean, according to the Lean Enterprise Institute, is to maximise customer value while minimising waste. Bahmu’s literature review on lean production refer to several authors such as Womack, stating that lean is a dynamic process of change driven by a systematic set of principles and best practices aimed at continuous improvement (Bahmu, 2013:878). Hayes and Pisano (cited by Bahmu, 2013:878) state that lean is called as such because it uses less or the minimum of everything to produce a product or to perform a service. Dankbaars’ (cited by Bahmu, 2013: 879) definition of lean could relate to AM, as it states that lean production can manufacture a more extensive variety of products at lower cost and higher quality, with less of every input compared to traditional mass production (Bahmu, 2013:879).

Japan’s industrial revival in the early 1950’s outlined some essential elements. Their economy was based on little resources and manufacturing companies had to limited scrap, use minimum space, simplify work to suit an unskilled workforce, keep all stock at minimum levels and to keep paying periods between raw materials and finished goods to a minimum. It was essential to eliminate waste at all cost and wherever possible. This was the beginning of Lean manufacturing, as implemented by Toyota’s Production System (TPS). This is summarised as a set of 14 principles in Table 2.4. below:

Table 2.4: Toyota Lean Principles (Liker, 2004:35-41), (Ballard, 2012:87)

Principle	Description
Principle 1	Base management decisions on a long-term philosophy, even at the expense of short-term financial goals.
Principle 2	Create a continuous process flow to bring problems to the surface.
Principle 3	Use pull systems to avoid overproduction.
Principle 4	Level out the workload.
Principle 5	Build a culture of stopping to fix problems, get the quality right the first time.
Principle 6	Standardised tasks and processes are the foundation for continuous improvement and employee empowerment.
Principle 7	Use visual control so that no problems are hidden.
Principle 8	Use only reliable tested technology that serves your people and processes.
Principle 9	Grow leaders who thoroughly understand the work, live the philosophy and teach it to others.
Principle 10	Develop executional people and teams who follow your company's philosophy.
Principle 11	Respect your extended network of partners and suppliers by challenging them and helping them to improve.
Principle 12	Go and see for yourself to fully understand the situation.
Principle 13	Make decisions slowly by consensus, considering all options; implement decisions rapidly.
Principle 14	Become a learning organisation through relentless reflection and continuous improvement.

2.6.2. Principles of lean

This section of the study is based on the work of Liker (2004). Liker (2004) emphasises 14 principles as the foundation of the TPS and are their unique approach to manufacturing. Toyota is acknowledged around the globe for its quality and consistency in manufacturing and the company invests large amounts of resources on perfecting their operations. Toyota managed to use this approach as a very effective method in claiming its position as the top automobile manufacturer in the world. Lean is often seen as a process where specific tools and quality techniques are used, such as just-in-time, kaizen, one-piece-flow, etc. Tools like these helped the "lean manufacturing" cause, but the real success of Toyota was based on its philosophy as a learning organisation, its understanding and motivation of people. (Liker, 2004:07).

Liker (2004) states that despite the considerable influence of lean in general, attempts to introduce it successfully at most companies, have been poor and superficial, although it has been proven to be highly successful at Toyota. It is important to consider that lean is not only about the use of tools, but to understand it as an entire system which needs to form part of the whole organisations' culture. It can only succeed if management is actively involved in the day-to-day operations and continuous improvement efforts. Part of this study's aim is to investigate the applicability of these 14 lean management principles in an AM environment.

The author has studied Toyota for over 20 years and divided these principles into 4 categories, incorporating and correlating Toyotas own internal documentation in the process. The principles, are devised into the 4 categories, including philosophy, process, people/partners and problem solving. (Liker, 2004:06).

The founder of TPS, Taiichi Ohno, described a lean manufacturing system as "looking at the time-line from the moment the customer gives an order to the point when the cash is collected, while reducing that time-line by removing the non-value-added wastes". (Liker, 2004:07).

Certain mass manufacturing companies like Ford, focused on the efficiency of individual processes, and that machine down-time is a non-value-added waste that does not make parts and money. Toyota's perception was different compared to most other mass manufacturers and discovered that when lead times are short and when production lines are kept flexible, quality improves. It was also found that customers would response more positively and that equipment and space are better utilised, resulting in higher productivity. Toyota realised that being lean is not about managing resources to their maximum levels, but rather about the way of turning raw material into a final product. Therefore, it sometimes can be seen as if Toyota is adding waste rather than to eliminate it, i.e. idle a machine, rather than stopping it; build-up stock to level-out the production schedule; selectively add and substitute overhead for direct labour; keep workers making parts as fast as possible; manual labour can often be better to use than automation. (Liker, 2004:08)

The transformation required by lean, is not only about supplying the customer with a product what and when he wants it. It is also a cultural transformation and a company's management commitment in the investment of its workers and creating a culture of continuous improvement. Focus on what the customer wants is very important, thus defining value through the customers' eyes and separating value-added steps from non-value-added steps.

This research is not the first attempt to integrate lean and project management. The focus in the following section is based on the different types of waste. Toyota identified 7 types of wastes and Liker included an eighth one (Liker, 2004:28-29):

Table 2.5: Types of Waste. (Liker, 2004:28-29)

Type of Waste	Description
Overproduction	Producing items for which there are no orders, generating extra staffing, transport and storage costs
Waiting (time-on-hand)	Workers waiting around for the next processing step, bottleneck, processing delays, equipment downtime, etc.
Unnecessary transport	Creating inefficient transport by carrying work-in-process long distances or moving material, parts, finished goods in/out storage or between processes.
Over or incorrect processing	Unneeded steps to process parts. Inefficiently processing parts due to poor product and tool design, causing unnecessary motion and producing defects. Providing higher quality products than what is necessary also creates waste.
Excess inventory	Excess raw material, work-in-progress or finished goods causing longer lead times, damaged goods, obsolescence, delay, transportation and storage costs. Extra inventory hides problems such as production imbalance, defects, late deliveries from suppliers, equipment downtime and long set-up times.
Unnecessary movement	Any wasted motion workers have to perform during their course of work, i.e. looking/reaching for or the stacking of parts, tools and walking.
Defects	The repair/rework, scrap, replacement production and inspection, causes wasteful handling, time and effort.
Unused employee creativity	Losing time, ideas, improvements, skills and learning opportunities by not listening to employees.

The fundamental waste as identified by Toyota is overproduction, since it causes most of all the other wastes. Producing more than what the customer requires, creates the build-up of inventory downstream and inventory end up waiting around for the next operation.

When comparing traditional process improvement with lean improvement, traditional improvement focuses on identifying local efficiencies, i.e. equipment and the value-added processes, by improving up-time, faster cycles, or replace a person with automated equipment. In a lean improvement environment, the focus is on the removal of any non-value-added steps, combined with a reduction in value-added time. A lean manufacturing environment focusses on the creation of production cells, and each cell consists of a close arrangement of people, machines or workstations in a processing sequence. These cells facilitate a one-piece flow of a product/service through different operations, like machining, welding, assembly, packing, one at a time, at a rate as determined by the needs of customer with the least amount delay and waiting time. (Liker, 2004:30-32)

2.6.3. Underlying values of lean management

Lean management is a process of change that focuses on the no-added value parts of processes, while other methodologies focuses on the part of the processes that add value. (Lopez-Fresno, 2014:91). Lean management is based on a process of continuous improvement and is not a methodology to reduce costs, but cost reduction derivates from its implementation. Lean management does not identify activity (movement) with value, it exists on the principle that it is possible to produce more with less movement. This will have a cost reduction effect and staff are more satisfied. Womack and Jones (2003:275) states how their lean principles are different from previous references on the subject of manufacturing management. "We are putting the entire value stream for specific products relentlessly in the foreground and rethinking every aspect of jobs, careers, functions, and firms to correctly specify value and make it flow continuously along the whole length of the stream as pulled by the customer in pursuit of perfection."

2.6.4. Lean project management approach

Lean capabilities are not merely firm-specific but are, instead, plant specific. For these plant-specific strategies to be successful, an organisation needs to ensure internal targets, and it requires the establishment and maintenance of relationships, with external partners and suppliers. (Crute, 2003:926).

The benefits of lean thinking are summarised by Womack and Jones (2003:27) in a few simple rules of thumb: The classic batch-and-queue production system needs to be converted into a continuous flow system. Pull is required by the customer to increase resource productivity, to ensure production throughput times are cut by 90 percent and inventories reduced in the system by 90 percent.

Table 2.6 below provides a summary of all five lean principles and the relative AM benefits and challenges each lean principle provides.

Table 2.6: Is AM lean?

Principle	Lean Requirements (Adopted from Womack, 2003:27)	AM Benefits and Challenges (Adopted from Ford, 2016:03)
Value	- The customer ultimately defines value. - Producers talk to customers in new ways. - Target cost is influenced by how much cost can be taken out with lean application methods.	***AM Challenges***: - Changing design outlook and approach in the use of AM. - Changing perceptions about AM as a manufacturing technology, which is not only reserved for prototyping, but expands to direct component and product manufacturing.
Value stream	Creating a value stream "map" identifying every action required to design, order, and make a specific product is to sort these actions into three categories: (1) those which actually create value as perceived by the customer; (2) those which create no value but are currently required by the product development, order filling, or production systems and so can't be eliminated just yet; and (3) those actions which don't create value as perceived by the customer and so can be eliminated immediately.	- Waste materials such as certain resins and powders can be reused. - Complicated and intricate structures can be build. - Final parts can display very low porosity levels. ***AM Challenges***: - Development and standardisation of new materials -Validation of the mechanical and thermal properties of existing materials and AM technologies. - Development of different material and multi-coloured systems. - Wastage of support structure materials must be minimised through improved design and build-up orientation.
Flow	- Focus on actual object, specific design, order and product itself. - Removing all impediments to the continuous flow of product. - Rethink specific work practices and tools to eliminate backflows, scrap and stoppages to ensure continuous flow. - Creation of dedicated product teams to conduct value specification, design, detailed engineering, purchasing, tooling and production planning. - Sales and Production Scheduling is core team members, ensuring that both orders and product flow smoothly from sales to delivery. - Products are built to order, thus no stoppages to the production process, thus having a clear knowledge of the system’s capabilities. - Synchronisation of the rate of production to the rate of sales to customers – takt time. - Eliminating long lead times by getting rid of batch-and-queue systems, ensuring that products are in continuous flow. - Spend time on the shop floor, continuous communication between staff to solve problems and implement solutions.	- Small batches of customised products are economically attractive relative to traditional mass production methods. - Direct production from 3D CAD models mean that no tools and moulds are required, so there is no switch over costs. ***AM Challenges***: - Automation of AM systems and process planning to improve manufacturing efficiency. - Deficits in designers and engineers skilled in additive manufacturing. - Non-linear, localized collaboration with ill-defined roles and responsibilities.

	- Thinking through tool changes to reduce changeover times and batch sizes to the absolute minimum. - Production is broken into product families and work progresses from each station to the next in accordance of takt time and at the same rate as final assembly. Work in each step is carefully balanced with work in every other step so that everyone is working to a cycle time equal to takt time. - Locate both design and physical production in the appropriate location to serve the customer.	
Pull	- No one upstream should produce goods or services, until the customer downstream is ready for it, thus working backwards through all the steps required to bring the desired product to the client. - First visible effect of converting from departments and batches to product teams and flow is the required time to go from concept to launch, sale to delivery, and raw material to the customer falls dramatically. - Drastically reduce changeover times and shrink batch sizes and don't make anything until it is needed and make it then immediately. - Order only parts daily when needed and in only the right amount. - Get rid of lead times and inventories so that demand is instantly reflected in new supply.	- Making to order reduces inventory risk, with no unsold finished goods, while also improving revenue flow as goods are paid for prior to being manufactured. - Distribution allows direct interaction between local consumer/client and producer. ***AM Challenges***: - Post-processing is often required. This may be due to the stair stepping effect that arises from incrementally placing one layer on top of another, or because finishing layers are needed.
Perfection	-Bring perfection into clear view so the objective of improvement is visible and real to the whole enterprise. -Set specific timetables to accomplish seemingly impossible tasks and then routinely met or exceeded them.	***AM Challenges***: - Cost and speed of production.

2.7. Traditional versus lean project management: Which approach?

It is clear from the literature review that different processes require different management approaches. It is claimed by Howell & Koskela (2002:07) that project management suffers from flawed assumptions and idealised theory. Consequent problems are easier to resolve informally when projects are simple, small and slow. Large traditional projects in comparison, which are complex and requires speed, appears to be counterproductive and have several penalties. The author believes that this creates self-inflicted problems that seriously undermine performance and a deficient theory is the root cause of the problems of project management. (Howell & Koskela, 2002:08)). It is therefore advised that the problems of theory must be solved first, before problems can be resolved in practice. Howell & Koskela (2002:08) quotes, "of all the approaches to production management, the theory and principles drawn from lean production seem to be best suited for project management."
Kilpatrick (2003:05) describes lean organisations like those who are more responsive to market trends, deliver products and services faster, and provide products and services less expensively than their non-lean counterparts. Lean crosses all industry boundaries, addresses all organisational functions, and impacts the entire system–supply chain to customer base. Table 2.7. below the researcher refers to Kilpatrick in comparing lean concepts between traditional and lean organisations.

Table 2.7: Lean Concepts. (Kilpatrick, 2003:05)

Concept	*Traditional Organisation*	*Lean Organisation*
Inventory	An asset, as defined by accounting terminology	A waste – ties up capital and increases processing lead-time
Ideal Economic Order Quantity & Batch Size	Very large – run large batch sizes to make up for process downtime	ONE – continuous efforts are made to reduce downtime to zero
People Utilisation	All people must be busy at all times	Because work is performed based directly upon customer demand, people might not be busy
Process Utilisation	Use high-speed processes and run them all the time	Processes need to only be designed to keep up with demand
Work Scheduling	Build products to forecast	Build products to demand

Labour Costs	Variable	Fixed
Work Groups	Traditional (functional) departments	Cross-functional teams
Accounting	By traditional guidelines	"Through-put" accounting
Quality	Inspect/sort work at the end of a process to make sure we find all errors.	Processes, products, and services are designed to eliminate errors.

Companies traditionally tend to build up substantial amounts of inventories to protect their interests and as buffers against variability and risk, whereas lean's approach to inventory is more structured. (Ballard & Howell, 2003:04). Table 2.8. lists the differences between lean and non-lean project delivery.

Table 2.8: Lean versus non-lean project delivery (Ballard & Howell, 2003:04)

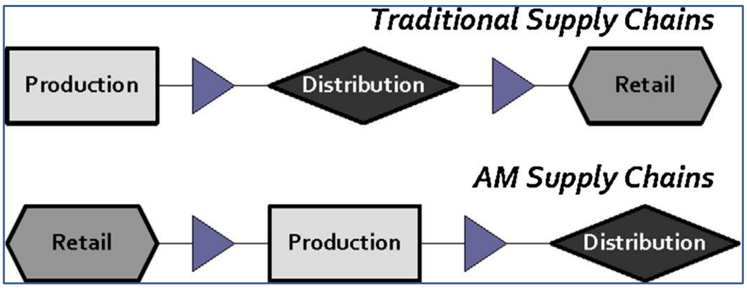
Lean	Non-lean
Focus is on the production system	Focus is on transactions and contracts
Transformation, flow and value goals	Transformation goal
Downstream players are involved in upstream	Decisions are made sequentially by specialists and 'thrown over the wall'
Product and process are designed together	Product design is completed, then process design begins
All product life cycle stages are considered in design	Not all product life cycle stages are considered in design
Activities are performed at the last responsible moment	Activities are performed as soon as possible
Systematic efforts are made to reduce supply-chain lead times	Separate organisations link together through the market and take what the market offers
Learning is incorporated into project, firm and supply-chain management	Learning occurs sporadically
Stakeholder interests are aligned	Stakeholder interests are not aligned
Buffers are sized and located to perform their function of absorbing system variability	Buffers are sized and located for local optimisation

2.8. Additive manufacturing a champion for lean

The benefits of AM are well recorded, such as the reduction in waste, new types of design, no tooling, reduced inventories and distributed manufacturing concepts. (UNIDO, 2003:53-54). AM is not only about reducing the use of materials, but also reduced energy usage, production space and equipment, assembly, part consolidation, set-up times, labour, transportation, packaging processes, delivery time and a reduced number of suppliers. An organisation is lean, when it can specify and line-up value, sequence all actions, conduct these activities uninterrupted as required, and perform these required activities more effectively. This process will lead to the five principles of lean thinking, namely value, value stream, flow, pull and perfection. (Womack & Jones, 2003:16)

As a disruptive technology, AM technology provides many benefits, which enables an organisation to manufacture flexible and customised products cost effectively. One main benefit is the production of physical and functionally integrated parts in a single step, without the need for any specialised tools and moulds or assembly activities. (Piller *et al.*, 2012:32). Therefore, AM technology champions the cause for lean through the significant affects it has on the costs of flexibility, individualisation, capital and marginal production costs.
Another benefit is that supply chains will change the emphasis from a production-distribution-retail model toward a model where retail takes place electronically, initiating manufacturing and final distribution to the end customer, as described in Figure 2.4. below. (Achillas, Aidonis, Iakovou, Thymianidis & Tzetzis, 2014:330).

Figure 2.4: TPM and AM supply chain comparison (Achillas et al., 2014:330)

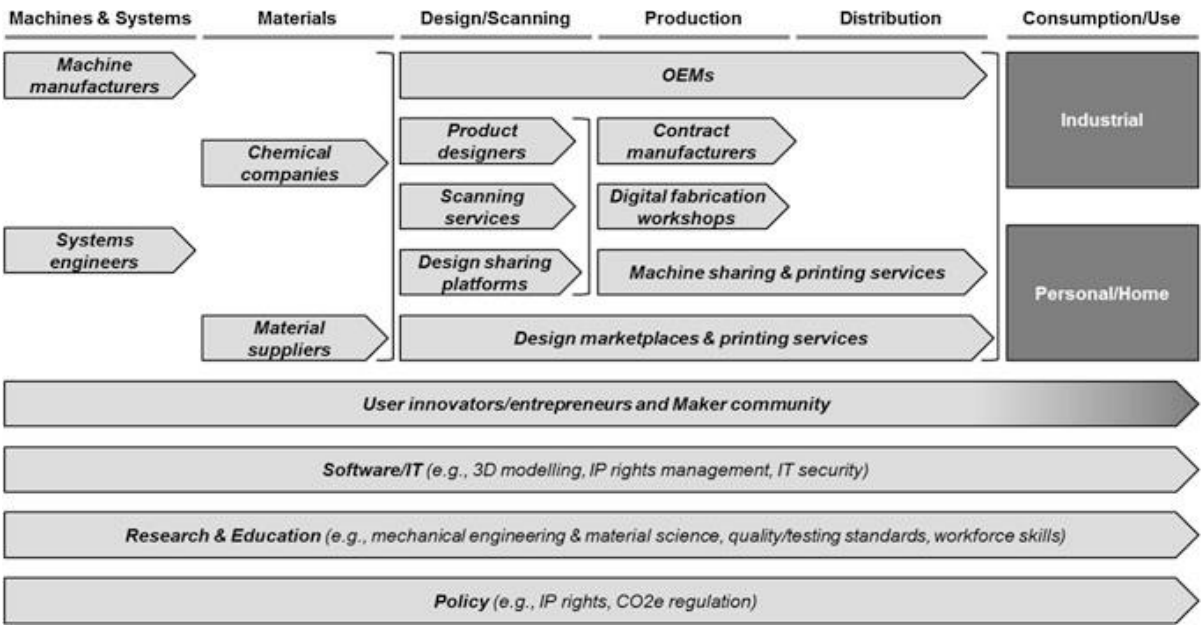


Additive manufacturing is not without limitations and the technology often struggles with slow production throughput times and some of these materials cannot be used for the same purpose as conventional materials. AM materials must often meet the material standards of conventional manufacturing processes, thus adding pressure on cost and finishing. Regular surface problems can occur, like surface cracking and warping and most manufactures and customers demand an additional surface finish. Industry standards for quality control needs to be established, such as specific terminology, process performance measurements and calibration. (Piller *et al*., 2012:36).

2.8.1. Is additive manufacturing lean?

Additive manufacturing in the early stages of its development was limited to the development of prototypes and the major purpose was to receive verifiable feedback during the development process of the product. These prototypes often made the development process more affordable and faster. (Gibson, Rosen & Stucker, 2010:07). The strength of the technology is the opportunity it represents to replace conventional production technologies for the continual manufacturing of parts and products. (Gibson *et al*., 2010:09). The fast growth in the number of 3D printers sold and used for home and industrial applications, extends the scale and scope of manufacturing options, therefore, additive manufacturing must be considered in the context of digital value chain activities. (Piller, 2012:40). Additive manufacturing must be part of an ecosystem which "encircles activities along a combination of both a conventional manufacturing value chain and a digital value chain of content/product design creation and distribution" The aforesaid is summarised in Figure 2.5 below.

Figure 2.5: AM ecosystem (Piller et al., 2012:41).



Research supports the view that additive manufacturing in South Africa (SA) has not reached the same level of maturity yet. Research performed in SA, addressed specific applications, rather than basic research. According to De Beer (2011:02), research institutions became technology demonstration centres and are in parallel with process development and improvements, to produce models and components. This research also affected some managerial aspects of the product development process, inclusive of rapid prototyping (RP) usage. AM role players in the local industry includes mainly research institutions and a small number of rapid manufacturers. These RP companies mostly have a mixture of AM technology and conventional manufacturing technologies such as laser cutting and CNC milling. Their levels of service mainly extend to the design and prototyping of new product developments.

AM provides industry and the "maker" community with support to create and capture value for their customers and shareholders, as new products are vital to the success and future of the modern company. Anand and Kodali (2008:02) refer to the new product development process (NPD) as the process that has a major influence on the outcome of a product, both technically and economically. This process is singled out when the customer's ideas and speculations are conceptualised into a physical model by capturing his or her needs and requirements in the form of structures, functions, features, procedures, drawings and technical specifications. Anand and Kodali (2008:02) further states that the needs of customers are highly specific and rapidly changing, although customers still want to have high quality and low-cost products/services. A lean framework for new product development is presented in Table 2.9. This framework consists of activities represented in the form of a sequence, required tools and techniques to support each activity. The sequence of activities is classified into various phases namely – define, review, investigate, verify, execute and repeat, in short, a DRIVER framework for lean new product development (LNPD). Table 2.9 thus describes the DRIVER framework for LNPD. This framework is supported by the five steps of lean management and explains the required activity that should be carried out in each step.

Table 2.9: LNPD tenets, activities and tools (Anand & Kodali, 2008:191)

Phase	Tenets of LM	Steps/activities	Tools/techniques used
Define	Define value (Identify the project, which is critical to the firm based on demand, investment etc.)	Identify a pilot project to which LNPD can be applied.	Decision making tools like cost-benefit analysis, risk analysis or multi-attribute models.
		Understand the current product development process.	Process mapping tools like flow chart, process chart etc.
Review	Identify the value stream.	Understand the wastes and value in the current development process.	Value stream mapping: depicting the current state.
		Understands the causes of wastes in NPD.	Cause and effect diagram, Why-Why analysis, Brainstorming and other problem-solving tools.
		Estimate how the future NDP process should be by eliminating waste.	Value stream mapping: depicting the future state.
Investigate	Flow the product (information)	Identify potential solutions to eliminate each waste.	Design for X, QFD, modularity, simulation and modelling, value engineering etc.
	Pull (Downstream activity pulls information from upstream activity)	Identify potential solutions to establish pull system in NPD.	Use of techniques like co-location, training, cross-functional teams, integrating mechanisms, concurrent engineering, etc.
Verify	Strive for perfection.	Implement potential solutions on a pilot project.	Gantt chart can be used for fixing time frames.
		Check the status of implemented solutions.	Performance measurement, audit, benchmarking.
Execute		Implement similar solutions across all NPD projects.	Effective documentation of the project incorporating failures, corrective actions and novel concepts, tools and techniques used etc.
Repeat		Continuously review the LNPD process and repeat the cycle.	

This framework highlights the importance of lean management tenets in the development of new products. As stated before in this section, AM's prime purpose was to offer an affordable and fast way to receive tangible feedback during the product development process. The following section will thus focus on literature relating to frameworks of project management and its application in the fields of traditional and additive manufacturing.

2.9. Frameworks

The basic definition of a framework as mentioned by the online English Oxford Living Dictionaries (2018) is a basic structure underlying a system, concept or text; a set of beliefs, ideas or rules that are used as the basis for making judgements, decisions, etc.

This section will focus on literature relating to the project management of traditional and additive manufacturing. A comparison will be made between the two manufacturing methods and the results will be used to identify the research gap.

2.9.1. PM Framework for Traditional Manufacturing

The project management framework provides a basic structure for understanding project management. The PMI is the authority on project management, and the PMBOK is used as a basis to research and refer to TPM and project management frameworks. Projects are usually divided into several project phases, and collectively they are known as the project life cycle, and each project phase is marked by the completion of one or more deliverable. (Salameh, 2014:52). TPM is made of distinct process groups that guide the management of projects through each process group's knowledge and skill areas. Project-management process groups are connected through the outputs each produces, each output becomes the input of another process (Salameh, 2014:54).

The basis for the traditional PM framework is outlined in PMBOK's literature as described by the PMI. The PMI's definition of TPM is the application of knowledge, skills, tools, and techniques to project activities to meet project requirements. Project completion includes the phases of initiating, planning, executing, monitoring, and controlling, and closing. These phases are occupied with accomplishing the demands of scope, time, cost, risk, and quality in the framework of planned stakeholder requirements through the application of 10 knowledge areas (Salameh, 2014:53). The TPM framework is summarised and outlined in Table 2.3 (*cf*. 2.5.1.1**.**) It reflects the mapping of the PM processes to the PM process groups of initiating, planning, executing controlling and closing to the 10 PM knowledge areas.

The advantage TPM has is that all steps and requirements of a project are defined before the start of execution. This advantage can lead to some limitations as projects rarely follow a sequential flow and it is uncommon for the client to define the requirements of a project completely and correctly. TPM is based on linear processes and practices and is driven by disciplined planning and control methods that are motivated by the assumption that project requirements and activities are predictable and that events and risks affecting the project are anticipated and controllable and once a phase is complete, it is expected that it will not be revisited (Salameh, 2014:55). Project management principles according to PMBOK, can be utilised in any project and industry. It is the respective scale of importance of these principles which varies between the different projects and industries. (Kerzner, 2012:29).
The aerospace and large construction industries are project-driven, therefore requiring a much higher monetary value of projects and a much more rigorous project management approach. (Kerzner, 2012:29). Many aerospace and large manufacturing companies have incorporated AM into their daily operations and state that aircrafts' configurations frequently change, generating complexity for project management, this complexity could vary in function in either customer's requirements or internal/external factors (Vieira & Romero-Torres, 2016:115). Unlucrative project industries may well be managed informally, although the process is similar to formal project management, the requirements in terms of the administration (paperwork), is kept at a minimum. (Kerzner, 2012:29).

2.9.2. PM for Additive Manufacturing

The role of PM in the aerospace environment has found that AM changes aerospace project management by eliminating manufacturing and assembling limits, by improving product design and by reducing lead-time for aircraft development, production and Maintenance, Repair and Over hall (MRO). AM enables the aerospace industry to eliminate waste in tooling, materials, labour and methods of production. This allows a reduction in time, and it improves efficiency throughout the aerospace supply chain and aircraft lifecycle (Vieira & Romero-Torres, 2016:118).

The aerospace industry does experience drawbacks like slow print speed, limiting AM use for mass production, technology costs, material quality problems and reliability and reproducibility limits. The authors do not offer a specific PM framework for AM in the aerospace environment, but states that PM should firstly focus on the intrinsic characteristics of aerospace products; secondly, PM should adopt innovative practices to develop better products with fewer resources; thirdly, invest capital in the design of their products in function of market needs and capacities. The fourth aspect is that the aerospace industry must deal with various problems related to the management of the supply chain. Lastly, the collaborative relationship with suppliers is encouraged, and project managers are encouraged to focus on two main approaches to conduct aerospace projects, namely product lifecycle management (PLM) and supply chain management (SCM). PLM enables to control product development complexity better while SCM permits better monitoring of suppliers. The author claims that, according to Vieira and Romero-Torres (2016:116), AM could strengthen PLM competencies that will improve performance such as innovation capacity, frequency and time-to-market, quality assurance, development costs and materials control.

In a study by Niaki and Nonino (2017:1420) on the review and future research agenda of AM, the research domains of AM management are explained, following the growing interest of scholars and practitioners in introducing AM technologies in managerial approaches. The aforementioned study focused on AM articles in all the research subfields relating to management, business, economic and social science. The scope of several other researchers in AM management who are mentioned in this research's literature review included mostly supply chain management, production economics, business models, product design and development, green products, innovation and creativity, technology management and strategies. Findings from the mentioned literature research identified eight factors and nine prolific future research directions about AM management (with factors suggesting a future direction) and are summarised in Table 2.10 below.

Table 2.10: Key AM research findings (summarised from Niaki & Nonino, 2014:1431)

Factor	Key Findings from Research	Prolific Future Research AM Management Areas
1. AM Technology Selection	Research in this field focuses on selecting the most appropriate AM technique and the selection criteria mostly include strength, quality, limitations, applications, defects, utilities, build time and cost.	Consolidating the decision-making framework theories by larger coverage of the AM technologies of practical interest.
2. Supply Chain Management	Most papers considered the impact of AM in supply chain management and researchers shown an increased interest in AM supply chain management.	Identifying supply chain management approaches for different products and process categories.
3. Product design and production cost models.	The capabilities provided to designers like the practical advantages of AM in design; and proposed models for production cost and time estimation.	Studying the impact of the combination of AM technologies with reverse engineering in product design. Examining the application of AM in a creative business.
4. Environmental aspects assessment	Energy consumption and other environmental aspects of AM, showing an increased attention among researchers and scholars.	Researching more cases or new dimensions of the environmental aspects of AM, which are still disputed.
5. Strategic Challenges	Challenges of the implementation and adoption of AM technology. The fundamental concern regarding management constraints, is: What has to change in my business in order for it to be successful?	
6. Manufacturing system frameworks	Systematic manufacturing framework for implementing AM for prototype and end use parts. Collaborative planning, control of production and web-based or networked manufacturing, e-manufacturing as an adaptive method.	Studying e-manufacturing as an adaptive method for this emerging technology. Focusing on CPC.
7. Open-source innovation, business and social impacts	The availability of design and 3D technology to the public. A full analysis of required resources and social requirements needs to be addressed.	Investigating AM technologies in open-source innovation and business.
8. Economics of AM	Concerns the framework for build time and cost estimation of the AM process, a reliable cost estimation model must be accomplished through knowledge of the entire process chain and by optimising the most valuable cost drivers.	Investigating impact of AM on market structures.

2.9.3. Traditional vs. Additive Manufacturing

Monzon, Ortega, Martinez and Ortega (2015:1115) quote a report by the Science and Technology Policy Institute, IDA, concerning the shortcoming of standards in AM and how it hampers on its use for parts production. The report mentions that parts produced by AM will need to meet the same levels of performance, as established by traditional manufacturing methods, to be fit for use. In relation to this, the need exists to establish repeatable processes and the production of reproducible parts, particularly in the medical, aerospace, and automotive industries.

AM and traditional manufacturing face various trade-offs, where AM offers industry higher levels of reductions in cost and time efficiency throughout the whole life-cycle and value chain. There is also a greater level of design flexibility and product customisation. In Table 2.11 some of the main advantages between AM and TM are compared.

Table 2.11: Comparative advantages of AM and traditional manufacturing (Vitale, Cotteleer & Holdowsky, 2016:08)

Advantages of AM	Advantages of Traditional Manufacturing
Design complexity: AM enables the creation of complicate and elaborate designs to exact dimensions, which can be challenging to manufacture using traditional methods.	*Mass production*: Traditional manufacturing is appropriate for high-volume production where fixed tooling and setup costs can be amortised over a larger number of units. AM is generally more competitive for low-to-medium volume production runs.
Speed to market: AM systems can manufacture products with little or no tooling, saving time during product design and development— and enabling on-demand manufacturing.	*Choice of materials*: Traditional manufacturing techniques can be deployed to a wider range of materials.
Waste reduction: AM typically uses less extraneous material when manufacturing components, significantly reducing or eliminating scrap and waste during production. This makes AM a more efficient process.	*Manufacturing large parts*: Despite advancements in "big area" or 3D printing envelope sizes, traditional manufacturing methods are still better suited to manufacture large parts.

The benefits of AM are well documented, although traditional manufacturing technologies, such as machining and casting, provide the highest parts quality level, according to surface finish and geometrical and dimensional accuracy. The mechanical properties are in most cases better than 3D printed parts because 3D printed parts are not filled by the material. The benefits of AM are numerous and does present the researcher with many opportunities, and he can compare it favourably with traditional manufacturing, as listed in Table 2.12 below.

Table 2.12: Comparison between AM and traditional manufacturing.

	Compared Object	
Compared Item	**Additive Manufacturing**	**Traditional Manufacturing**
Fundamental principle	Compose product by material layers	Remove unnecessary parts
Applied phase	Design phase	Manufacture phase
Product variation	Mass customisation/personalisation	Mass production
Total output	Low production	High production
Manufacturing speed	Slow	Fast
Price of unit product	High	Low
Diversity of utilized material	Depends on AM technology	Almost everything
Advantage	1. Less material required 2. More environmentally friendly 3. Ease of design improvement 4. High degree of customisation 5. No need of tool and jig	1. Less Cost 2. Higher produce speed 3. Mature technique 4. Almost no limitation of product types
Weakness	1. Higher cost 2. Slower produce speed 3. Technique is not matured enough 4. Limited type of product by the utilised material	1. More material wasted 2. Less environment friendly 3. Hard to change the design 4. Lack of ease of customisation 5. Need of tool and jig

The research literature in the previous sections highlighted the key-principles and differences between TM and lean and AM. This information provided us with a clear understanding of what is required to identify the research gap, as discussed below.

2.10. Research Gap Findings

Considerable literature with information on traditional project management theories and the application of it in different industries are available. The advent of AM technologies as a developing manufacturing technique presents some opportunities for researchers in different fields. Various studies according to Niaki and Nonino (2017:1421), in the management research stream have been performed; however, they are still in the developing phase and are published in journals covering different research areas: technology management, robotics, manufacturing automation, rapid prototyping (RP), sustainability, ergonomics, etc. Despite all the reviews of AM in different sciences and research areas that contribute to this innovative technology, limited available research covers the management of AM and proposes research directions focused on its strategic and operational dimensions.

The literature on TPM showed that it is based on linear processes and practices and project requirements, which are well defined prior to execution. The drawback is that steps and processes in projects seldom occur in order and customers seldom predict project requirements correctly (Salameh, 2014:55).

The literature on AM, however, is unclear on how PM is performed within the AM environment and what type of PM methodologies needs to be followed. If the assumption is made that AM is lean, then the comparison can be made between the PM of TM and that of AM. Literature is also silent on the application of lean in an AM environment, although it is clear from the literature review that a lean approach would benefit AM, such as the focus on waste reduction, speed to market and design complexity. The literature on AM showed that AM would benefit and perform better in a lean environment compared to TPM. Other significant AM lean benefits, such as the involvement of customers in the design process, the mapping of the value streams, the elimination of long lead times, minimum flow, only producing goods when needed and keeping stock levels at a minimum, distinguish itself from TPM. Literature is also inadequate on what type of PM challenges organisations might face when only dealing with AM.

The literature key findings confirm that current and future AM management research will benefit from investigating areas such as decision-making framework theories, supply-chain management and AM technologies in open-source innovation and business. Lastly, it was noted from these key research findings that no studies were found covering the PM of AM projects.

The objective of this research therefore requires the development of a lean project management framework for AM. The objective of the study is supported by the facts as mentioned above that no studies found explicitly targeted lean project management for additive manufacturing, and none has, to the researcher's knowledge, dealt with the development of a lean PM framework for the AM environment.

2.11. Summary

PM has become an essential function within organisations, because of the benefits associated with it, as mentioned in this chapter. TPM and LPM are both beneficial methods of PM, and it all depends on the manufacturing scenarios, as to which approach will be taken. AM provides manufacturing companies with the option to develop new products in a lean and cost-effective manner and managing projects may require a different approach. This chapter provided prove for the study, identified the research gap, the elements that constitute both lean and traditional project management. The next chapter focuses on the study area and the research methods used in the study. Knowledge obtained from the literature review, allowed the research to define and structure the research problem into the following research question if AM is identified as a lean manufacturing technology, how do AM organisations manage their design and development projects? The next chapter thus focuses on the research methodology and will discuss the research design concerning the research context, framework, constructs and questions, outlining of the data collection and analysing strategies.

Chapter Three: Research methodology

3.1. Introduction

This chapter focus on the research methodology. It will discuss the research design concerning the research context, framework, constructs and questions, outlining of the data collection and analysing strategies. This chapter demonstrates, that this study sought to fulfil the research purpose through an exploratory qualitative research approach with the aim to get research findings, conclusions and impact. The choice of research approach was motivated by the central research questions, variables and the lack of lean project management in additive manufacturing. This research will aim to combine background theory/literature, using knowledge on project management, lean and additive manufacturing to develop a framework.

As a disruptive technology, additive manufacturing may bring about a change in thought on how manufacturing takes place. Disruptive technology is based on best practice which resides in experts and their opinions. Conventional manufacturing can impose many constraints, whereas additive manufacturing may bring about a paradigm shift from design for manufacturing to manufacturing for design. This paradigm shift has created and will lead to more market opportunities and increased applications for additive manufacturing such as 3D faxing, in which the sender scans a 3D object in cross sections and sends out the digital image in layers, and then the recipient receives the layered image and uses an additive manufacturing machine to fabricate the 3D object.

Additive manufacturing offers multiple advantages over conventional manufacturing techniques, including reduced material waste and energy consumption. By adding materials layer by layer to create 3D objects, waste materials are greatly reduced. Shortened time-to-market, just-in-time production, and fabrication of structures not possible previously, is now a reality. Additive manufacturing will not replace conventional manufacturing methods in the foreseeable future, especially for the high-volume production of parts with low complexity and high accuracy. However, additive manufacturing may still bring revolutionary advances to the manufacturing industry through its integration with conventional manufacturing technologies. (Huang, 2015:2-4). Management of projects in this field may well require a different or separate approach compared to traditional manufacturing.

Project management has been a long-standing approach promoted by various bodies, intended to assist organisations, especially project managers, to manage project activities by applying a set of knowledge, skills, tools and techniques to meet user and stakeholder needs. By using effective project management practices, it may assist organisations to better plan, manage, execute and control projects, thus resulting in better performance and productivity and contributing the success of software projects. Although it has been widely acknowledged that good project management cannot guarantee project success, poor project management usually results in project failure. The literature review demonstrated that current and significant developments are taking place in additive manufacturing and the technology is increasingly used in large scale manufacturing, such as in the aeronautics industry. Project management is still required in this added additive environment, but there is no clear indication from this literature study, which specific project management approach is best or need to be applied to additive manufacturing.

Various project management frameworks and methods have been developed covering all aspects of managing projects with the purpose of increasing the project success rate. The most prominent and internationally recognised project management framework is the PMBOK, which is the factual standard for project management. (Salameh, 2014:54-57).

Considering the lean nature of additive manufacturing technology, the researcher has not confirmed whether lean is applicable in additive manufacturing, or not. This study will therefore investigate the applicability of lean and develop a framework for project management in an additive manufacturing environment.

The following chapter outlines and discusses the reasons and methods employed for the data collection in this study, including the research design, choice and reasons for data collection methods. The discussion of the questionnaire and the chosen sample is included. The research process of the secondary data is highlighted and followed by an analysis of the questionnaire results.

3.2. Research design

3.2.1. Deductive or inductive

This research design will refer to the approach used to collect and analyse data about this specific research topic. The research design will outline the research strategy, methods, questions, outcome and the criteria for the study. There are various employed research strategies and each strategy, in general, can be used for exploratory, descriptive and explanatory research and the findings either deductive or inductive. Saunders, Lewis and Thornhill (Saunders, 2009:141) emphasise that no research strategy is inherently superior or inferior to any other and what is most important, is whether it will enable to answer the research questions and meet objectives. The employed research strategy will be guided by the research questions and objectives, the extent of existing knowledge, time and resources available; equally, it is important to note that these strategies are not mutually exclusive. (Saunders *et al*., 2009:141).

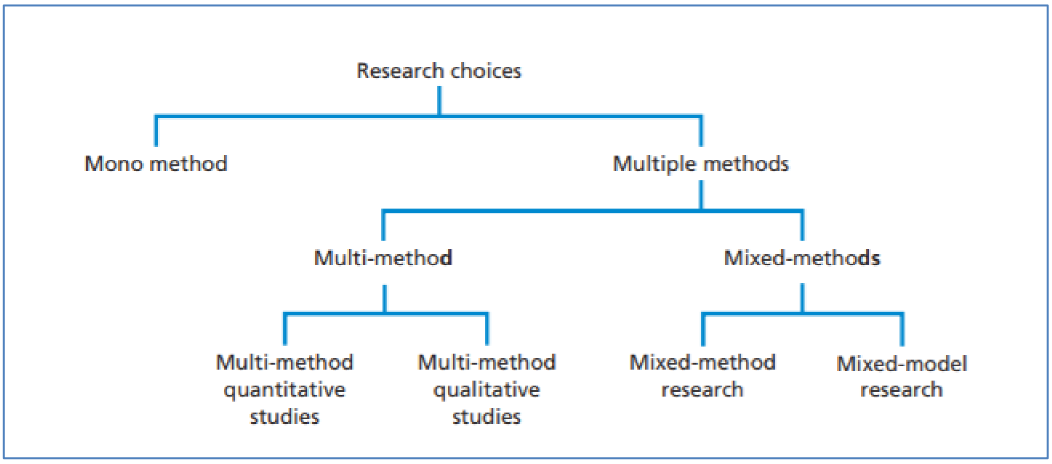
3.2.2. Quantitative or qualitative methods

From the literature research, some authors consider research design as the choice between qualitative and quantitative research methods or to the selection of specific methods of data collection and analysis. “Individual quantitative and qualitative techniques and procedures do not exist in isolation” (Saunders *et al*., 2009:154). According to Saunders et al. (2009:154), “in choosing your research methods, you will therefore either use a single data collection technique and corresponding analysis procedures (mono-method) or use more than one data collection technique and analysis procedures to answer your research question (multiple methods)." Figure 3.1. explains the different research choices.

Employing a mono-method, the researcher will combine either a single quantitative data collection technique, such as questionnaires, in this instance the Delphi method, with quantitative data analysis procedures. Alternatively, a single qualitative data collection technique, such as in-depth interviews, combined with qualitative data analysis procedures is used (*cf.* Figure 3.1).

For collecting and analysing data about the project management and lean principles in additive manufacturing, a single data collection technique and corresponding analysis procedures (mono-method) were chosen.

Figure 3.1: *Research choices (Saunders et al., 2009:152)*



3.2.3. Delphi study

The choice of research approach was motivated by the central research questions, variables and the lack of lean project management in additive manufacturing. The choice of method was prompted by the ability to allow leeway for a choice of viewpoints about the topic. One such method, the Delphi technique is ideal for policymaking and predetermining outcomes and can be used to collect expert views for a more extensive objective. The application of the qualitative Delphi method is extensive and covers many research scenarios, resulting in textual consensus data. Research which is focused around the collection of data and is preoccupied with group-based data, can be resolved with the qualitative Delphi method. (Sekayi & Kennedy, 2017:2757).

Hasson has summarised conclusions using Delphi as a research method in the form of a checklist. (Iglesias, Thompson, Rogowski & Payne, 2016:1163-1170). They include:

- Clarify the research problem, notice that the Delphi technique lends itself to group involvement.
- Identify the resources available and skills of the researcher.
- Understand the technique's process and decide upon which medium to use (electronic or written communication).
- Decide on the structure of the initial round (either qualitative or quantitative) and the number of rounds to employ.
- Determine the meaning of `consensus' in relation to the studies aims.
- Give careful thought to the criteria employed, the justification of a participant as an expert', the use of non-probability sampling techniques, either purpose or criterion methods;
- Give attention to issues which guide data collection: the discovery of opinions, the process of determining the most prominent issues referring to the design of the initial round, and the management of opinions, analysis and handling of both qualitative and quantitative data.
- Consider the method of the presentation of results (graphical and/or statistical representations) with an explanation of how the reader should interpret the results.
- Address issues of ethical responsibility, anonymity, reliability, and validity issues in an ongoing manner throughout the data collection process.

The above checklist along with the recommendations from Skulmoski, Hartman and Krahn (2007:9-10) is not intended to be definitive but will act as a guide to exploit this research using the Delphi methodology.

As this research is focused on the additive manufacturing industry, particularly the management of projects in this field, it is challenging to decide which specific factors are important in a particular situation, or environment. This research therefore requires the knowledge and experience of a panel of experts within this area. This decision will thus be made in the form of a Delphi study. This phase of the research will aim to determine what criteria or factors are required to perform a comprehensive lean project management assessment within additive manufacturing. Applying the Delphi method in this research will aim to enhance our knowledge of project management in the additive manufacturing environment.

From the literature study, the researcher is of the opinion, that there is a need to define and implement a project management methodology that specifies the steps and tasks that are required to manage AM projects in a persistently. The goal of such a methodology or model will be to ensure that 'good' and 'best' project management practices are identified and applied across all projects in a typical additive manufacturing company.

3.2.4. Delphi technique – facilitator appointment

For this research to be useful, using the Delphi technique, a researcher and several experts had to be appointed. The selected participants were all well versed and experts in the related fields of additive manufacturing, lean and project management. These participants or panel of experts provided a sufficient and diversified perspective on the related topics, and the final number of panellists were around eight and 10. The researcher developed the questionnaires, analysed the data and prepared the feedback for the round of questionnaires. The research question was clearly defined, and it aimed to keep the scope narrow, thus allowing experts to provide quality responses and to identify a reasonable number of ideas, thoughts and criteria.

3.2.5. Delphi technique – an iterative process

To be successful, the process involved a number of rounds, where solid feedback was given back between rounds to the participants. Research conducted using the Delphi as an applicable method, and it has been found used, in a range of research to develop, determine, predict and to validate in an extensive range of fields. **Typically, a Delphi will be conducted over three rounds. However, single and double round Delphi studies have also been completed**. Sample sizes varied in these studies from four to 171 "experts" and the conclusion is that no “typical” Delphi exist, and that the technique must be modified to suit the environment and research problem (Skulmoski *et al*., 2007:5).

Participants also had the opportunity to modify their responses anonymously. The process followed in this research focused on one, possibly two phases, more if required. Delbecq (cited by Boynton, 2006:326), described the Delphi process as a process which comprises of two or more sets of comments from a cluster of contributors. These responses to an initial questionnaire are then compiled and summarised and in the subsequent questionnaire(s), respondents are provided with compiled responses. Respondents are then asked to assess their initial positions with those of other study participants and provide additional feedback.

Turoff (2002:88-89), outlines four research objectives which call for the use of the Delphi technique. These are to investigate fundamental assumptions or information leading to contrasting views; to explore any information which may bring about consensus on the part of the respondents; to compare informed assumptions on a particular subject with a spectrum of disciplines and to inform the respondent group as to any distinct or interdepended aspects of the subject. Delphi is appropriate when examining particular research problems, therefore focus must be placed on the characteristics of the research problem and the administrative issues stemming from the topic in selecting this approach. Alternative data collection methods, including mail surveys or dialogue schedules and the decision to employ the Delphi technique must be centred around the appropriateness of the available alternatives.

A study conducted by Okoli on the Delphi method as a research tool, the Delphi method was found to be a stronger methodology for a rigorous query of experts and stakeholders. Many different techniques have been used in various research studies such as action research, cooperative inquiry and participatory action research. However, the "Delphi method is recommended above that of a traditional survey approach and among other high-performing group decision analysis methods (such as nominal group technique and social judgment analysis)" (Okoli, 2004:06). The view formed from the review on this research technique, is that the Delphi method is a desirable option, as it does not require the experts to meet physically, which could be impractical for international experts in the additive manufacturing field. As pointed out by Okoli, although there may be a relatively limited number of experts with knowledge about the research questions, the Delphi panel size requirements are modest.

3.2.6. Delphi technique – study design

3.2.6.1. How

This research considered the following Delphi design considerations as laid out by Skulmoski *et al.* (2007:05) in a study on the Delphi method for graduate research. The first important consideration is to make the decision early in the research design phase, as to whether the research questions will be focussed or broad-based. This research focussed on the elements of lean management in additive manufacturing. Therefore, the questions are focussed and designed to lead the Delphi participators towards a clear objective. A broad approach, however, collected more data and open-ended questions, requiring more time-consuming analysis (Skulmoski *et al.*, 2007:10).

3.2.6.2. Expert criteria

Skulmoski (2007:10) points out that Delphi participants should meet four "expertise" requirements: i) sufficient knowledge and experience with the concerns under review; ii) competency and commitment to cooperate; iii) sufficient time to participate in the Delphi; and, iv) effective communication skills. Commitment to cooperate in a multi-round Delphi is dependent on the feedback rate after each round. Field experts employ considerable judgement, but because of very busy schedules, they may not be able to participate fully. Therefore, questions put forward should be appealing, well-written and to the point, to ensure their participation.

As this research is focused on the additive manufacturing industry, particularly the management of projects in this field, it is difficult to decide on which specific factors are important in a certain situation, or environment. This research therefore called upon the knowledge and experience of a panel of experts within this area, in the form of a Delphi study, to make that decision. It was the aim of this phase of the research to identify what different criteria or factors were needed to be evaluated during a comprehensive lean project management assessment within additive manufacturing. The reason for applying the Delphi method in this research is to improve our knowledge or understanding of problems, opportunities, solutions, or to develop forecasts of project management in the additive manufacturing environment.

The researchers' view from the literature study, affirms the need to define and implement a project management methodology, that specifies the steps and tasks that are required to manage new additive manufacturing projects in a consistent manner. The objective of such a methodology or model will be to ensure that 'good' and 'best' project management practices are identified and applied across all projects in a typical additive manufacturing company.

3.2.6.3. Number of participants

The study needed to consider the sample size, and although there are no fixed and definite rules, certain factors had to be considered. Skulmoski (2007:10) points out that if a study sample is homogeneous, then a smaller sample of between 10 to 15 people may produce sufficient results. Increased sample sizes above a certain threshold, can make the Delphi management and analysing process cumbersome. The results of a larger group can be verified more effectively, but for a smaller sample, verification can be conducted with follow-up research. Often a single Delphi study will suffice for a master thesis, and for a PhD dissertation, the Delphi study is verified with a follow-up study. The objective of the research determines the number of rounds and most research require two or three Delphi iterations (Skulmoski *et al.*, 2007:11).

3.2.6.4. Mode of interaction

Initial Delphi surveys were pen and paper-based, although, still an option, other mediums are available, as suggested in this research. This research made use of electronic mail, as it made the research process accessible to both the researcher and the Delphi participants. The processing time was fast, and the received data was already in digital format, assisting interpretation. (Skulmoski *et al.*, 2007:11).

Guidelines according to ESOMAR World Research, on online/Internet research recommend that the identity of the researcher and details why the participant was chosen to participate. Benefits of participation must be highlighted and a statement on how privacy will be addressed during the study. ESOMAR also recommends three over-riding guiding principles for online researchers, first, treat the respondent with respect; second, researchers must consider consumer uncertainties and thirdly, researchers must be attentive in sustaining the separation between research and commercial activities (ESOMAR, 2011:03).

3.2.6.5. Results

The presentation of the results in the Delphi study will be thoroughly discussed further on, and importance is placed on the appropriate analysis techniques used. The method of data analysis is directly linked to the type of questions used in the Delphi study.

3.2.6.6. Verification

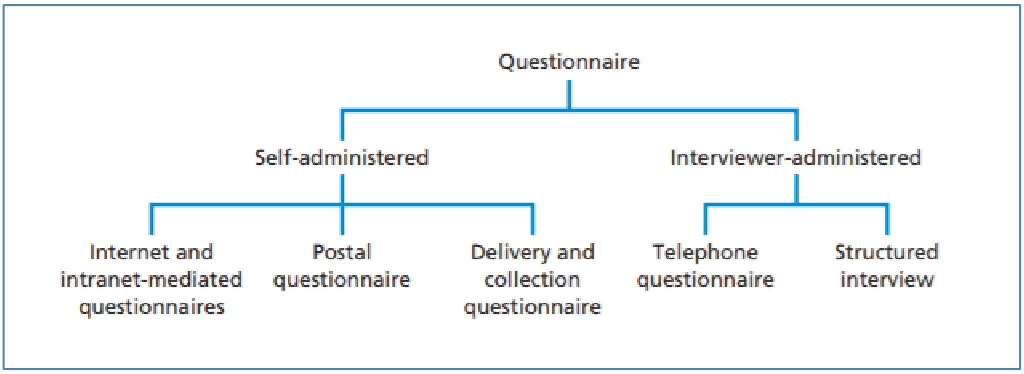
Difficulties identified with the verification process, using Delphi, is the generalisation of results to a widespread population due to sample size, narrow perceptions or distinct agenda and geographic location. These difficulties have result researchers to recommend follow-up studies to enhance and verify their findings. The research of related sets of questions must be extended to a similar sample from other geographical locations (Skulmoski *et al.*, 2007:11-12).

3.3. Method of data collection

3.3.1. Questionnaire

A questionnaire is designed according to the different ways it is administered and equally important, the amount of contact a researcher has with the respondents. Self-administered questionnaires (*cf.* Figure 3.2), are usually completed by the respondents, and such questionnaires are administered electronically using the Internet (Internet-mediated questionnaires) or intranet (intranet-mediated questionnaires) (Saunders *et al.*, 2009:362).

Figure 3.2: Types of questionnaires (Saunders et al., 2009:152)



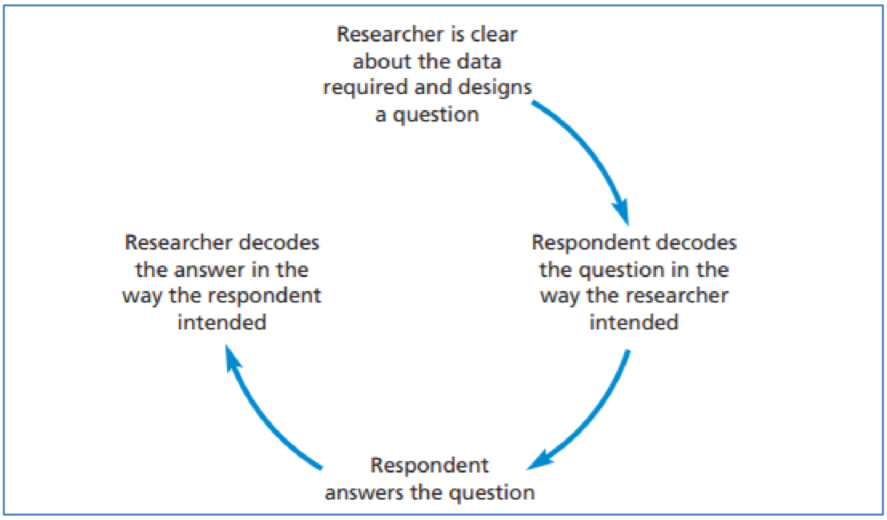
A self-administered, email survey, using Survey Monkey, was chosen as the most appropriate data collection method (*cf.* Appendix A). A questionnaire served as the primary method for the gathering of information and resulted in statistical data. The choice of the research design was influenced by the cost-effectiveness, speed/timescale, broad geographic reach and ease of use. Each respondent was requested to reply to an identical list of questions, requiring no conducted interviews due to the geographic reach of respondents. The research method provided convenience and a warranted overview of present views about lean principles and project management in additive manufacturing.

It is stressed that the questionnaire offered only one chance to collect the data needed. It is therefore essential that the appropriate characteristics were selected to answer the research questions and to address the objectives. It is thus crucial to have reviewed the literature carefully and to discuss ideas with supervisors, colleagues and all other interested parties (Saunders et al., 2009:367). Attention was paid to the layout of the questionnaire to improve the likeliness of a high response rate, and a cover letter (*cf.* Appendix B) was attached to highlight the research topic and the reasons for the study, for the same reason.

3.3.2. Questionnaire design

The design and structure of questions and the rigour of a pilot test will result in data that is internally validated, reliable and responsive. The questionnaire will, therefore, enable accurate and constant collected data. Saunders *et al.*, (2009:372) state that at least four stages (*cf.* Figure 3.3) must occur if the question list is to be valid and reliable. The design of the questionnaire will ultimately require the researcher to do substantial rewriting in the design stage, to ensure that the respondent decodes the questions in the way as attended by the researcher. The use of a word processor or survey design software such as SurveyMonkey.com™, Snap Surveys™ or Sphinx Development™ is recommended (Saunders *et al.*, 2009:372).

Figure 3.3: Stages that must occur if a question is to be valid and reliable (Saunders et al., 2009:372)



3.3.3. Questionnaire

3.3.3.1. Questionnaire Design

The statements in the questionnaire were generated from the literature review in Chapter Two. These items were based on two focus areas, namely lean management principles in manufacturing and project management processes and knowledge areas.

The first focus area is based on lean management principles, as described by Liker (2002). The principles have been the foundation of the Toyota Production System (TPS) and are their unique approach to manufacturing. The principles are summarised into four groups (four P's), namely philosophy, process, people and partners and finally problem-solving. This study represents a more in-depth look at lean principles as we know it in the traditional manufacturing environment. Another major lean study included work researched by Womack and Jones (2003). The authors defined a lean manufacturing enterprise as a five-step process which includes defining the customer value, defining the value stream, making it "flow", a "pull" system and continuous improvement. The view of this research is that a more in-depth look at lean could champion the cause for additive manufacturing to be proven as lean manufacturing technology. **It is important to take cognisance of the fact that lean must be seen as an integrated system, that must filter through an organisation's culture.**

The second focus area is based on the project management framework, as prescribed by the PMI (2013: 47-49). Every project needs five process groups, namely: initiating, planning, executing, monitoring and controlling and closing. The purpose of these process groups is to put together processes that often operate around the same time on a project or with similar input and outputs. It is thus the logical way of putting things together in a group that needs to be done in a project.

Key aspects of a project are categorised according to 10 project management knowledge areas. Each knowledge area is made up of a set of processes, each with inputs, tools and techniques, and outputs. These knowledge areas also assume specific skills and experience to accomplish project goals, and they are formed by grouping the 51 processes of project management into specialised and focused areas. Knowledge areas are designed to consolidate processes which have common knowledge characteristics. The grouping of the processes means that knowledge areas are divided to keep the same type of skill set (or knowledge) in one group. Knowledge areas are grouped according to the skill required to manage that specific process, and there is no relationship between knowledge area and process group.

The PMBOK guide defines a process as "a set of interrelated actions and activities performed to achieve a specified set of products, results, or services." Processes serve as a roadmap for keeping the project going in the right direction. Suitable processes are based on sound principles and proven practices that are extremely important for ensuring a project's success. Employing these processes can help reduce misunderstanding and uncertainty among the project manager and the project stakeholders. (PMI, 2013:50-60).

3.3.3.2. Types of questions and their measurement

This research delivered various types of questions to collect the opinions of respondents. The questionnaire can be viewed in Appendix A.

Demographic questions: Only two questions were provided and addressed some of the characteristics of the respondents. Questions in this research were kept short and related only to the type of department and role in the organisation. The advantage of this type of information is that it can be used later to compare responses between different groups. For example, “Please specify your role; that is, the one in which you currently work primarily (that is, 50% or more of your time)” (*cf*. Appendix A).

Closed-answer questions: This was the easiest type of question, as it came in the form of a drop-down menu. The research participants were provided with a list of countries, as to where they reside. For example, “Indicate the country in which your work is based. (Drop-down menu)” (*cf*. Appendix A).

Open-answer questions: No open-answer questions were asked, as it can often be very time consuming and the e-platform used, provided a fast and efficient way to respond.

Rating questions: This is a scaling technique, and it aims at measuring respondents’ intensity of feelings, at the current point in time, such as the level of agreement and disagreement with a proposition. A five-point Likert scale was deployed, including a middle-position or “not sure” indicating the respondent’s neutrality on the aspect. The technique less threatening to the respondent, than admitting they don’t know (Saunders *et al.*, 2009:378-380). For example, “Quality should be a built-in mechanism and defects detected immediately when they occur” (*cf*. Appendix A).

Ranking questions: No ranking questions were employed.

Matrix questions: This provided the respondents with the two or more similar questions at the same time. The responses to the questions in the matrix/grid are recorded where the cell and column meet. For example, “To what extent, in your opinion, does the following PM knowledge areas play a significant role in the Initiation process of additive manufacturing projects?” (*cf*. Appendix A)

3.3.3.3. Questionnaire layout, wording and length

The questionnaire consisted of 26 questions and 22 related to lean and project management. The questionnaire was designed for an interval of 10 minutes. A pilot test was run with a subsample, to encourage feedback and promote any refinements based on respondents’ comments. The layout of self-administered questionnaires should be attractive to encourage the respondent to fill it in and to return it, while not appearing too long (Saunders *et al.*, 2009:387).

The order of the questions was based on their relevance to the focus areas and their difficulty. General questions were asked first, while questions and topics that are more complex were asked later in the questionnaire. A clear route was followed through the questionnaire and questions were grouped into two focus areas (Saunders *et al.*, 2009:388). The first refers to the lean principles, regarding the philosophy, processes, people and partners and problem-solving. The second relates to project management processes and knowledge areas. Certain questions were shortened, and emphasis was placed on the fact that these questions should be self-explainable and not embarrass the respondent regarding his or her knowledge. Questions are one statement based. In general, a statement is made, and then the question or opinion is asked in the questionnaire.

3.3.3.4. Pilot-testing and assessing validity

Pre-testing prior to using a questionnaire to collect data, is a valuable step in the research process. The purpose of the pilot test **"**is to refine the questionnaire so that respondents will have no problems in answering the questions and there will be no problems in recording the data. It will enable you to obtain some assessment of the questions' validity and the likely reliability of the data that will be collected" (Saunders *et al.*, 2009:394). It is recommended that a group of experts comment on the representativeness and suitability of the questions, as well as allowing them to make suggestions on the structure of the questionnaire and will establish content validity. The number of respondents with whom the pilot will be presented to depends on the research questions, the research objectives, size of the research project, time and money resources available and how well the initial questionnaire was developed. Saunders *et al.* (2009:394) state that for most student questionnaires a minimum number of 10 respondents will suffice, and for extensive studies, 100 to 200 responses would be usual. It is also stressed that even if a student is extremely pushed for time, it is better to pilot test the questionnaire using friends and family, than not at all, as this would give you at least some indication regarding the questionnaire face validity.

This study undertook pre-testing in three stages, including face validity and content validity. Face validity does not involve quantifying any data, but whether the questionnaire appears to make sense, or not. Content validity refers to whether the questionnaire reflects the content of the topic under investigation.

The first phase of the pilot test required a group of experienced researchers to check the questionnaire for any potential problems and errors. The initial effort aimed to establish the face validity of the questionnaire. The researcher was required to comment on the content of the questionnaire and to indicate any shortcomings. Suggestions, based on the feedback, were made to the original questionnaire. The researcher included alterations to some of the choices of wording and phrases, font size and the number of open questions. After the completion of these changes, the questionnaire was re-sent to another group of researchers for the same process and approval.

The second phase of the pilot-test was used to check the content validity of the research questionnaire and identify any problems. The respondents for this exercise were chosen, as they are experts in the field of additive manufacturing, and they are also representative of the sample population. The respondents comprised two engineers and one full-time lecturer. They represented an engineering department and the "MakerSpace" environment, dedicated to the design, development and manufacturing of small-scale prototypes and industry parts. The questionnaire was emailed to the respondents for comment on the formulation of the questionnaire items, the layout, wording, length and any other problems while working through the questionnaire. Respondents were also encouraged to indicate any shortcomings in the questionnaire, which might be of interest in their working environment. The responses received from the respondents were moderate, but positive and only minor changes were suggested. These changes required the researcher of this study to clarify specific terms, such as "Flow" and "Pull", and eliminating the use of abbreviations, such as "PM and AM", replacing them with "project management and additive manufacturing".

For the third stage of the pilot-test, the questionnaire was sent to an experienced additive manufacturing expert, and who is also an experienced researcher. The face validity of the questionnaire was rechecked, and the questionnaire was scrutinised again for errors in design and other technical problems. Some of the comments returned during this process, included phrasing of some of the answers. The Likert scale of some of the answer options was changed, for example, a middle value was added, and the zero-value removed.

The final questionnaire is included in Appendix A. This reflects the changes made during the pilot-testing phase.

3.3.3.5. Sample

The sample population aimed to gain an understanding of how respondents manage their projects in an additive manufacturing environment. These respondents are employed in various capacities, including research, design, management and manufacturing. The reason for the sample selection, was influenced by the fact that these participants have reached a particular specialist and executive level and have been successful in working in an additive manufacturing environment. It is the view that they were most likely to be able to offer insights into this manufacturing environment, from which a better understanding could be built.

The use of a sample was required, as the entire additive manufacturing population is too large, although small, compared to traditional manufacturing. It would be impractical, too expensive and time consuming to survey the entire population. The population of this study was made up of staff and members of research, development, manufacturing organisations and higher education institutions. Respondents were chosen from within these groups and they needed preferably to be involved in the project management and design and development projects within an additive manufacturing environment. These participants were also asked to provide further contact details of colleagues, which enabled the researcher to establish contact with others who are influential to the research topic.

The purpose was to achieve a representative sample of the population and to achieve a broad spectrum of opinions and experiences. The sampling error might have been reduced, due to the direct involvement of experienced respondents in their various selected fields. The risk was reduced considerably, as only respondents with relevant experience or involvement in additive manufacturing, were directly contacted.

A sample size of 12 from companies and institutions were achieved. Respondents were invited to take part in the questionnaire via email, through a fully electronic survey (e-survey). This e-survey was found to be the ideal and preferred option.

Respondents logged on to a specially designed homepage to fill out the questionnaire. The survey was conducted in “SurveyMonkey”, an Internet-based survey software. The advantage of this type of survey is that a larger geographic audience can be reached and that the collected data could be immediately analysed.

3.3.3.6. Desk research

Most studies include the design of collection methods for primary data. Data which the researcher did not collect for himself directly from subjects or respondents, are secondary data. The research environment provides the researcher with large quantities of information, especially through the Internet and it saves the researcher considerable time. This information, such as statistics, reports, articles, etc. are available through other researchers, industry and institutions. (Greener, 2008:73).

This research relied partially on secondary sources to provide concrete information required to relate ideas and findings to that of other researchers. This information supported efforts during this research to avoid the repetition of time-consuming information collection processes. The researcher was provided with the opportunity to gain extensive data and to analyse it in a much shorter time. The information gathered from these sources during this research, was based on trusted and robust representative samples, covering various regions and groups. In addition, these based studies were performed by experienced researchers and research organisations, applying structured collection and information control processes. The secondary literature in this study provided a basic understanding of the researched topic, required concepts and theories, research methods and strategies.

3.3.3.7. Systematic review process

Locating relevant secondary data requires time and effort. The first stage requires the researcher to establish whether the sort of data needed, available is as secondary data and secondly, where to locate the data you need. The process employed in this research for secondary literature, was based on a systematic review process.

Firstly, key aspects of the research topic were brainstormed to determine keywords for the literature research in various journal databases. During this process, additional keywords were added, which derived from the reviewed articles. The following list of keywords was deployed for the secondary literature research:

- "lean" and "lean manufacturing"
- "lean management" and "project management"
- "frameworks" and "additive manufacturing"

These and other additional keywords related to specific terms to broaden or limit the search results. The primary search process utilised various meta-search engines, computer search resources and databases as provided by the North-West University (NWU) library. The inter-library loans system provided further assistance for assessing rare material, as well as literature held by other universities. The process proceeded by gaining an overview of the most recent information and researchers on the topic. The reference lists of articles and books were browsed to expand the knowledge and information base on the journal articles, authors and research keywords.

The use of web-sites/pages provided the researcher with the quickest access to an arrange of information on the research topic. The Internet provided the researcher with the advantage of linking multiple pages and increasing the range of suitable material, providing new ideas and subjects that have recently been discussed in the topic area. The Internet web-pages that supplied reliable information were recorded by listing them on a reference list, and on the web browser, for access again at a later point in time.

The review of journal articles followed the process, and these were distinguished according to their reliability, content, required information on the topic, and the suitability of the research data. The literature was grouped into three categories to evaluate the content of the articles:

A) Articles of every description which includes information of relevance to the topic, i.e. project management in additive manufacturing environments.
B) Articles of every description which included information relevant to the research question, i.e. information on additive manufacturing a lean technology.
C) Articles of every description that includes information less relevant to the topic, i.e. general information on manufacturing frameworks.

At the beginning of the literature review process, challenges were experienced in terms of reliability and sufficiency of data provided, as the authors' opinion was not always clearly articulated. The challenges were resolved through a thorough understanding of information, and an overview of the most popular researchers in the field. Required additional information about specific sources was obtained through web searches, as required. Finally, the literature research resulted in the identification and classification of articles published in peer-reviewed journals, studies reported in books and Internet articles.

3.4. Analysis of data

This research employed the Delphi technique and followed a consensus-based approach. Fink (1984:979) describes consensus as a "collective agreement", and their designs are based on group facilitation methods. These employed methods determine the level of agreement among a group of experts through the accumulation of different views, into clarified approved opinion. Fink (1984:979) points out three main consensus designs, namely the Delphi technique, the consensus development technique and the nominal group technique. The classic Delphi technique requires, if needed, multiple rounds of questionnaires, usually between two and three rounds. The first round usually generates qualitative data, used to develop the questionnaire. A modified Delphi is employed, if the study requires the researcher to develop a questionnaire from literature, or from previous research. The other two consensus designs are heavily reliant on discussions and in-person meetings (Fink, 1984:980).

This research employs the modified Delphi technique, given the need that the questionnaire had to be developed from literature and that data had to be collected from respondents nationally and internationally.

The questions or statements developed for the initial round of the Delphi process were prepared from the findings generated from the literature research. Questions or statements focused on lean management principles, project management processes and knowledge areas within the additive manufacturing environment. Initial draft questionnaires were developed and passed by experts and colleagues for a review on appropriateness and clarity.

3.5. Determining consensus

Numerous Delphi studies have used certain levels of consensus to quantify consensus amongst experts. The level of agreement in this study was done according to a five-point Likert scale. The level of agreement or disagreement for example, included: strongly agree, agree, somewhat agree, disagree and strongly disagree. Von der Gracht discusses various means of assessing the point of consensus (2012). Von der Grachts' (2012:1528) literature review revealed that "various Delphi studies had used various types of subjective or descriptive statistics for the determination of consensus and the quantification of its degree". Table 3.1 below summarises the results in this field (Von der Gracht, 2012:1529). According to the author, and with reference to the summary in Table 3.1, it is apparent that some chosen levels might seem arbitrary.

Table 3.1: Consensus measurement by qualitative analysis and descriptive statistics (Von der Gracht, 2012:1529)

Measure of consensus	Literature Examples of Criteria
Stipulated number of rounds	Research indicated that three iterations are typically enough to identify points of consensus.
Subjective analysis	- The expert's rationale for a response had to be consistent with the mean group response. - A consensus is pursued through a series of personal interviews over several days.
Certain level of agreement	- In keeping with most other Delphi studies, consensus was defined as 51% agreement among respondents. - Consensus was achieved on an item if at least 60% of the respondents agreed and the composite score fell in the “agree” or “disagree” range.” (on a five-point Likert scale). - More than 67% agreement among experts on nominal scale (yes/no) was considered consensus. - More than 80% on a five-point Likert scale in the top two measures (desirable/highly desirable) was considered consensus. - Consensus defined as more than 95% agreement in the first Delphi round.
APMO Cut-off Rate (average percent of majority opinions)	- Calculate an APMO Cut-off Rate of 69.7%, thus, questions having an agreement level below this rate have not reached consensus and are included in the next round. - CalculatedAPMO Cut-off Rates of 70% (first round) and 83% (second round) for consensus measurement.
Mode, mean/median ratings and rankings, standard deviation.	- The mode was used as an enumeration of respondents who had given 75% or more probability for a particular event to happen. If this value was above 50% of the total respondents, then consensus was assumed. - Mean responses within an acceptable range (mean ±0.5) and with an acceptable coefficient of variation (50% variation) were identified as an opinion of firm consensus. - Consensus was achieved if ratings (4-point Likert scale) for the items fell within the range of mean ±1.64 standard deviation. - An analysis of mean rank, percent of managers ranking a variable in the top 10, and standard deviation, indicated a sufficient level of consensus had been attained.
Interquartile range (IQR)	- Consensus is reached when the IQR is no larger than two units on a 10-unit scale. - Consensus was obtained if the IQR was 1 or below on a seven-point Likert scale.

	- The respective consensus criterion was an IQR of two or less on a nine-point scale. - IQR of one or less is found to be a suitable consensus indicator for four- or five-unit scales. - IQR ranged from 0.00 (most agreement) to 3.00 (least agreement). Items with an IQR larger than 1.00 indicated a lack of consensus and were retained for the second interview. - Measured consensus in his study as more than a 1-point change in the interquartile range over three Delphi rounds. - Calculate the amount of convergence of group opinions by a formula using the interquartile ranges. A higher value of its outcome near to 1.0 indicates a higher degree of convergence.
Coefficient of variation	- The authors found the coefficient of variation at or below 0.5, which was to them a cut-off point conventionally accepted as indicating reasonable internal agreement. - A consistent decrease of the coefficients of variation between the first and the second round indicated an increase in consensus (greater movement toward the mean).
Post-group consensus	- Post-group consensus concerns the extent to which individuals – after the Delphi process has been completed – individually agree with the final group aggregate, their final round estimates, or the estimates of other panelists.

Various contrasting percentages have been used, which lead to the assumption that measures are often specified after the analysis has been conducted. Von der Gracht (2012:1529) states that the determination of consensus by a certain level of agreement distinctly worthwhile is if nominal scales or Likert scales are used for the degree of agreement. Thus, the author points out that the definition of a certain level "can be based on accepted standards" (Von der Gracht, 2012:1530). From the literature by Von der Gracht, it seems that there is no agreement on the best approach and that the "certain level of agreement" the most commonly used approach is. Considering the latter and the reference to the use of Likert scales for the level of agreement, this "certain level of consensus" approach was adopted for this research. The assumption is made from the literature that a common figure of between 70% and 80% is used for agreement, although no set standard for the target percentage agreement could be confirmed. However, consensus will be interpreted as 80% in the two top measures for each statement in the questionnaire. These high measures typically include Agree strongly and Agree.

3.6. Credibility and reliability

The trustworthiness of research findings is imperative and "every research study must be evaluated in relation to the procedures used to generate the findings." (Graneheim & Lundman, 2004:109). The use of concepts related to quantitative research, such as validity, reliability and creditability, is applicable in qualitative content analysis. (Graneheim & Lundman, 2004:109-110).

Graneheim & Lundman (2004:110) believes there is no single correct meaning or universal application of research findings, but only the most probable meaning from a particular perspective. "In qualitative research, trustworthiness of interpretations deals with establishing arguments for the most probable interpretations. Trustworthiness will increase if the findings are presented in a way that allows the reader to look for alternative interpretations." (Graneheim & Lundman, 2004:110).

The researcher's first aim in this study regarding the primary data quality was to consider the reliability or the consistency of measures. The study should be able to produce the same results if an identical study was to be repeated at a later stage, or with a different topic. One such method of testing reliability is to make use of the test-retest method. This method was not used in this study, as this would have resulted in much longer periods of data collection and analysis, than what was available. Test questions were not employed either in this study, as it was felt that these questions might be substantially equivalent. The respondents might suffer fatigue as the questionnaire might become too long and similar questions might be spotted and that they might refer to their previous answer. The employed measurement for the internal reliability of the primary data collected was covered by the number of questions including the various topics relevant to the research objectives. The employed measurement, however, also provided the study with a clear and constant indication of the respondents' knowledge about the topic. The response rate to the questionnaire in the study was also used as an indication for high reliability of the gathered information.

The second attribute of primary data that can be measured is validity. As mentioned previously in this chapter, face validity was achieved through the questionnaire discussions with experts. Concerning attaining external validity, a representative primary data sample was collected through the questionnaire. Our validity was increased through the implementation of the study at several different workplaces, with respondents representing various workplaces. The implementation of the study at various workplaces provided the researcher with the broadest population possible. The biggest threat to reliability and validity is observation bias and one way to revert this is to ask questions about the conclusions, like what was meant and what other interpretations could have been put forward (Saunders *et al.*, 2009:297).

3.6.1. Delphi results

The Delphi statements commenced by capturing the respondent's professional role and country of residence. Respondents were sent reminders during the initial round, ensuring feedback on assessment levels of agreement or disagreement on each statement. The Delphi study consisted of 26 questions, and no comment boxes were provided with the questionnaire statements. Questions commenced with open-ended statements, and the majority of the questionnaire consisted of matrix questions. The data was collected via an online questionnaire, using SurveyMonkey and this same platform was used for descriptive analysis. This analysis included the frequencies and percentages, to determine if consensus was reached for each statement.

Responses of all the respondents were provided and analysed, highlighting the levels of consensus achieved, and not achieved, for each of the statements. The statements which did not achieve consensus, were deemed non-agreement.

The results were formalised firstly, according to the respondent's participation. The second summary included the professional roles occupied by respondents followed by country of origin.

Consensus was determined by the number of statements which obtained consensus, divided by the total number of statements provided. The results which obtained consensus were highlighted in table format. The consensus is stated as the combination of those statements viewed, as for example, agreed and strongly agreed upon (80%). The statements which did not obtain consensus was tabled along with their levels of consensus. Graphs were also provided for each statement.

The analysis of the consensus feedback was outlaid according to specific key findings. These included the key areas of consensus and the main areas of non-consensus. All statements were listed and tabled according to the number of responses and the percentage of agreement (i.e. strongly agreed, agreed) to statements relating to specific topics.

3.6.2. Interpretations

Findings are analysed, and interpretations are made in Chapter Four. The analysis commences with the profiling of the sample. The total response rate, the type of institution or industry they represent, the position the participants occupy within their environment and the country of origin.

The responses were analysed and discussed and summarised into four groups (four P's), namely philosophy, process, people and partners and finally problem-solving. Responses and levels of agreement of each statement are highlighted under these headings. The analysis and discussion then focus on the main project management principles and their levels of agreement. Graphs and tables are provided outlaying the responses for each statement.

3.7. Ethics

Ethics involves "moral choices we need to make affecting decisions, standards and behaviour. The practical aspects of a study and the potential isolation of you as researcher, as well as the possible inexperience, can all contribute to a feeling of doubt and concern" (Greener, 2008:40-42). The researcher is thus responsible for the collection of data in an ethical manner. Respondents were not harmed during the research process or identified through the publication of the research findings. Privacy was maintained, and respondents were not required to provide any sensitive information. Respondents' identities were kept secure, and questionnaires received back, were identified through numbering the questionnaires.

Participation in the study was on a voluntary basis, and the questionnaire (*cf.* Appendix A) was accompanied with a cover letter (*cf.* Appendix B) clarifying the objective of the study, content and how the information will be used.

Feedback on the results was made available to all respondents, if required, for comment. The option was also given to respondents on whether they would like to view the results of the study and the final developed framework.

3.8. Limitations of the methodology

It might be argued that a research study without limitations, could indicate that the researcher might be unprofessional and unethical. A few problems were faced during the data collection process. The number of replies was low, as some of the potential respondents did not react to any calls for responses. Possible reasons for these actions may include: little or no knowledge on the chosen topic; available time to respond to the questions.

3.9. Conclusion

This chapter outlined the relevant methods of data collection to address the research objectives. In Chapter Four, attention is given to the findings and their interpretations and the analysis of the research.

4. Chapter Four: Findings and analysis

4.1. Introduction

This chapter provides an analysis of the results of the questionnaire which focussed on the lean principles and project management principles in additive manufacturing. The analyses start with the formulation of the participants' profile. The analysis continuous with the respondents' overview and perceptions about the philosophy required for additive manufacturing. The characteristics required for the processes in this manufacturing environment is outlined next and then followed up by the overview of what is required from an organisations' people and partners. This section on lean is concluded with an overview of the considered characteristics/factors when managing projects in additive manufacturing.

The following focus area concentrates on the project management requirements within an additive manufacturing organisation. The questionnaire focusses on the five process areas in project management and outlines key factors according to the required project management knowledge areas within the additive manufacturing environment.

Results from all statements will be discussed and analysed and the certain levels of agreement stated within this discussion. Certain statements contain detailed elements and the overall combination of these levels of consensus will be viewed as successful or not.

4.2. Questionnaire results

The research study delivered the following results, as discussed in the sections below. This discussion and analysis are structured to discuss the influence of lean first in additive manufacturing and then secondly respondents' feedback on the project management of this manufacturing technology.

Firstly, a portfolio on the participants was devised, this included the type of industry their involved with, their position within the specific organisation and then their origin of country. This portfolio was covered by Statements 1 to 3 in the questionnaire. The statements are not represented in chronological order, it starts with the discussion on the four pillars of lean, namely the philosophy (Statement 4); processes (Statements 7 to 12, 14 to 17); people and partners (Statements 18, 20 to 22); and problem solving (Statements 22 again and 23 to 25). The statements which are not mentioned under lean, are all discussed under the main section on the project management characteristics. This discussion and analysis on the project management characteristics includes Statements 5, 6, 13, 19 and 26. The summary of this chapter is highlighted in the conclusion (*cf.* 4.4), and the chapter is followed by Chapter Five, which discusses the development of the framework for lean project management in additive manufacturing.

4.2.1. Participants

The questionnaire was distributed to a sample of 64 respondents. These respondents represented various companies and institutions and are actively involved in the design and development of new products in the additive manufacturing environment. Companies amongst the sample included the Southern Gauteng Technology Station, North West University's Maker Space, Rapid 3D, Sasol and Aerosud. The study was conducted nationally and internationally and included countries, such as the USA, UK and Germany, although only respondents from South Africa replied.

The first three questions aimed to formulate a portfolio of the respondents. The total response rate was 19%, whereby the majority represented either institutions of learning or small to medium-scale private industry AM role players. Only 33% of the respondents represented the additive manufacturing industry. A total of seven (58%) respondents from the learning institutions and five (42%) from the additive manufacturing industry were achieved. The majority of the respondents, which accounts for 42% of the positions, were represented by the AM industry. The majority of these respondents have senior design and development roles in their respective organisations

Respondents represented mainly South Africa, although the request was sent out to various other industry and institution representatives around the world.

4.2.2. Lean characteristics

The following sections discuss the statements as used in the Delphi questionnaire. They are discussed in detail under four primary sections, namely philosophy, processes, people and partners, and problem-solving. Each of the highlighted statements represents a corresponding question, as used in the questionnaire during this Delphi study.

4.2.2.1. Philosophy

Statement 4: The respondents were required to indicate their perception (strongly disagree, agree, no view, agree, strongly agree) on the philosophy required as an organisation or business in additive manufacturing. Table 4.1 illustrates this by showing the number of responses and the percentage agreement relating to the mission of a company and their philosophy towards growth and profit making. The level of agreement for this statement was established at 75%.

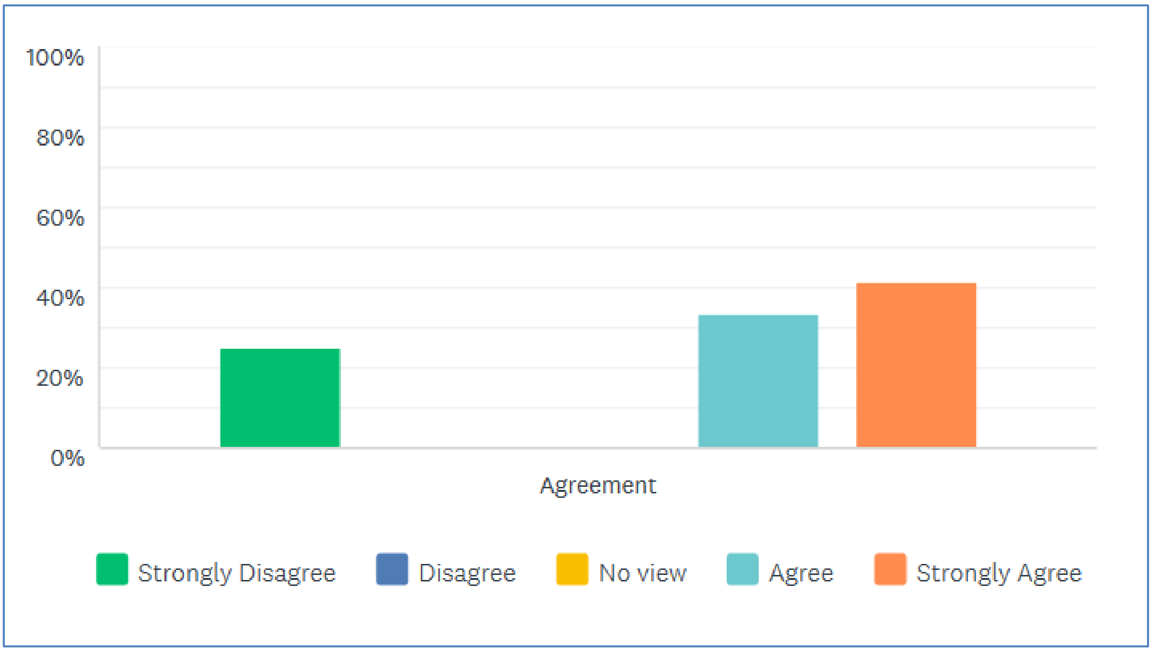
Table 4.1: The number of responses and % agreement: required company philosophy in additive manufacturing

STATEMENT	SD	D	NV	A	SA	%A
The mission of a company should never be focused on profit making or kpi performance (short-term) but should consist of three parts: contribute to the growth of the economy, the well-being of employees and the growth of the company. profit making is a requirement to achieve these three.(n= 12)	3	0	0	4	5	75%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.1 illustrates the percentage distribution of respondents' perception of the philosophy required as an organisation within additive manufacturing. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of perception of an organisations' philosophy.

Figure 4.1: The percentage distribution of respondents' perception of the philosophy required as an organisation within additive manufacturing



The above graph indicates that 42% "strongly agrees" and 33% "agree", that a strong philosophy contributes to the growth of the economy, the well-being of employees and company growth and 25% "strongly disagree" with the statement. It could be argued that those respondents who strongly disagree, might not be experienced enough to offer an informed opinion, as they are not actively involved in any form of management. It could also be argued that these respondents feel that a strong company philosophy and profit-making does not matter in this environment, or that short-term profits or goals are more important. Reasons for this could be that the additive manufacturing industry is too young or small in comparison with the mainstream traditional manufacturing environment. Focussing on the short-term might be a matter of financial survival and temporary growth in this manufacturing environment.

4.2.2.2. Processes

The respondents were required to indicate their perception in regarding the technical issues of lean manufacturing in an additive manufacturing environment. A total of eight statements relates to the technical side of lean in this study.

As stated in Statement 7 in the questionnaire, flow is a way in which all types of wastes are identified, and the creation of a continuous flow system is strongly advised. To find out the extent to which the most important types of wastes occur in additive manufacturing, the extent of the different types of wastes was rated according to "non", "very low", "low", "large", "very large" and "excessive".

Statement 7: Table 4.2 illustrates this by showing the number of responses and the percentage agreement relating to the different types of waste. The total level of agreement for overproduction was established at 100%. It is clear that all the respondents view this technology as an effective way of manufacturing, where products are only produced as required, attempting to keep any unnecessary production to the absolute minimum.

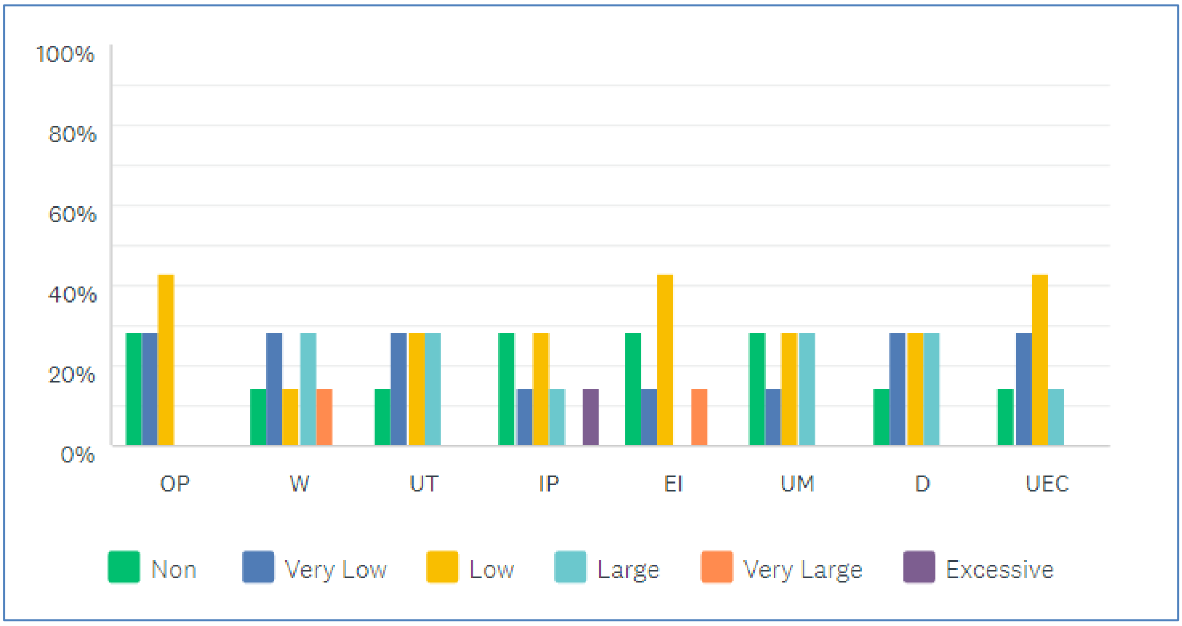
Table 4.2: The number of responses and % agreement: extent of the types of waste in additive manufacturing

STATEMENTS	E	VLG	LG	L	VL	N	%A
Overproduction (n = 11)	0	0	0	4	3	4	100%
Waiting (time-in-hand) (n = 10)	0	1	3	2	3	1	60%
Unnecessary transport (n = 11)	0	0	4	2	3	2	64%
Over or incorrect processing (n = 11)	1	0	1	4	2	3	82%
Excess inventory (n = 11)	0	1	1	4	1	4	82%
Unnecessary movement (n = 11)	0	0	3	2	3	3	73%
Defects (n = 11)	0	0	4	3	3	1	64%
Unused employee creativity (n = 11)	0	1	2	3	4	1	73%

(N = non, VL = very low, L = low, LG = large, VLG = very large, E = excessive, %A = percentage agreement)

Table 4.2 displays consensus for 37.5% (3 divided by 8) of the statements relating to the different types of waste. The individual levels of consensus are discussed in the following sections. Figure 4.2 illustrates the percentage distribution of respondents' perception of the extent of the various types of waste within additive manufacturing. The ordinate shows the total number of respondents in percentage terms and on the abscissa the types of wastes and respondents' levels of perception.

Figure 4.2: The percentage distribution of respondents' perception of the extent of the various types of waste within additive manufacturing



OP = overproduction, W = waiting, UT = unnecessary transport, IP = Incorrect/over processing, EI = excess inventory, UM = unnecessary movement, D = defects, UEC = unused employee creativity.

Figure 4.2 indicates that concerning overproduction, 36% of respondents believe that there is no overproduction taking place in additive manufacturing, 27% believe it is very low and 36% views it as being low. No overproduction could be a sign of very good planning and resource usage, where a very low to a low amount of could indicate certain or limited levels of demand changes. These changes could include sudden client ordering and engineering changes, including technical issues such as hardware and software, material and supply chain issues. It is apparent that respondents see additive manufacturing as a very productive technology, producing only on demand.

From Figure 4.2, it could be argued that a balanced view of waiting exists amongst the respondents. Table 4.2 indicates a level of agreement of 60%, which supports the latter statement. 10% of the respondents believe there are no waiting occurring, which could again be attributed to very good planning. Respondents, 30% of them believe that waiting is very low, with an additional 20% believing it is low. Low levels of waiting could be attributed to reasonable successes regarding planning, monitoring and control and sound engineering efforts with low technical issues involved. Large and very large levels of waiting are observed from the distribution in Figure 4.2. It can be deduced that respondents could view these levels of waiting as inefficient production time. The reason for this is that certain additive manufacturing production processes can be very time-consuming, comparing to traditional processes such as milling and projection-moulding. This could potentially harm or limit mass-production potential.

Response from participants in term of unnecessary transport confirms that 18% believes that it is non-existent, 27% is very low and 18% is low. Table 4.2. indicates a level of agreement of 64%. Typical additive manufacturing processes confirms very little transport within the processes itself, and it would be quite logical to accept that there are very low levels of unnecessary transport involve. Compared to traditional manufacturing, additive manufacturing's' supply chain is much more centralised in a specific location, serving the world market from that location. Respondents did indicate a large figure of 36%, it could also be that the production is decentralised, where production facilities are spread around regional, national and international locations.

Over or incorrect processing is viewed as low in general, with 27% believing that there are none, 18% thinks it is very low and 36% low. This could be attributed to good engineering skills, technology and planning; and only producing on demand. A large figure of 9% and an excessive figure of 9% is assigned, and an 82% level of agreement is indicated in Table 4.2. indicating no consensus. The large and excessive figures could indicate specific problems with design, insufficient planning and communication.

The distribution indicated in Figure 4.2 shows that excess inventory in additive manufacturing reasonably low is. 36% of respondents view excess inventory as zero, 9% very low and 36% as low. This could be attributed to very good planning and execution of projects and only producing on demand. Additive manufacturing allows very little excess material on some of the processes and it allows very little room for raw material, finished goods and work-in-progress to cause any lead times. A very large and large figure of 9% respectively, is observed from respondents' responses, possibly indicating a lack of production planning, stock control, defects, inconsistent and late supplier deliveries, additional set-up times and machine downtime.

Figure 4.2 indicates that in terms of unnecessary movement, 27% of respondents believe that there is no unnecessary movement taking place in additive manufacturing, 27% believes its very low, 18% believe it is low. The level of agreement is at 73%. The low levels of agreement confirm that additive manufacturing has a very different approach compared to traditional manufacturing concerning the motion workers must perform. Additive manufacturing requires the least amount of movement from workers in terms of tooling, stacking and other required walking tasks. A figure of 27% viewed as being large was observed from the graph, and this could be attributed to the handling of raw material, stock keeping or warehouse and production duties.

According to Table 4.2 the percentage of agreement was 64% for defects. Figure 4.2 shows an even distribution with 9% of respondents believing that there are no defects. Reasons for no defects could relate to very good design and engineering capabilities, good planning and control. Lower levels of defects might occur, as illustrated in the above graph, 27% as very low and 27% as low. This could be attributed to design changes and changed customer demands. The latter mentioned issues also influence large (27%) volumes of defects as observed from the graph. Other reasons for defects could be attributed to technical system issues like the maintenance and calibration of machines, in-situ defects per part mass and thermal properties of materials.

Participants agree that unused employee creativity is a valuable entity in additive manufacturing, and it is viewed as a low-wasteful entity. Respondents viewed that 9% of unused employee creativity exists, 27% view it as low and a much higher percentage of 36% as low. The level of agreement was established at 73%, as outlaid in Table 4.2. Although not reaching the required level of agreement, the low levels of wasted unused employee creativity could be related to the use of better and modern design tools and software. Additive manufacturing offer designers much more freedom, compared to traditional manufacturing processes, encouraging them to create more innovative designs, which are manufacturable. A large percentage of 18% believe that unused employee creativity is wasteful. The reason for this could be that designers and engineers which are using additive manufacturing technology, trained in a specific way which promoted the capabilities of traditional manufacturing. These approaches might be embedded in engineers and designers, thus limiting their creative skills, which could be focused only on how to create geometry, rather than the design itself.

Statement 8: Not every part of a process can be done as a one-piece flow. To avoid overproduction, pull systems can be used, ensuring that parts/products should only be delivered exactly what, when and in the correct amount. Respondents support this statement, and a level of agreement was achieved of 92%, as illustrated in Table 4.3.

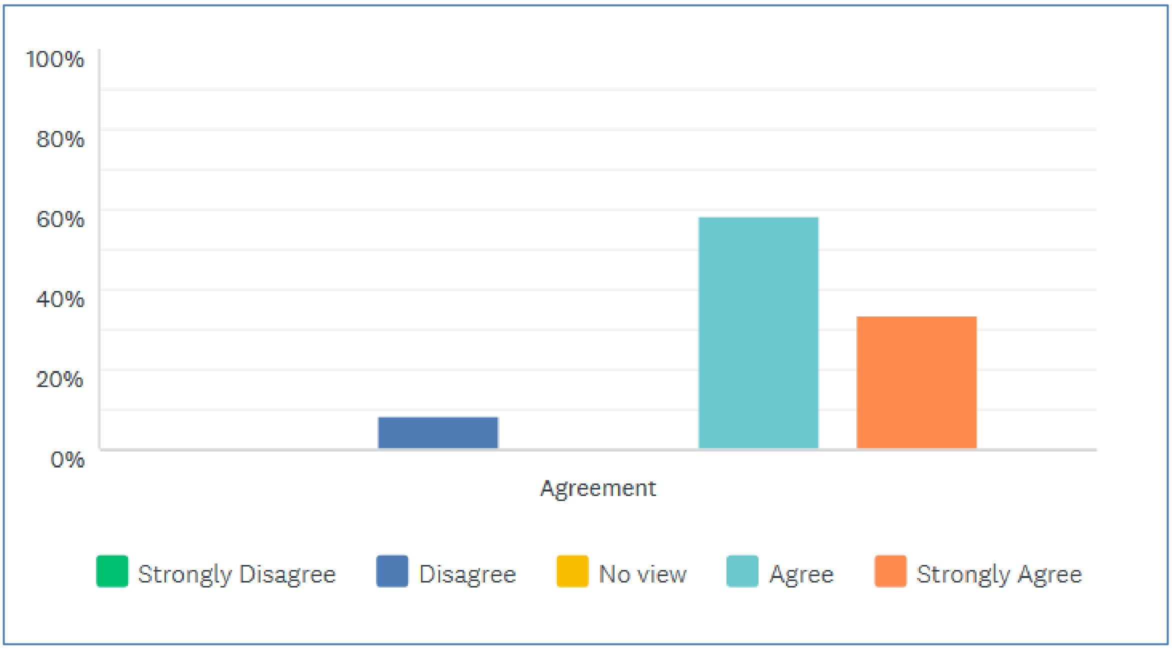
*Table 4.3***:** *The number of responses and percentage agreement: pull-systems in additive manufacturing*

STATEMENT	SD	D	NV	A	SA	%A
Not every part of a process can be done as a one-piece flow. To avoid overproduction, pull systems can be used, ensuring that parts/products should only be delivered exactly what, when and in the correct amount. (n = 12)	0	1	0	7	4	92%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.3. illustrates the percentage distribution of respondents' agreement on pull-systems in additive manufacturing. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of perception of pull-systems within additive manufacturing.

Figure 4.3: The percentage distribution of respondents' agreement on pull-systems within additive manufacturing



It is observed from the above figure that 58% of respondents are in agreement and 33% strongly agrees. A strong response like this could confirm the fact that overproduction, as described in Statement 7 on waste, is an element which is kept to the minimum. A very strong focus is put on avoiding waste, producing only what and when it is required. It confirms that additive manufacturing could inherently employ pull, as large parts of some process could be confined as a one-piece flow. This strong agreement could be supported by other inherent factors such as product and process re-design, material input processing capabilities and the improvement thereof; and product customisation. A smaller number of respondents disagreed (8%) with the statement, possibly siting that pull cannot be employed to avoid overproduction in additive manufacturing. This could be that respondents believe that waste is present in larger numbers and that industry still tend, or they feel that the traditional approach of push, is more apparent in establishing customer demand.

Statement 9: The levelling out of work schedules is essential, as it eliminates unevenness, and in turn eliminates the overburdening of people and equipment and non-value-added wastes. This approach has various possible benefits for additive manufacturing. It is clear from Figure 4.4 that respondents have agreed excessively (50%), that this manufacturing technology provides the manufacturer with the flexibility and freedom to produce for the customer, what and when they require the end product. A level of agreement of 83% is achieved, as seen from Table 4.4.

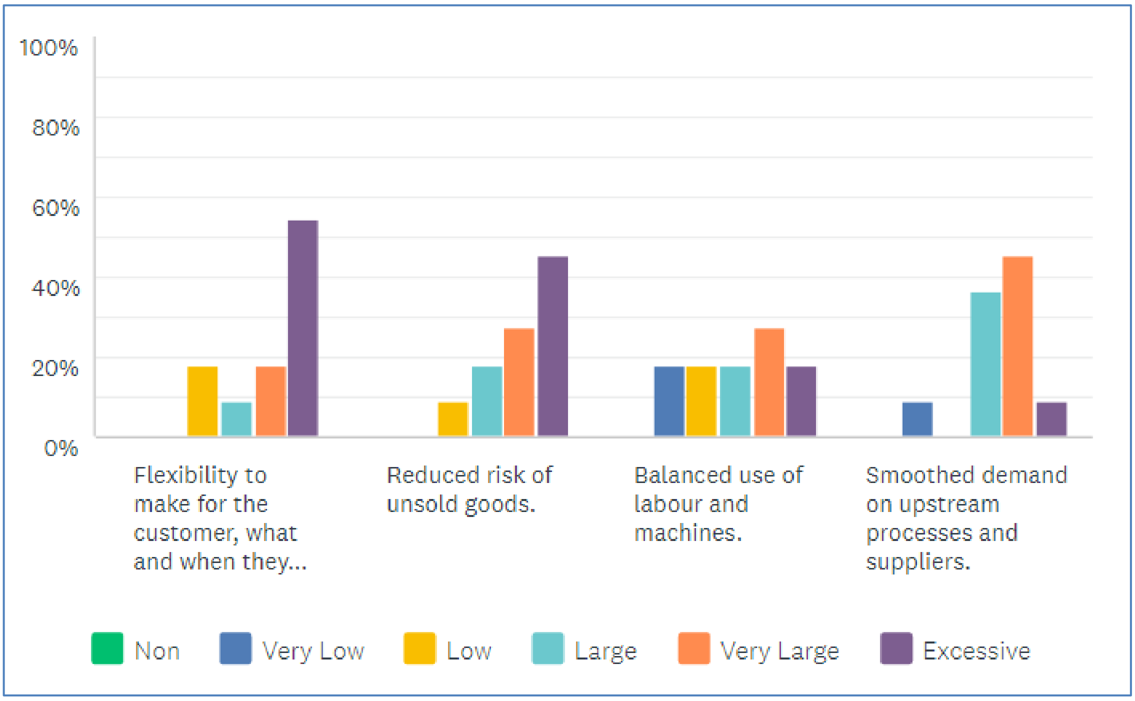
Table 4.4: The number of responses and percentage agreement: benefits of levelling out of work in additive manufacturing

STATEMENTS	N	VL	L	LG	VLG	E	%A
Flexibility to make for the customer, what and when they want it. (n = 12)	0	0	2	1	3	6	83%
Reduced risk of unsold goods. (n = 12)	0	1	1	2	3	5	83%
Balanced use of labour and machines. (n = 12)	0	2	2	2	4	2	67%
Smoothed demand on upstream processes and suppliers. (n = 12)	0	1	0	4	6	1	92%

(N = non, VL = very low, L = low, LG = large, VLG = very large, E = excessive, %A = percentage agreement)

As mentioned above, respondents were asked about their opinion on the benefits associated with the levelling out of work within additive manufacturing. Figure 4.4 illustrates the distribution of respondents' feedback. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of perception on the benefits associated with the levelling out of work within additive manufacturing. It is clear that respondents agree on flexibility, reduced risk of unsold goods and smoothed demand, as very important elements, with all achieving a good level of agreement.

Figure 4.4: The percentage distribution of respondents' view on the benefits of the levelling out of work within additive manufacturing



An excessive figure of 50%, a very large agreement figure of 25% and a large percentage of 8% was recorded, confirming respondents' strong perceptions towards the freedom and flexibility of additive manufacturing. Reasons for this could be that flexible developed and customised products are much more economically attractive compared to traditional mass production methods; no use for tools and moulds; and customisation and modifications are easier, as designs are directly manufactured from digital files. 17% of respondents do not value flexibility as a benefit and attach a low value of importance to it. Reasons for this could be that some designers and engineers feel that the cost and speed of production not good enough is and in some cases some developers and clients might have the perception that additive manufacturing is only applicable for prototyping and not for direct component and product manufacturing.

The second point of agreement amongst respondents is the extent to what the reduced risk of unsold goods in additive manufacturing benefits an organisation. An excessive figure of 42% agrees. This could reflect good design and manufacturing capabilities, communication skills with clients and the capability to efficiently make to order. This could also allow organisations to reduce the risk of unnecessary inventory with no unsold goods, while improving revenue flow, as goods are paid for prior to being manufactured. The influence as illustrated from the graph tapers down to 25% (very large), 17% (large), combining with the first figure to confirm a level of agreement of 84%. Percentages of 8% each are recorded for the lower and very lower levels and could be attributed to some respondents' view on waste, overproduction and the reliability of functional parts.

The third recorded benefit amongst respondents is on the use of labour and machines. The percentage distribution from the graph is evenly spread out with a percentage of 17% for very low, low, large and excessive, apart from a percentage of 33% for very large. The opinions are similar, and it might show that respondents are divided evenly on the statement or they are unsure of any such benefit towards additive manufacturing. This opinion is reflected in Table 4.4. where the percentage of agreement is established at 67%. Reasons could be attributed to different types of application within specific manufacturing organisations. Some organisations might just concentrate on prototyping for new product developments, whereas other organisations might be running a full manufacturing environment, as apparent in the aeronautics industry. Thus, some manufacturing could be less time consuming, while others could service industry and take much more time to produce parts and products. The higher recorded value of 33%, could reflect respondents view or experience in this manufacturing environment, where the manufacturing technology levels out the resources in terms of technology and labour. This might automatically lend itself to quality, standardisation of work, productivity and continuous improvement.

The fourth benefit focus on the smoothed demand on upstream processes and suppliers. A percentage of agreement of 92% is achieved according to the values in Table 4.4. This statement could be linked directly to the last statement, where the levelling of work could support smoothed demand and upstream processes, as to what and when a product is needed. Respondents agree (excessive – 8%, very large – 50%, large – 33%), as stated in previous statements that the elimination of unevenness is fundamental in managing irregular production schedules and the illumination of waste. A small percentage of 8% believe it has no benefit to additive manufacturing, possibly of low production levels, and that manufacturing could be based on low volume prototyping. Respondents agree in general that to achieve the lean benefits of continuous flow and the levelling out of work, the support of a smoothed demand on upstream process and suppliers is required. This could result in a well-managed demand on customers, equipment and suppliers, and as it becomes easier, cheaper and faster to manage.

Statement 10: To establish the percentage agreement of respondents, relating to the overburdening and unevenness of people and equipment, respondents were asked to indicate their level of agreement or disagreement with the statement in Table 4.5. The table indicates a level of agreement (disagree, strongly disagree) of 50%.

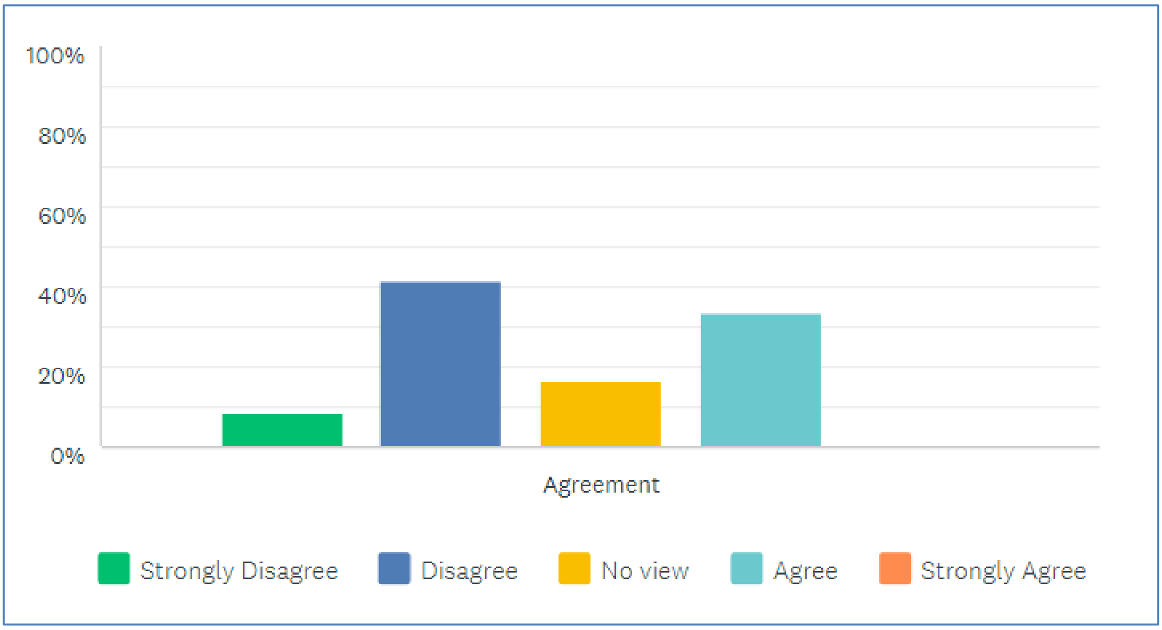
Table 4.5: The number of responses and percentage agreement: overburdening of resources in additive manufacturing

STATEMENTS	SA	A	NV	D	SD	%A
Overburdening of people and/or equipment, or unevenness (over or under allocation) of work to people and equipment are applicable in additive manufacturing. (n = 12)	0	4	2	5	1	50%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.5. illustrates the distribution of respondents' feedback. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of agreement relating to the overburdening of resources in additive manufacturing.

Figure 4.5 The percentage distribution of respondents' level of agreement relating to the overburdening of resources in additive manufacturing



It is clear from the figure above that respondents' opinions are evenly divided, with 8% and 42% believing that people and machines are not overburdened, and that unevenness not a major problem area in additive manufacturing is. Reasons for this could be that workloads are levelled out in busy manufacturing environments, or simply that the workloads are not severe enough for machines to be pushed, and very limited manual labour is involved. The nature of certain development work, like customised parts, does not always require large repetitive manufacturing solutions. The rest of the respondents (33% - agree) feels that there could be a case for this argument in the statement, as additive machines, depending on the manufacturing environment, are sometimes prone to various technical system and material issues and other quality issues. The other 17% has no view, which could be a result of a lack of knowledge on the subject or could view both views as appropriate.

Statement 11: Table 4.6 illustrates the responses and percentage agreement, relating to quality as a built-in mechanism and the detection of defects as they occur. The level of agreement or disagreement with the statement in Table 4.6 indicates a level of agreement (strongly agree, agree) of 100%.

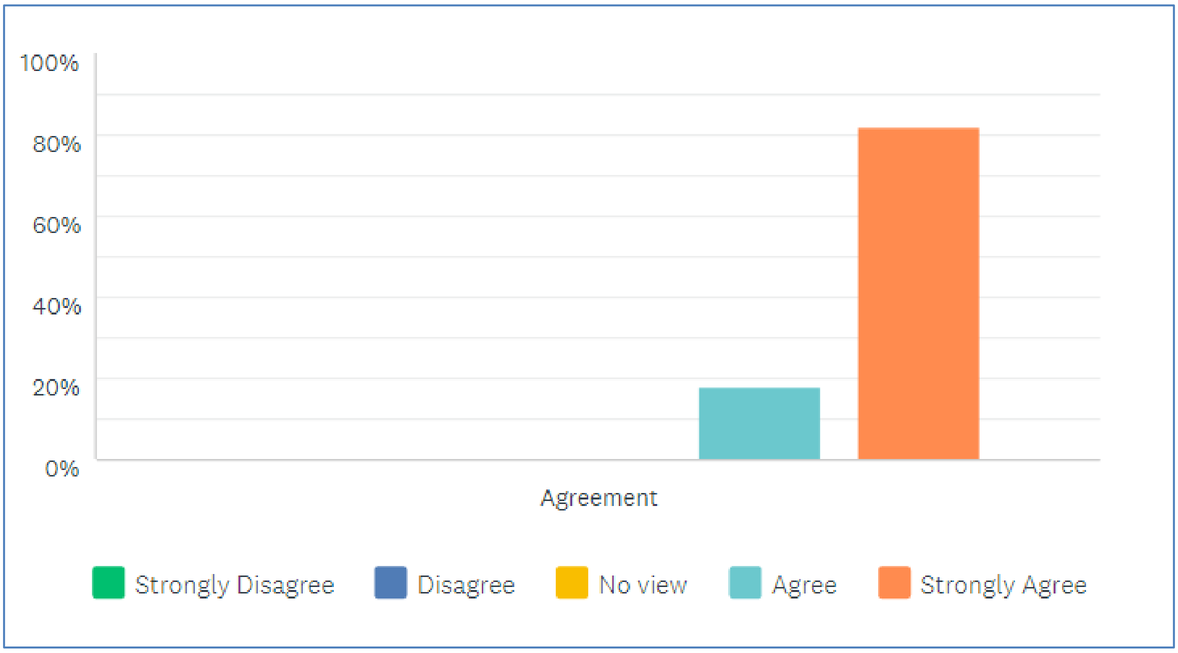
Table 4.6: The number of responses and percentage agreement: quality in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
Quality should be a built-in mechanism and defects detected immediately when they occur. (n = 11)	0	0	0	2	9	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

The following chart illustrates the level of respondents' agreement relating to the statement above. Figure 4.6. illustrates the distribution of respondents' feedback, although only 11 respondents replied to this statement. The vertical axis shows the total number of respondents in percentage terms and on the horizontal axis the respondents' level of agreement relating to quality as a built-in mechanism in additive manufacturing.

Figure 4.6: The percentage distribution of respondents' level of agreement relating to quality as a built-in mechanism and the detection of defects as they occur in additive manufacturing



It is clear from Figure 4.6 that all respondents have the same view on quality, 82% of respondents agree strongly and 18% strongly that quality should be a built-in mechanism and that defects must be detected immediately when they occur. Respondents possibly place considerable importance on manufacturing products correctly the first time, as this built-in quality approach is more productive and less-costly compared to inspecting and repairing problems afterwards.

Statement 12: Respondents views and levels of agreement were acquired in terms of whether they agree, that problems in additive manufacturing needs to be anticipated as early as possible and that countermeasures should be put into place, before they occur. Table 4.7 confirms a solid level of agreement of a 100%, which with the previous statement in Question 11, confirms respondents' importance regarding quality.

*Table 4.7**:** The number of responses and percentage agreement: anticipated problems in additive manufacturing*

STATEMENTS	SD	D	NV	A	SA	%A
Problems should be anticipated as early as possible and countermeasures should be put in place before problems occur. (n = 12)	0	0	0	3	9	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.7. illustrates the distribution of respondents' feedback. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of agreement relating to anticipated problems in additive manufacturing.

Figure 4.7: The percentage distribution of respondents' level of agreement relating to anticipated problems in additive manufacturing

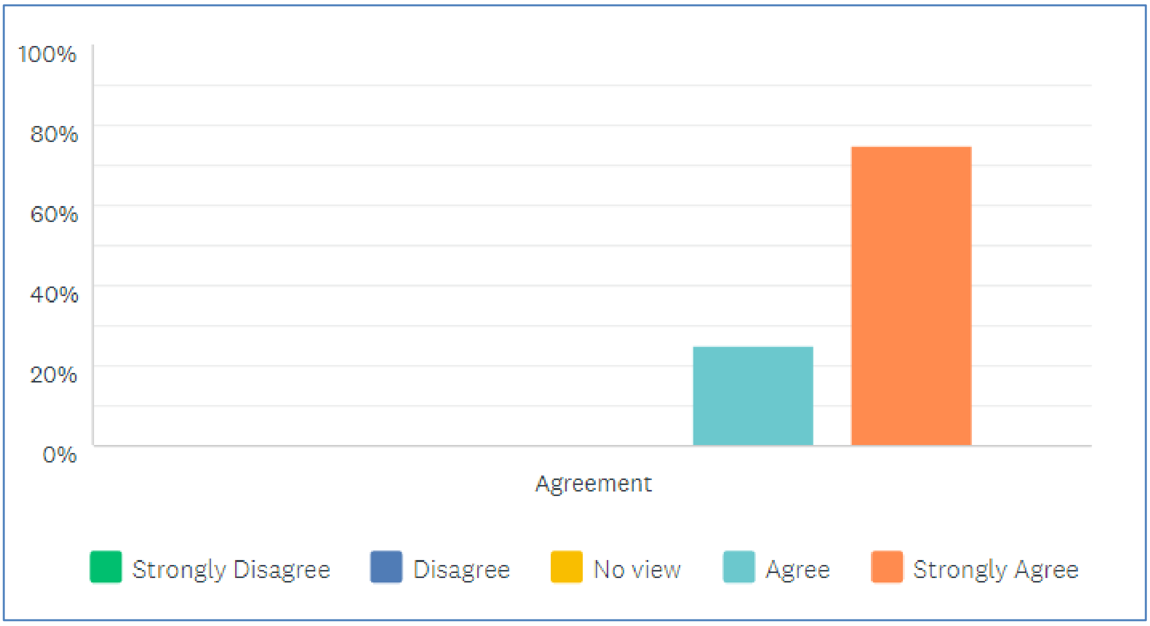


Figure 4.7 shows that 75% of respondents strongly agree and 25% agree that it is safe to assume that it is everyone's responsibility in an organisation to prevent problems and put countermeasures into place, as this ultimately affects quality and productivity.

Statement 14: Respondents were asked how important certain elements were in the standardisation of work in additive manufacturing. The statements in Table 4.8 referred to takt time, sequencing and inventory. A high level of agreement was achieved amongst respondents for all three of the stated elements, 92%, 91% and 91%, respectively.

Table 4.8: The number of responses and percentage agreement: elements of built-in quality in additive manufacturing

STATEMENTS	N	VL	L	LG	VLG	E	%A
The time required to complete one job according to customer demand. (n=12)	0	1	0	2	4	5	92%
The sequence of processes or of doing things. (n=12)	0	1	0	1	6	4	91%
The inventory on hand needs to accomplish the required standardised work. (n=12)	0	1	0	0	8	3	91%

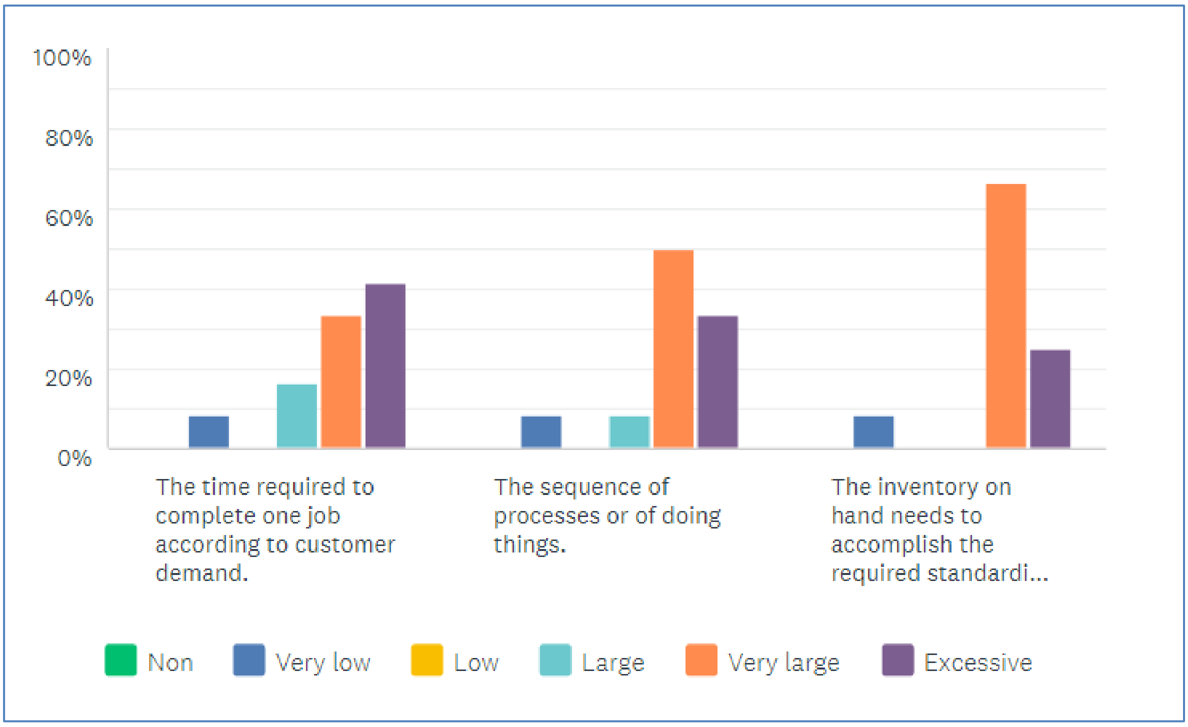
(N = non, VL = very low, L = low, LG = large, VLG = very large, E = excessive, %A = percentage agreement)

Figure 4.8. provides an overview of the elements of standardised work. The vertical axis shows the total number of respondents in percentage terms and on the horizontal axis, the respondents' level of perception on the elements associated with the standardisation of work within additive manufacturing. Figure 4.8 illustrates that an excessive (42%) number of respondents believe that the time required to complete a single job, needs to be according to customer demand, also known as takt time. A very large percentage of 33% and a percentage of 17% believe it is important. This could relate to good process and machine scheduling and planning, ensuring products are produced on customer demand. A small number (8%) of respondents believe it has very low relevance in quality. Reasons for this could be the type of technology that was employed.

The sequencing of tasks reflects an excessive value of 33% and half of the respondents (50%) believes it has very large importance. A smaller amount reflects a large value of 8% and another believes it has a very low relevance of 8%. This low relevance could be attributed to low levels of work and the type of technology employed.

Respondents believes very strongly (67%) that the inventory on hand needs to accomplish the standardised work on hand. An excessive amount of 25% is achieved, whereas only 8% believes it has low relevance.

Figure 4.8: The percentage distribution of respondents' level of agreement relating to elements of built-in quality in additive manufacturing



A very similar pattern is followed for all three statements, with a strong level of agreement, stressing the fact that quality depends on a process which is standardised and stabilised.

Statement 15: Respondents views and levels of agreement were acquired in terms of whether they agree, that an employee would be regarded as the most important valuable resource, analyst and problem solver. Table 4.9. confirms a solid level of agreement of a 100%, which indicates that respondents might view this as the basis for flexibility and innovation in additive manufacturing.

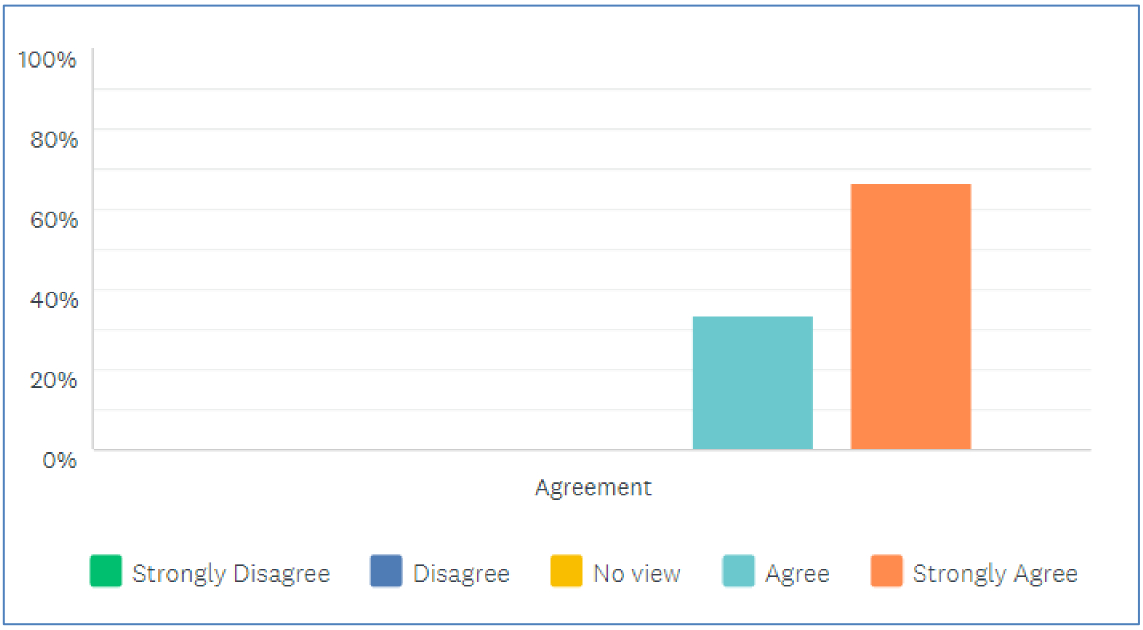
Table 4.9: The number of responses and percentage agreement: flexibility and innovation in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
An employee is regarded as the most important valuable resource, analyst and problem solver, this ultimately forms the basis for flexibility and innovation. (n = 12)	0	0	0	4	8	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.9. illustrates the distribution of respondents' feedback. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of agreement relating to flexibility and innovation in additive manufacturing.

Figure 4.9: The percentage distribution of respondents' level of agreement relating to flexibility and innovation in additive manufacturing



From Figure 4.9, the response is overwhelmingly positive, with 67% of respondents agreeing strongly and the remaining 33% agreeing. By comparing these results with the results in Statement 11, it can be argued that a similar view towards standardisation exist. Specific standards can be useful guides to allow for employees' flexibility, creativity and innovation.

Statement 16: Respondents' level of agreement regarding visual controls in processes of the value-added work. Respondents agree that one should be able to visually inspect a process, a piece of equipment, inventory or a worker performing a job according to standards. The following table illustrates the responses and percentage agreement, relating to visual controls in additive manufacturing. The level of agreement or disagreement with the statement in Table 4.6. indicates a level of agreement (strongly agree, agree) of 100%.

Table 4.10: The number of responses and percentage agreement: visual controls in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
To avoid hidden problems visual controls should be integrated into processes of the value-added work. It should be able to visually inspect a process, a piece of equipment, inventory or a worker performing a job according to standards. (n = 12)				9	3	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.10: The percentage distribution of respondents' level of agreement relating to visual controls in additive manufacturing

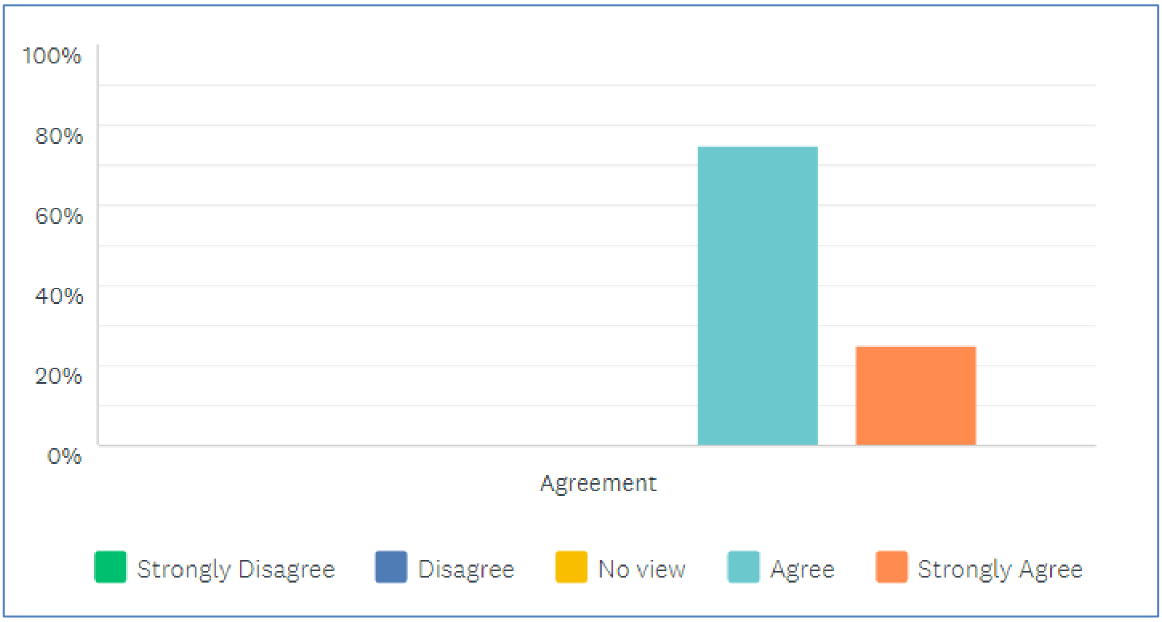


Figure 4.10. indicates that most respondents agree (75%) and strongly agree (25%) that visual controls should be integrated into processes. This response supports the feedback in Statement 14 regarding quality, and it could provide the researcher with a glimpse of how to perform work according to standards.

Statement 17: Table 4.11 below illustrates the responses and percentage agreement, relating to whether thoroughly tested technology should be implemented without employee resistance and process disruption. The level of agreement or disagreement (strongly agree, agree) is 50%.

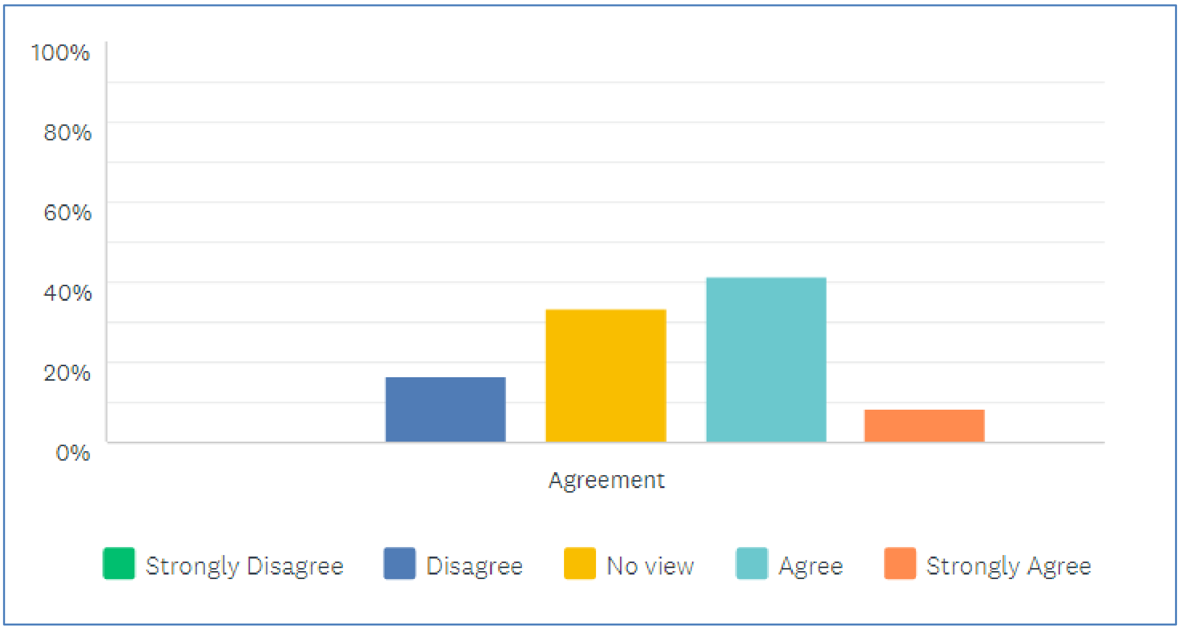
Table 4.11: The number of responses and percentage agreement: technology in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
Only reliable and thoroughly tested technology should be implemented without employee resistance and process disruption. (n = 12)		2	4	5	1	50%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.11 illustrates the results of respondents towards the use or implementation of technology in an additive manufacturing environment. The level of agreement is depicted on the horizontal axis and the total number of respondents in percentage terms on the ordinate.

Figure 4.11: The percentage distribution of respondents' level of agreement relating to technology in additive manufacturing



When comparing the findings from the graph, respondents' views are evenly divided. A large percentage (33%) has no view, and 17% disagrees. It can be argued that respondents who have no view, feel that they have insufficient knowledge on the matter. The 17% which disagrees, might think that technology does not need to be thoroughly tested before usage, or they could assume that the technology is good enough without any testing or test runs. This could be valid, but it might influence workflow and quality if the technology is not suitable and workers might resist changes eventually. A percentage figure of 42% agrees that technology must be proven before any expensive acquisitions are made and buy-in from workers is essential for it to be used effectively. A strong agreement of 8% is recorded. These respondents might strongly feel that consensus must be achieved amongst people before any of the earmarked technology is implemented and that it would have a strong operational focus on waste elimination.

4.2.2.3. People and partners characteristics

The respondents were required to indicate their perception regarding the sustainable long-term-growth of an additive manufacturing organisation. The focus is ultimately on the investment of an organisation's own people and partners. The following three statements under the above heading relates to the lean theory that people within an organisation, are valued as the most important asset.

Statement 18: Table 4.12 shows a 100% level of agreement regarding the physical experience a worker must acquire to fully understand methods and processes.

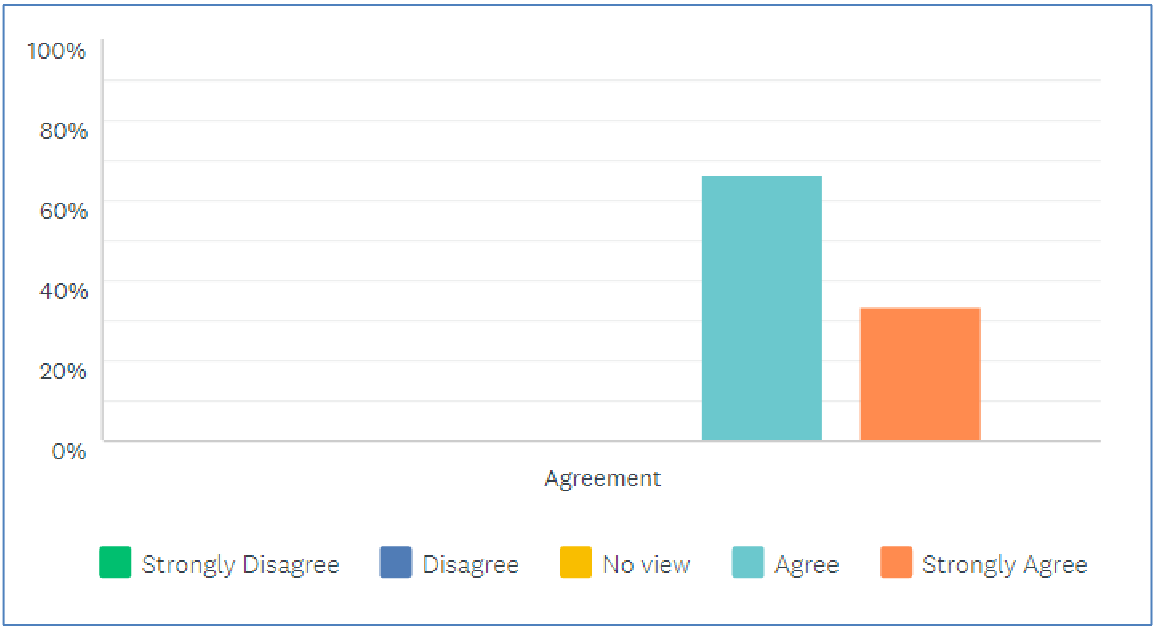
Table 4.12: The number of responses and percentage agreement: actual manufacturing environment in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
Actual manufacturing situations should be observed in detail and it is necessary to understand how work gets done in the manufacturing environment. (n = 12)	0	0	0	8	4	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.12 illustrates the distribution of respondents' feedback. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of agreement relating to the actual manufacturing environment and their knowledge of work in additive manufacturing.

Figure 4.12: The percentage distribution of respondents' level of agreement relating to the actual manufacturing environment in additive manufacturing



The prominent levels of agreement are confirmed in the graph, with 67% of respondents agreeing and 33% strongly agreeing with the statement. Respondents might feel that to improve processes and work done, and to cultivate the next generation of workers and leaders; workers must get their hands dirty. If it is not done, then workers might get a totally wrong impression of the current situations, leading to wrong decision making.

Statement 20: The second statement in this section reads, that in industry, the focus is placed on how to streamline supply chains through advanced information technology. It is also stated that very low focus is placed on how to forge relationships across firms and how to strive towards a common goal. The number of responses of important elements and levels of agreement from respondents is highlighted in Table 4.13. A high level of agreement was achieved amongst respondents for three of the stated elements, 92%, 92% and 100%, respectively. Transferred knowledge and technology reached 75%.

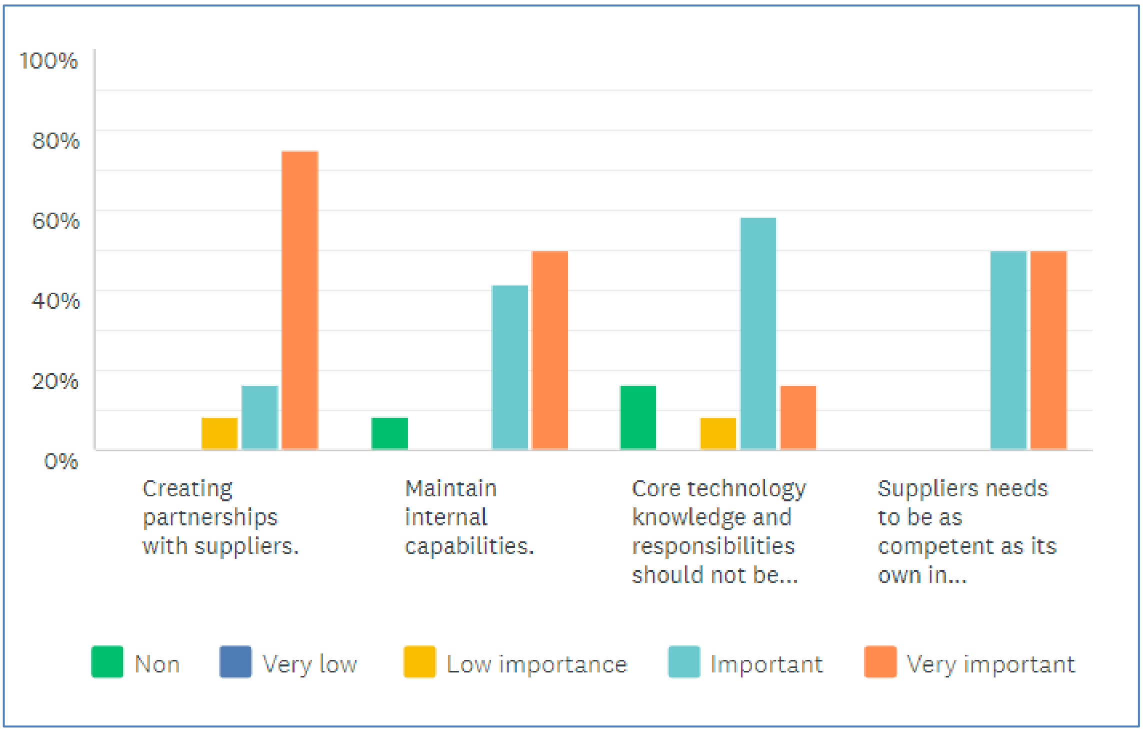
Table 4.13: The number of responses and percentage agreement: elements of cross-firm relationships in additive manufacturing

STATEMENTS	N	VL	LI	I	VI	%A
Creating partnerships with suppliers. (n=12)	0	0	1	2	9	92%
Maintain internal capabilities. (n = 12)	1	0	0	5	6	92%
Core technology knowledge and responsibilities should not be transferred to suppliers. (n = 12)	2	0	1	7	2	75%
Suppliers needs to be as competent as its own in delivering product, components and materials. (n = 12)	0	0	0	6	6	100%

(N = non, VL = very low, LI = low importance, I = important, VI = very important, %A = percentage agreement)

The distribution of the elements is illustrated below in Figure 4.14. The vertical axis shows the total number of respondents in percentage terms and on the horizontal axis, the respondents' level of perception on the elements associated with cross-firm relationships. They include the same elements as stated in Table 4.13.

Figure 4.13: The percentage distribution of respondents' level of agreement relating to the elements of cross-firm relationships in additive manufacturing



The figure above illustrates that respondents placed a very high importance rating (75%) on creating partnerships with suppliers and 17% believe it is important. The reason according to respondents is that suppliers might be viewed as part of their value chain and need to be treated and valued as their own and challenged. 8% of respondents feel that supplier partnerships have low-level importance, as they might not be very dependent on their support at all.

Respondents have placed a high importance rating on maintaining its capabilities with 50% viewing it as very important and 42% as important. Reasons might be that trusted internal capabilities are a competitive advantage they will have over rival manufacturers, and it could secure self-reliance. A very small percentage (8%), believed that it has no importance, possibly of low reliance on suppliers and their type of organisation.

Core technology and responsibilities should not be transferred to suppliers according to respondents, of whom 58% believe it is important and 17% view it as very important. This could implicate an organisations' desire to master all necessary technology and become the expert in the field, whereas 8% attach low importance to it and 17% no importance at all.

Very high importance is put on the capability of suppliers and they are viewed as an extension of their organisation in terms of producing and delivering high-end products and components on time. 50% of the respondents viewed this as very important and the other 50% as important.

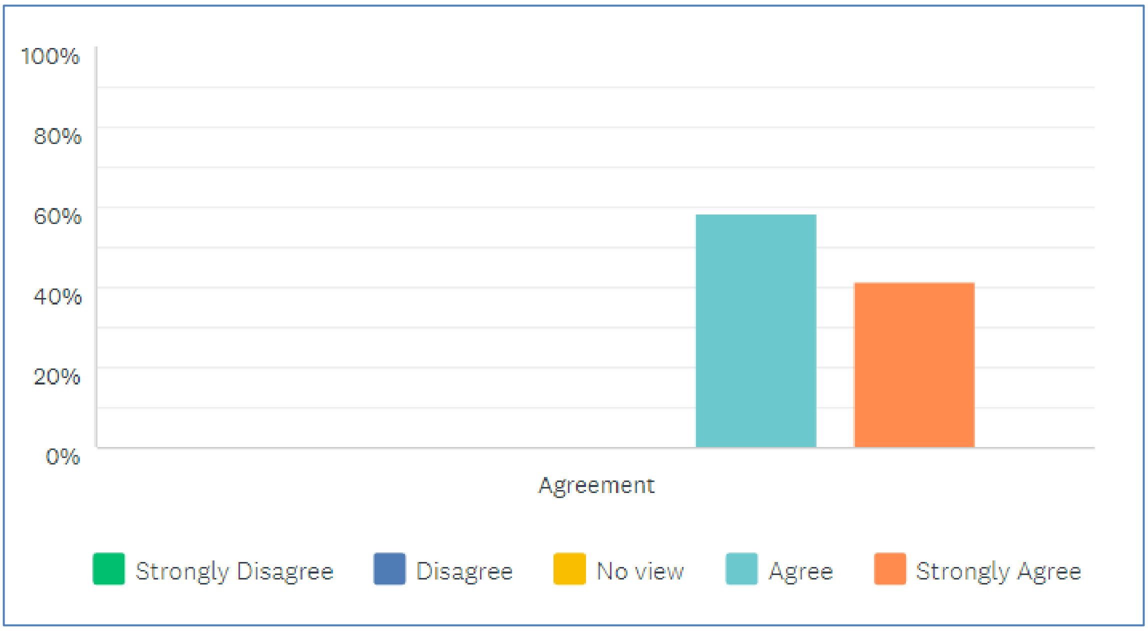
Statement 21: In Table 4.14 a 100% agreement was achieved, viewing true learning as an enterprise, as a well-established and stabilised relationship between a business and its suppliers.

*Table 4.14**:** The number of responses and percentage agreement: knowledge acquisition in additive manufacturing*

STATEMENTS	SD	D	NV	A	SA	%A
True learning as an enterprise suggests that relationships between your own business and suppliers must be stabilised to the point where the business relationship is fair, processes are stable, and expectations are clear. (n = 12)	0	0	0	8	4	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Table 4.14: The number of responses and percentage agreement: knowledge acquisition in additive manufacturing



The percentage distribution in Figure 4.14. confirms an agreement of 67% and a very strong agreement of 33%. All respondents agree that supplier relationships must be stabilised to the point where the business partnerships are fair, processes are balanced, and expectations are straightforward. To be part of this, the supplier might need to re-evaluate and re-developed its internal culture to become a learning organisation.

4.2.2.4. Problem solving characteristics

To become a learning organisation, an organisation needs to be able to solve problems and any improvements must be implemented through consensus. To achieve consensus amongst workers or team members is important. Otherwise, new implementations will not work. The following statements will focus on problem-solving.

Statement 22: Table 4.15 below illustrates the responses and percentage agreement, relating to how well respondents their businesses understood and how they manage to solve problems on the production floor. The level of agreement (strongly agree, agree) is 100%.

Table 4.15: The number of responses and percentage agreement: problem-solving in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
What is seen first-hand in the manufacturing environment does not always show up in reports. Participants must be encouraged to see and experience problems on the production floor at first hand and have an open mind and ask the question "why" to every matter. (n = 12)	0	0	0	7	5	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

The image in the graph below illustrates the total number of respondents in percentage terms on the vertical axis and the horizontal axis the respondents' level of agreement.

Figure 4.15: The percentage distribution of respondents' level of agreement relating to problem solving in additive manufacturing

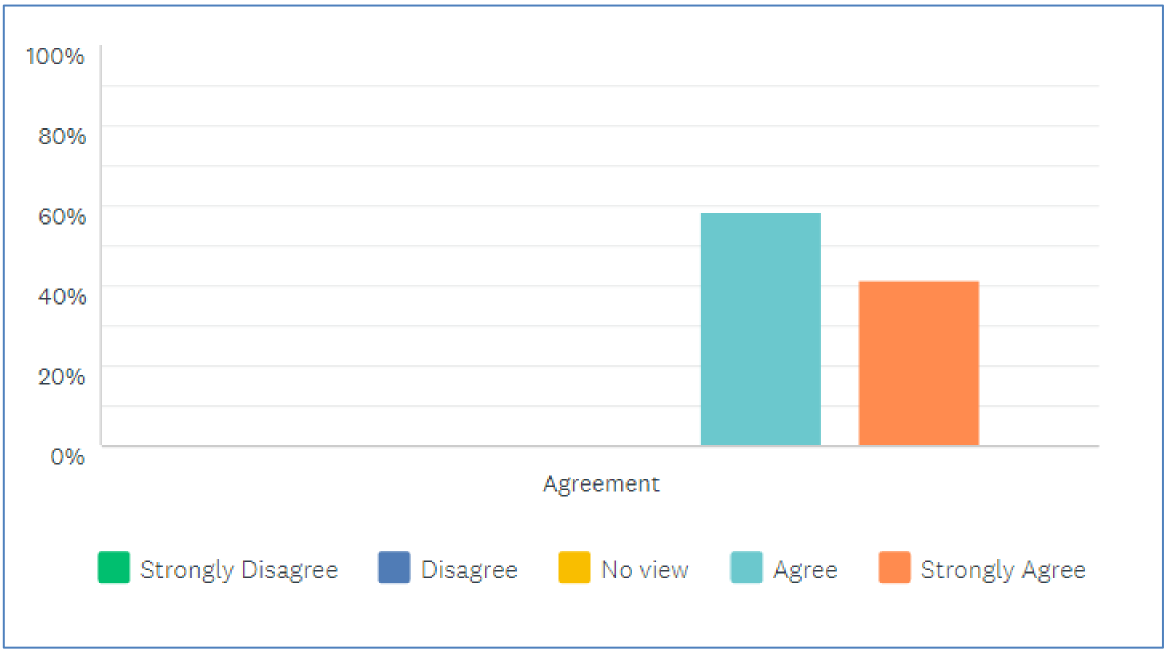


Figure 4.15 above illustrates a percentage distribution of 58% for respondents agreeing and 42% for respondents that agrees strongly. Respondents are aware that solving problems entails asking why to every matter and that it is very important to understand the business and manage it from the floor.

Statement 23: Respondents were asked to what degree they agree or disagree with the statement, when decisions need to be taken and implemented. A strong level of agreement of 92% was achieved, confirming the need for consensus before implementation.

Table 4.16: The number of responses and percentage agreement: decision making in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
The key to decision making is that a great deal of learning should take place upfront before a decision is made, planned or implemented. All relevant parties should get involved, all facts must be uncovered, and resistance worked out through consensus and support before implementation takes place.	0	0	1	7	4	92%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.16 shows the feedback by respondents regarding decision making, consensus and implementation. The vertical axis displays respondents' percentage agreement, and the horizontal axis displays the levels of agreement. The various levels of agreement are depicted in different colours.

Figure 4.16: The percentage distribution of respondents' level of agreement relating to decision making in additive manufacturing

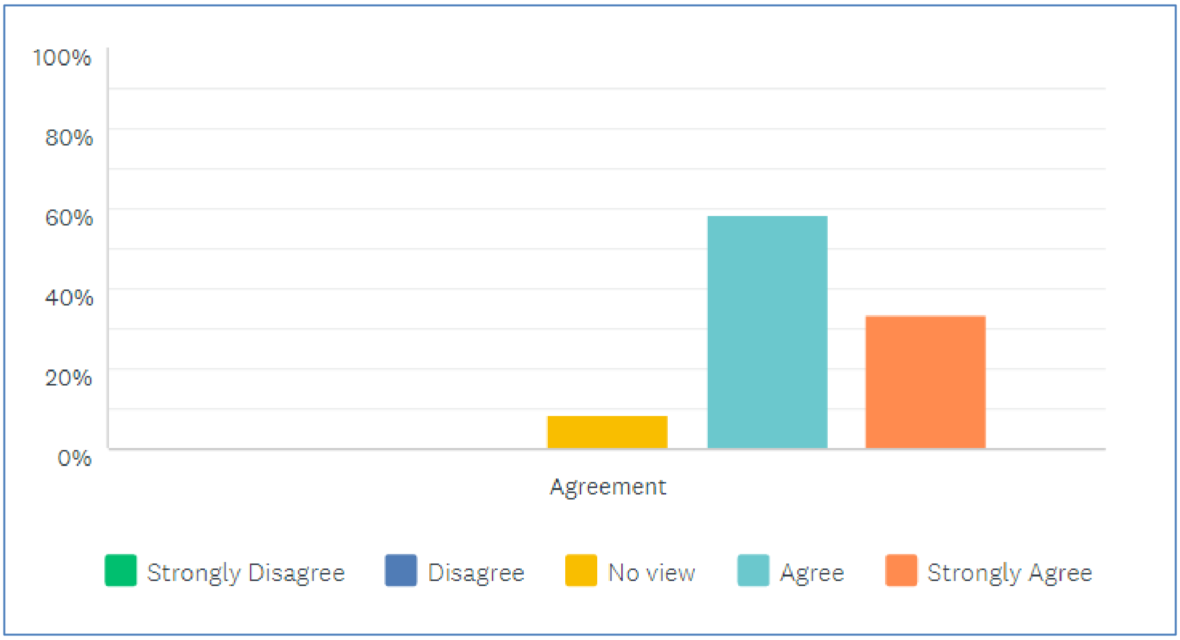


Figure 4.16. shows that 58% of respondents agree and 33% agrees strongly with the statement. This could indicate that respondents value the way they get to decisions, as important as the quality of the decision itself. The process of making decisions could take time but might be fast and efficient to make. A smaller percentage of 8% has no view. These respondents might not require consensus, or decisions are easy enough, because of the size and type of organisation.

Statement 24: Respondents were asked to voice their views on one key element in any successful business, namely the ability to learn. Again, a high a level of agreement was achieved of a 100%. It is clear that respondents view learning as a key element to invoke and sustain adaptation, innovation and flexibility. Table 4.17 illustrates the responses and level of agreement.

Table 4.17: The number of responses and percentage agreement: learning in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
Adaptation, innovation and flexibility have become the necessary ingredients for survival and the hallmarks of a successful business. To sustain these elements of such organisational behaviour, it requires one key component: the ability to learn.				5	7	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.17 below, illustrates the distribution of respondents' feedback. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of agreement relating to the ability to learn in additive manufacturing.

Figure 4.17: The percentage distribution of respondents' level of agreement relating to the ability to learn in additive manufacturing

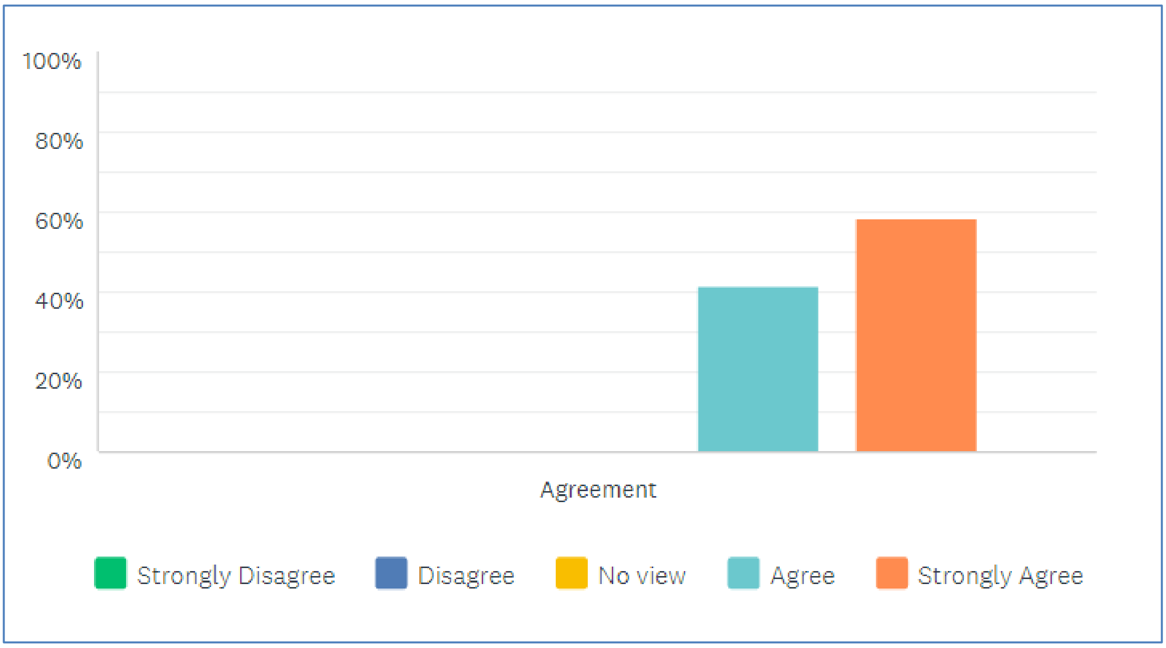


Figure 4.17 shows that 58% of respondents strongly agree and 42% agree, that to survive as a successful business, it must be able to adapt, innovate and be flexible. Respondents might view standardisation and innovation in the same light, learning from mistakes equally, and to determine the root causes of these mistakes might empower people in their organisations to implement the necessary measures.

Statement 25: To establish the percentage agreement of respondents, relating to detailed problem-solving, respondents were asked to indicate their level of agreement or disagreement with the statement in Table 4.18. The table indicates a level of agreement (disagree, strongly disagree) of 100%.

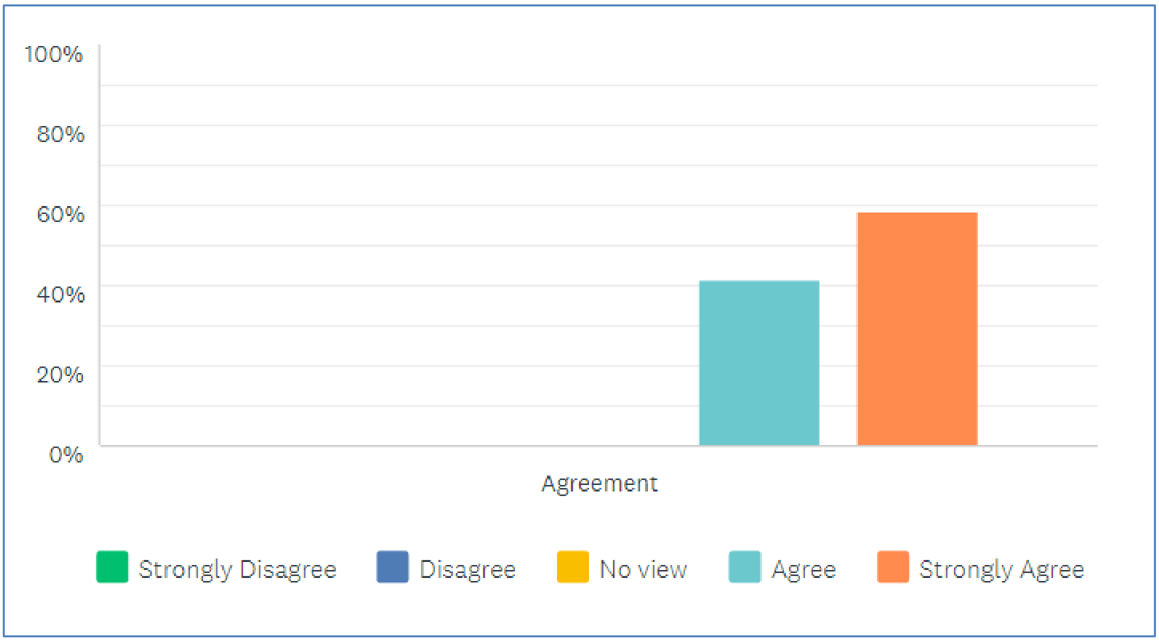
Table 4.18: The number of responses and percentage agreement: detailed problem-solving in additive manufacturing

STATEMENTS	SD	D	NV	A	SA	%A
Many problems do not call for complex statistical tools, but requires detailed problem solving. This detailed thinking and analysis is a matter of discipline, attitude and culture. True problem solving requires finding the root cause rather than the source of the problem. The answer is achieved by searching deeper, by asking why the problem occurred.				5	7	100%

(SD = strongly disagree, D = disagree, NV = no view, A = agree, SA = strongly agree, %A = percentage agreement)

Figure 4.18. illustrates the distribution of respondents' feedback. The ordinate shows the total number of respondents in percentage terms and on the abscissa the respondents' level of agreement relating to detailed problem solving in additive manufacturing.

Figure 4.18: The percentage distribution of respondents' level of agreement relating to detailed problem-solving in additive manufacturing



The figure above illustrates that respondents agrees strongly (58%) and 42% agree it is important to find resolve problems at the source. Clarifying the problem properly and focussing on exactly where the problem might be important to respondents and encouraging learning and personal growing.

4.2.3. Project management characteristics.

Respondents were asked to what degree specific knowledge areas influence the specific processes as outlaid by the PMBOK (PMI, 2013:50). Respondents represent various fields within the additive manufacturing environment. Although PMBOK is recognised as one of the main references for project management in mainstream or traditional manufacturing, this Delphi study attempted to collect the views from various participants within additive manufacturing. The scale that was used to collect the extent of influence on the project management processes and knowledge areas, ranged from non, weak, fair, good, very good and best practice. The levels of agreement which achieved consensus and no-consensus are presented in the following section.

4.2.3.1. Overview of the main characteristics when initiating projects.

The first project management process group studied, is the Initiation process and it aims to determine to what extent specific project management knowledge areas, play a role in additive manufacturing.

Statement 5: Consensus (70%) was obtained from 7 out of 10 statements in round 1, relating to the initiation of projects in additive manufacturing. Table 4.19 illustrates those statements for which consensus (agreement level of 80% and above) was obtained and not obtained (below 80%).

*Table 4.19**:** The number of responses and percentage agreement:* ***initiation*** *of projects in additive manufacturing*

STATEMENTS	N	W	F	G	VG	BP	%A
Integration	0	0	2	3	6	1	83%
Scope	0	1	0	3	8	0	92%
Schedule	0	0	0	3	7	2	100%
Cost	0	0	2	0	5	5	84%
Quality	0	0	2	1	5	4	83%
Resources	0	2	2	1	3	4	66%
Communication	0	1	1	1	7	2	83%
Risk	0	1	2	1	7	1	74%
Procurement	0	1	2	2	5	2	75%
Stakeholders	0	0	1	6	4	1	92%

(N = non, W = weak, F = fair, G = good, VG = very good, BP = best practice, %A = percentage agreement)

Figure 4.19 illustrates the percentage distribution of respondents' feedback. The ordinate shows the total number of respondents in percentage terms and on the abscissa the various project management knowledge areas. The various levels of the extent of influence, are depicted in different colours in the bar chart.

*Figure 4.19**:** The percentage distribution of respondents' level of agreement relating to the different project management knowledge areas during the Initiating process group in additive manufacturing*

Figure 4.19 above shows that the characteristics "Integration" (good = 25%, very good = 50%, best practice = 8%); "Scope" (good = 25%, very good = 67%); "Schedule" (good = 25%, very good = 58%, best practice = 17%); "Cost" (very good = 42%, best practice = 42%); "Quality" (good = 8%, very good = 42%, best practice = 33%); "Communication" (good = 8%, very good = 58%, best practice = 17%); "Stakeholders" " (good = 50%, very good = 33%, best practice = 8%) are viewed by the majority of respondents as the most essential project management knowledge areas that assist the initiation process in additive manufacturing. It is important

to note that although “Resources”, “Risk” and “Procurement” was viewed as less important, “Risk” played a significant role in the initiation process according to 58% of respondents. According to PMBOK (PMI, 2013: 54), the initiating process group consists of those processes performed to define a new project by obtaining authorisation to start the project, and the areas project management should focus on, is “Integration” and “Stakeholders”. Comparing the results of all the knowledge areas, it is apparent that apart from project integration management and project stakeholder management; project scope, schedule, cost, quality and risk management might have a significant impact, according to respondents, on the initiation process of project management in additive manufacturing. This view from respondents might stem from a lack of knowledge on the initiation of projects. Although the project charter and the stakeholder register are used as inputs to processes in other process groups, such as Planning, it might be beneficial to place more emphasis on some of the elements associated with these knowledge areas, during the outlaying of the project charter and the stakeholder analysis.

4.2.3.2. Overview of the main characteristics when planning projects.

The initiating process group’s function is to provide a clear view of an entire project’s requirements, whereas the planning process group provides guidelines for combining details required to complete project phases successfully. The results in this section will focus on the extent, specific project management knowledge areas play and their role during the planning process group.

Statement 6: Consensus (80%) was obtained from 8 out of 10 statements in round 1, relating to the planning of projects in additive manufacturing. Table 4.20 illustrates those statements for which consensus (agreement level of 80% and above) was obtained and not obtained (below 80%).

*Table 4.20: The number of responses and percentage agreement: **planning** of projects in additive manufacturing*

STATEMENTS	N	W	F	G	VG	BP	%A
Integration	0	0	0	3	7	2	100%
Scope	0	1	0	1	7	3	92%
Schedule	0	1	1	1	5	4	83%
Cost	0	0	1	1	6	4	92%
Quality	0	1	1	0	6	4	83%
Resources	0	1	2	3	4	2	75%
Communication	0	1	1	3	5	2	83%
Risk	0	1	3	0	6	2	67%
Procurement	0	2	0	3	4	3	83%
Stakeholders	0	1	1	5	3	2	83%

(N = non, W = weak, F = fair, G = good, VG = very good, BP = best practice, %A = percentage agreement)

Figure 4.20 illustrates the percentage distribution of respondents' feedback. The vertical axis illustrates the total number of respondents in percentage terms and on the horizontal axis, the various project management knowledge areas. The various levels of extent of influence, are depicted in different colours in the bar chart.

Figure 4.20: The percentage distribution of respondents' level of agreement relating to the different project management knowledge areas during the initiating process group in additive manufacturing

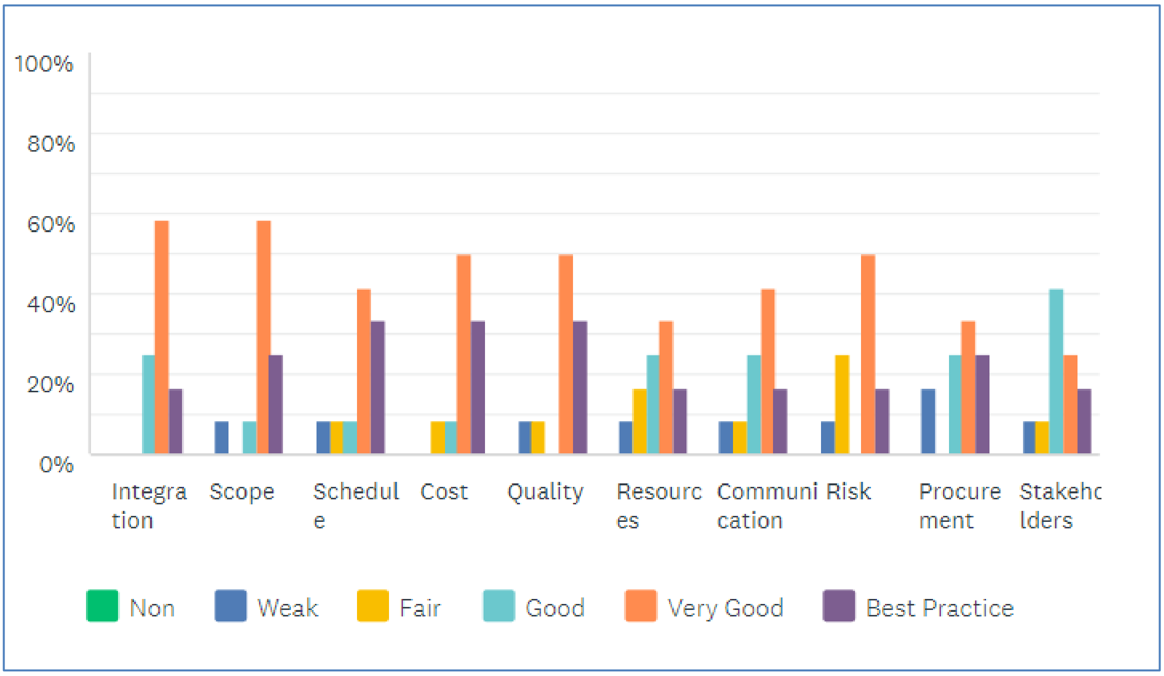


Figure 4.20 displays the percentage distribution of the following characteristics, "Integration" (good = 25%, very good = 58%, best practice = 17%); "Scope" (good = 8%, very good = 58%, best practice = 25%); "Schedule" (good = 8%, very good = 42%, best practice = 33%); "Cost" (good = 8%, very good = 50%, best practice = 33%); "Quality" (very good = 50%, best practice = 33%); "Communication" (good = 25%, very good = 42%, best practice = 17%); "Procurement" (good = 25%, very good = 33%, best practice = 25%); "Stakeholders" " (good = 42%, very good = 25%, best practice = 17%). These characteristics are viewed by the majority of respondents as the most essential project management knowledge areas, assisting the planning process group. It is worth noticing that respondents viewed "Resources" and "Risk" as less important, possibly of the nature the technology and the reduced risk this technology provide in manufacturing.

4.2.8. Executing

The executing process group, according to PMBOK (PMI, 2013: 56), comprises of those processes performed to complete the work, as defined in the project management plan to satisfy specifications. This involves the integration and coordination of people and all other resources to carry out the project management plan. The following section, the third project management process group, studied, is the executing process group and it will look at what extent specific project management knowledge areas play in additive manufacturing.

Statement 13: Consensus was obtained from 5 out of 10 statements (50%) in round 1, relating to the executing of projects in additive manufacturing. Table 4.21 illustrates those statements for which consensus (agreement level of 80% and above) was obtained and not obtained (below 80%).

*Table 4.21: The number of responses and percentage agreement: **execution** of projects in additive manufacturing*

STATEMENTS	N	W	F	G	VG	BP	%A
Integration	0	1	0	2	7	2	92%
Scope	0	3	2	1	4	2	58%
Schedule	0	0	1	2	4	5	92%
Cost	1	1	2	1	5	2	67%
Quality	0	0	1	1	4	6	92%
Resources	0	1	1	3	4	3	83%
Communication	0	1	0	1	6	4	92%
Risk	0	2	2	3	2	3	67%
Procurement	1	2	0	2	4	3	75%
Stakeholders	0	1	3	3	2	3	67%

(N = non, W = weak, F = fair, G = good, VG = very good, BP = best practice, %A = percentage agreement)

Figure 4.21 displays the percentage distribution of respondents' feedback relating to the execution of projects in additive manufacturing. The ordinate shows the total number of respondents in percentage terms and on the abscissa the various project management knowledge areas. The different colours in the bar chart represent the various levels of the extent of influence.

Figure 4.21: The percentage distribution of respondents' level of agreement relating to the different project management knowledge areas during the executing process group in additive manufacturing.

Figure 4.21 above shows that the characteristics "Integration" (good = 17%, very good = 58%, best practice = 17%); "Schedule" (good = 17%, very good = 33%, best practice = 17%); "Quality" (good = 8%, very good = 33%, best practice = 50%); "Resources" (good = 25%, very good = 33%, best practice = 25%) and "Communication" (good = 8%, very good = 50%, best practice = 33%) are viewed by the majority of respondents as the most essential project management knowledge areas that will assist the Executing process in additive

manufacturing. When comparing the results from all the knowledge areas, it is important to note that respondents agree "Integration", "Schedule", "Quality", Resources" and "Communication" possibly the most important areas of focus should be. Less attention was applied to "Risk", "Procurement" and "Stakeholder", possibly of risk factors being small, very little procurement is required, and stakeholders are not fully involved at this stage of the development. "Schedule" is mentioned by respondents as an influential project knowledge area, possibly of time constraints, takt time and manufacturing/3D machine printing speeds.

4.2.9. Monitoring and controlling

The monitoring and controlling process group, according to PMBOK (PMI, 2013: 57), aims to achieve three important things, namely the tracking, reviewing and regulating of project progress and performance. This fourth project management process group studied, aim to establish the extent, specific project management knowledge areas have in additive manufacturing.

Statement 19: Consensus (40%) was obtained from 4 out of 10 statements in round 1. Table 4.22 illustrates those statements for which consensus (agreement level of 80% and above) was obtained and not obtained (below 80%).

Table 4.22: The number of responses and percentage agreement: ***monitoring and controlling*** *of projects in additive manufacturing*

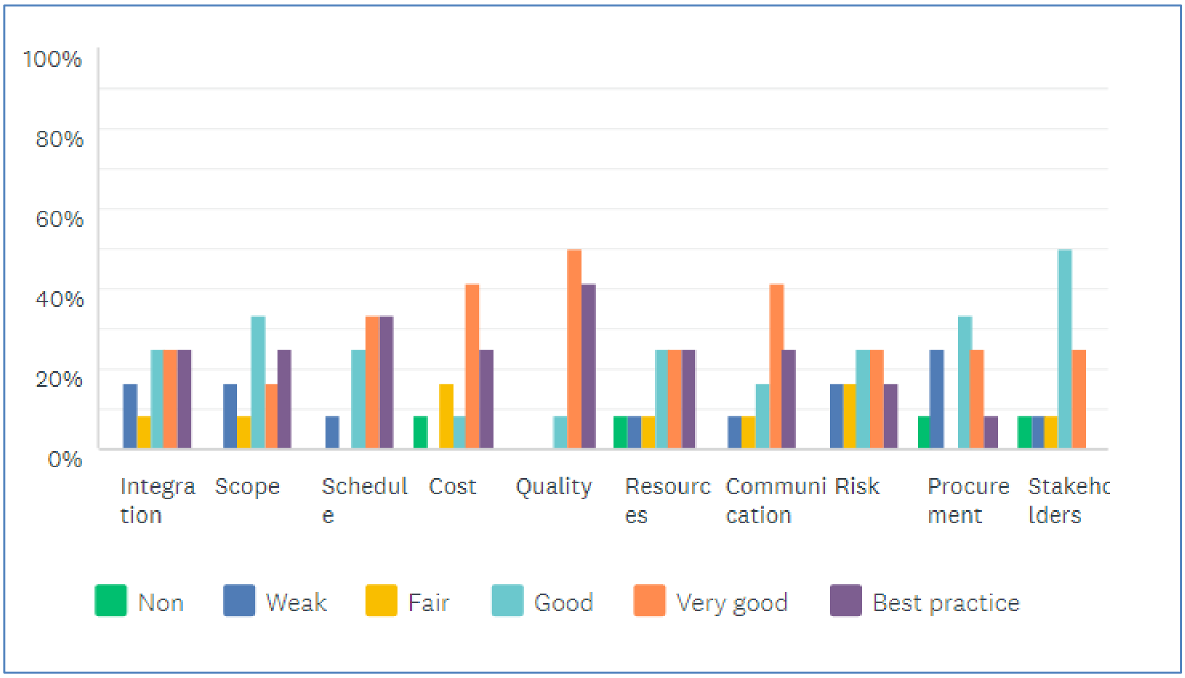
STATEMENTS	N	W	F	G	VG	BP	%A
Integration	0	2	1	3	3	3	75%
Scope	0	2	1	4	2	3	75%
Schedule	0	1	0	3	4	4	92%
Cost	0	0	0	1	6	5	100%
Quality	0	0	0	1	6	5	100%

Resources	1	1	1	3	3	3	75%
Communication	0	1	1	2	5	3	83%
Risk	0	2	2	3	3	2	67%
Procurement	1	3	0	4	3	1	67%
Stakeholders	1	1	1	6	3	0	75%

(N = non, W = weak, F = fair, G = good, VG = very good, BP = best practice, %A = percentage agreement)

Considering the results from respondents, Figure 4.22 displays the percentage distribution relating to the monitoring and control of projects in additive manufacturing. The vertical axis displays the total number of respondents in percentage terms and on the horizontal axis the various project management knowledge areas. The different colours in the bar chart represent the various levels of the extent of influence.

Figure 4.22: The percentage distribution of respondents' level of agreement relating to the different project management knowledge areas during the monitoring and controlling process group in additive manufacturing



Regarding the respondents feedback on monitoring and controlling, Figure 4.22 above shows that the characteristics "Schedule" (good = 25%, very good = 33%, best practice = 33%); "Cost" (good = 8%, very good = 42%, best practice = 25%) "Quality" (good = 8%, very good = 50%, best practice = 42%); and "Communication" (good = 17%, very good = 42%, best practice = 25%) are viewed by the majority of respondents as the most essential project management knowledge areas that will assist the monitoring and controlling process in additive manufacturing. Respondents agreed that more attention needs to be focused on the knowledge areas of "Schedule", "Cost", "Quality" and "Communication", although the other knowledge areas are essential in project management. Reasons for these could be that the scope of the project could be fixed at a stage of the projects' lifespan and less integration is required, therefore, resources are well-managed, and risks are very low. Good material and process management might therefore not require additional procurement functions, keeping client feedback to the minimum.

4.2.10. Closing

The project closing process group, according to PMBOK (PMI, 2013: 57), consists of those processes performed to conclude all activities across all project management process groups to formally complete a project. The results in this section will focus on the extent, specific project management knowledge areas play and their role during the closing process group.

Statement 26: Consensus (50%) was obtained from 5 out of 10 statements in round 1, relating to the closing of projects in additive manufacturing. Table 4.23 illustrates those statements for which consensus (agreement level of 80% and above) was obtained and not obtained (below 80%).

*Table 4.23: The number of responses and percentage agreement: **closing** of projects in additive manufacturing*

STATEMENTS	N	W	F	G	VG	BP	%A
Integration (n=11)	0	2	1	1	5	2	72%
Scope	0	2	1	1	6	2	75%
Schedule	1	1	0	0	6	4	83%
Cost	1	0	0	3	4	4	92%
Quality	0	0	0	1	5	6	100%
Resources	0	2	1	2	5	2	75%
Communication	0	1	0	2	4	5	92%
Risk	1	2	1	2	5	1	67%
Procurement	1	1	2	3	4	1	67%
Stakeholders	0	1	0	4	5	2	92%

(N = non, W = weak, F = fair, G = good, VG = very good, BP = best practice, %A = percentage agreement)

Figure 4.23 illustrates the percentage distribution of respondents' feedback. The vertical axis illustrates the total number of respondents in percentage terms and on the horizontal axis, the various project management knowledge areas. The various levels of the extent of influence, are depicted in different colours in the bar chart.

Figure 4.23: The percentage distribution of respondents' level of agreement relating to the different project management knowledge areas during the closing process group in additive manufacturing

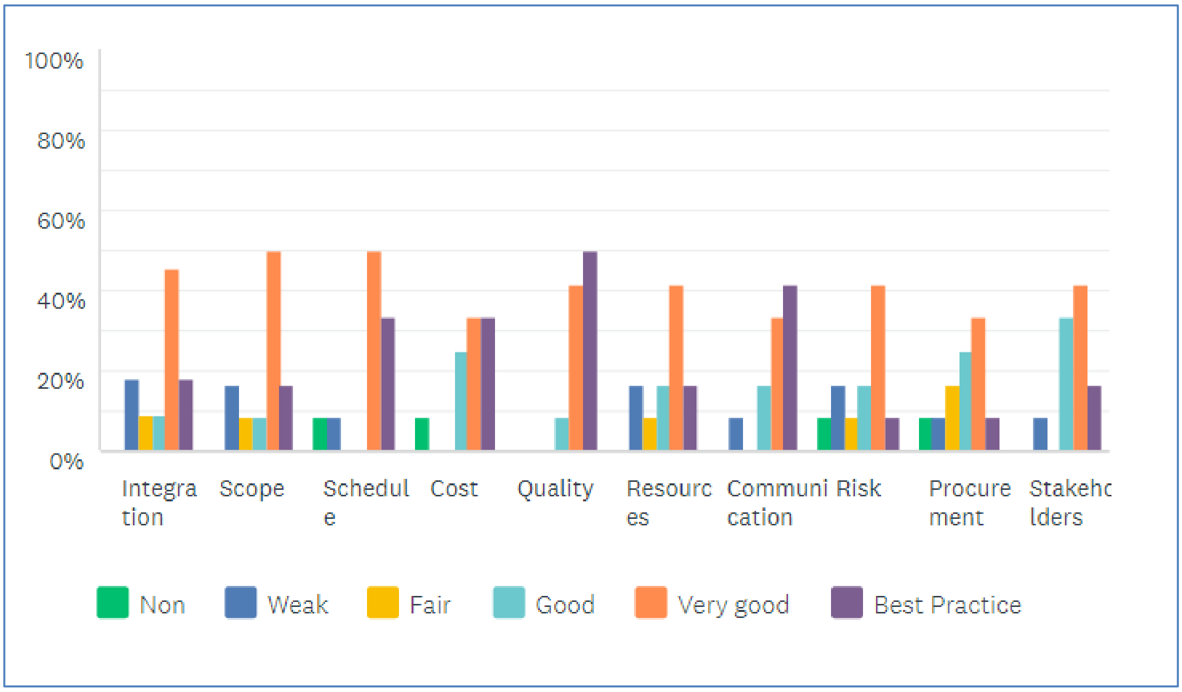


Figure 4.23 give respondents' feedback on closing, the figure above shows that the characteristics "Schedule" (good = 25%, very good = 33%, best practice = 33%); "Cost" (good = 8%, very good = 42%, best practice = 25%) "Quality" (good = 8%, very good = 50%, best practice = 42%); "Communication" (good = 17%, very good = 42%, best practice = 25%) and "Stakeholders" (good = 33%, very good = 42%, best practice = 17%) are viewed by the majority of respondents as the most essential project management knowledge areas that will influence the closing process in additive manufacturing. Although "Integration" and "Procurement" plays a very important role in closing, respondents agreed that more attention could be focussed on the knowledge areas of "Schedule", "Cost", "Quality", "Communication" and "Stakeholders". Reasons for these could possibly be that the schedule, cost and quality something critical is before delivery of the final product takes place. True customer engagement, where proper communication skills are required to close a possible stakeholder close-out for the project.

4.3. Concluding findings and agreements for lean project management, within additive manufacturing

The previously analysed findings of the questionnaire highlighted the respondents' views towards the characteristics or elements that may be essential when managing projects in additive manufacturing. These findings have shown the major extent as to what is confirmed within the literature, and what the majority of respondents agree upon. As a result, it is now appropriately to summarise this chapter, highlighting the overall findings or agreements, as required in the lean managing process of projects.

4.3.1. Management principles in lean

Table 4.24 summarises the focus areas and linked statements with consensus, as per each statement relating to the various studied lean management principles as prescribed by Liker (2004: 06-07).

Table 4.24: Consensus and focus of lean management principles in additive manufacturing

	Management principles in lean	Focus areas	Linked statements	Consensus (Y/N)
Philosophy	1. Base management decisions on a long-term philosophy, even at the expense of short-term financial goals.	Philosophy	4.	Yes

Processes	2. Create a continuous process flow to bring problems to the surface.	Flow, waste, planning.	7.	No
	3. Use pull systems to avoid overproduction.	Pull, overproduction, customer demand.	8.	Yes
	4. Level out the workload.	Workload, overburdening.	9., 10.	Yes
	5. Build a culture of stopping to fix problems, get the quality right the first time.	Quality, problem-solving.	11., 12.	Yes
	6. Standardised tasks and processes are the foundation for continuous improvement and employment empowerment.	Standardisation, takt time, sequence, inventory, flexibility, innovation.	14.,15.	Yes
	7. Use visual control so that no problems are hidden.	Control, quality, standards, flow, waste.	16.	Yes
	8. Use only reliable tested technology that serves your people and processes.	Value-adding, technology.	17.	No
People & partners	9. Grow leaders who thoroughly understand the work, live the philosophy and teach it to others.	Resources, quality, philosophy.	18.	Yes
	10. Develop exceptional people and teams who follow your company's philosophy.	Resources, suppliers, technology.	22.	Yes
	11. Respect your extended network of partners and suppliers by challenging them and helping them to improve.	Processes, suppliers.	20.,21.	Yes
Problem solving	12. Go and see for yourself to fully understand the situation.	Resources, technology, philosophy.	22.	Yes
	13. Make decisions slowly by consensus, considering all options; implement rapidly.	Resources	23.	Yes
	14. Become a learning organisation through relentless reflection and continuous improvement.	Resources, philosophy, innovation, flexibility.	24.,25.	Yes

Firstly, respondents agreed on the need for a long-term philosophy within additive manufacturing and that those management decisions must be based on solid values which are geared towards the growth of a company and its employees. Although short-term financial approaches could overshadow this view, it could ultimately be a matter of survival in the long-term.

According to respondents, processes within additive manufacturing provides a good element of flow, which is necessary to promote value-added work and reduce waste. When additive manufacturing technology is compared to traditional manufacturing, it is agreed upon by respondents that there is a low requirement for large or unnecessary batch-and-queue systems. Inventory levels are controlled, problems and inefficiencies are more visible and most types waste is minimised, when the technology is applied. Although consensus was not achieved on all the types of waste, respondents supports the view that additive manufacturing provides good flexibility, built-in quality, creates higher productivity, less waste, improved safety and morale amongst employees, less floor space and it reduces the cost of inventory.

Overall findings confirm that additive manufacturing could inherently employ pull, as large parts of some processes could be confined as a one-piece flow. Respondents are of the opinion that significant parts of their processes could employ pull to avoid overproduction and prioritise work. Feedback verifies the fact that respondents believe that additive manufacturing might be a better or natural manufacturing technology to provide a customer with what, when and in the amount, they require a product in. This could ultimately allow employees to focus on the right tasks at the right times, while reducing waste.

Respondents agree that additive manufacturing does provide flexibility to correspond manufacture according to customer demand and that the threat of unsold goods proportionately lower is. A mixed response towards the overburdening and unevenness of machines and resources was received, potentially highlighting the nature and relevant age of the technology.

Respondents agreed that for a process to be successful, a manufacturing plant should be stopped when defects are detected. In traditional manufacturing this process would be viewed as counterproductive, as plants are usually run as for as long as possible at maximum levels. Additive manufacturing provides industry with the luxury of halting a manufacturing process, inspect and repair the product via technology, at the source as they occur. This advantage encourages workers to anticipate problems very early on and it encourage employees to alter the speed of a process to ensure that the right quality is built-in the first-time round. This supports respondents earlier view on company philosophy, relating to the long-term success of an organisation.

Standardisation amongst respondents had a strong presence and it was stated that it influences quality and innovation. It promotes worker morale and tasks needs to be done in a specific sequence, according to customer demand, with the stock available. As this industry is still viewed as a developing manufacturing technology, people and research still contributes to what is required in the implementation of standards.

Views on visual control support the previous statements, referring to flow, pull and flexibility. This function is an important integrated element of value-added work and respondents view it as essential in the waste elimination process. Simple measures of control and reporting are agreed upon as often being the favoured.

The agreement on the elimination of waste in additive manufacturing processes confirms a divided opinion on whether any new technology needs to be evaluated and thoroughly tested before it is implemented. If performed incorrectly, this process could lead to excessive waste. Unnecessary capital could have been spent on technology which does not fulfil the intended needs, arguably demoralising employees. On the flip-side, workable technology could have an impact on processes and eliminate waste, without the need to disrupt processes.

To gain valuable experience, respondents agreed that it could be achieved, by being actively involved in the organisations manufacturing processes. This could develop knowledge gain and transfer; and employees, therefore will contribute to the continuity, quality and philosophy of the organisation.

Feedback reflects the need to have excellent individuals that will excel in what they do. In additive manufacturing emphasis is placed on specific skills and technology needed to support teamwork. If good teamwork exists, then individuals could deliver skills and outputs, more than what is required from them.

Cross-firm relationships with suppliers are very important, while an organisation maintains its internal capabilities. Limited knowledge can be transferred to suppliers and industry partners, as long as these suppliers show the same level of competency and commitment to delivering products, components and material. Agreement amongst respondents shows that these cross-firm relationships are important, especially in problem-solving. This could extend to the development of new processes, material, quality and planning in additive manufacturing. This process of learning requires that these relationships must be stabilised to the point where the business relationship is fair, processes are stable, and expectations are clear. The supplier needs to redevelop their internal culture and become a learning organisation.

Feedback confirms that respondents trust efforts where employees actively experience problems in the additive manufacturing environment with an open mind. Processes need to be understood in detail, as well as the flow of work. Work needs to be standardised and must be evaluated and analysed critically.

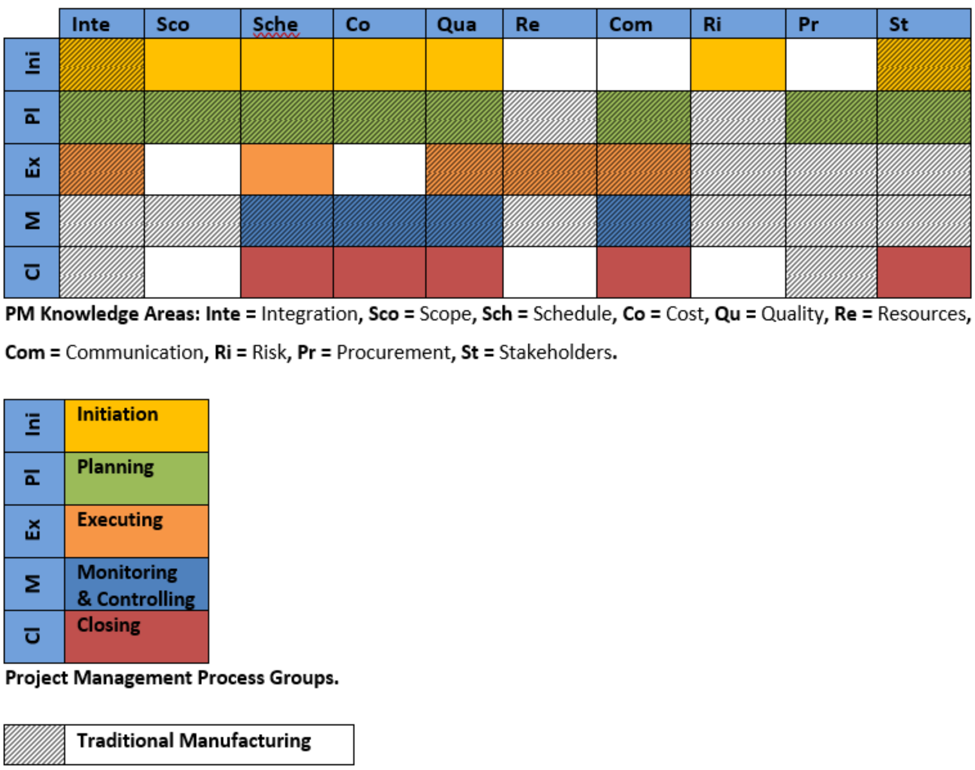
The decision-making process needs time and great care up to the point where the decision is to be made fast and efficient. Consensus must be reached fast with the support of simple and visual information. A well-thought-out solution could include elements such as the scope, labour or resources, time, cost and controls.

Respondents agreed that continuous learning from mistakes, determining the root causes of problems, effective countermeasures and the transfer of knowledge to the correct people in the organisation, will result in an approach which is part of the organisation's culture. To be adaptable, flexible and innovative; processes need to be stable, and waste and inefficiencies should be visible. Employees should take responsibility if something went wrong, propose countermeasures, find the root cause and prevent a repeat of the same problem. This process of continuous learning should take time and the process of plan-do-check-act (PDCA), should be encouraged.

4.3.2. Project management

The following section is a summary of the influence, specific project management knowledge areas have on the studied project process group areas, in additive manufacturing. Results reflect the feedback from respondents and report their views on the areas of influence. The level of agreement was used as a measurement for plotting the results in Figure 4.24 below. "Initiation" is recorded in yellow, "Planning" in green, "Executing" in Light brown, "Monitoring & Controlling" in blue and "Closing" in maroon. Table 4.24 above illustrates those knowledge areas where respondents' feedback has reached consensus (agreement level of 80% and above) for each of the project management process groups for additive manufacturing. The areas marked in diagonal lines, illustrates the influence the specific project management knowledge areas have on the project process group areas in traditional or conventional manufacturing. The table below is adapted from the PMBOK project management process group and knowledge area mapping.

Figure 4.24: Influence of PM knowledge areas on PM process groups in AM(PMBOK, 2013: 61)



Respondents agree that most projects usually require similar processes to achieve success in project management, including additive manufacturing. Feedback confirms a certain process group and knowledge area mapping for additive manufacturing, and it is compared to traditional manufacturing in the figure above. During the Initiation Process Group when projects are defined and authorised, respondents emphasised on extra project management knowledge areas. Normally during this management process group, especially in traditional manufacturing, the focus is only on Integration and Stakeholder management. Feedback in this instance, claims that project management needs to take cognisance of the scope, schedule, cost, quality and risk, even before the planning process group is commenced. This feedback might also be attributed to a lack of respondents' understanding of the Initiating process. A risk is regarded as an important component of the Initiation Process Group and is only prominent during this process group.

The planning process group will be more involved with what is required for the scope, schedule, cost, quality and risk; if compared to what is required in the Initiation Process Group. In traditional or conventional manufacturing, all ten knowledge areas are important, but in additive manufacturing, feedback shows that resources and risk, less focus experience from project management according to this study.

The executing process group shares integration, quality, resources and communication with traditional/conventional manufacturing, except that it requires added focus on scheduling. Although the latter three knowledge areas are shared by traditional manufacturing, this Process Group normally requires a focus on risk, procurement and stakeholders.

The monitoring and controlling process group normally requires all 10 knowledge areas during the mapping process during traditional manufacturing. Feedback states that these focus areas are less involved and only schedule, cost, quality and communication focus is required. Finally,

Closing from an additive manufacturing perspective is more involved, compared to traditional manufacturing. This includes the knowledge areas of schedule, cost, quality, communication and stakeholders.

4.4. Conclusion

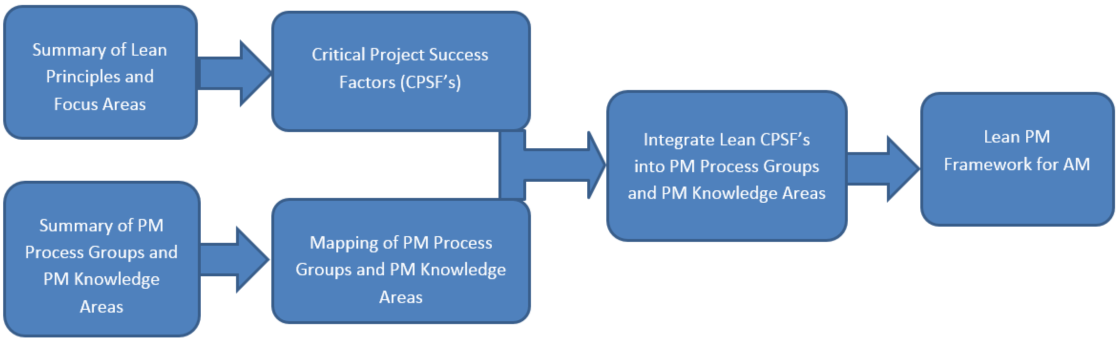
The above results and analysis were based on a single round Delphi study, due to time and cost limitations and the response rate. The response rate was 19% from a list of 64 respondents. Although the study was a single round study with a relatively high number of questions, great care was taken to ensure that the questionnaire could be completed comfortably and accurately within the prescribed 10-minute timeframe. The researcher, however, felt that the design and execution of this single-round Delphi study will install confidence in the respondents' results and opinions. Despite the mentioned limitations, the researcher believes that the results will have both research and practical implications. Chapter Five follows next, which is a culmination of Chapters Three and Four. The chapter will focus on the combination of lean and project management factors, to develop a framework required to design and develop products in additive manufacturing.

5. Chapter Five: Development of a lean project management framework for additive manufacturing.

5.1. Introduction

This chapter will layout the detail of the development of the lean project management framework. The approach in which it was developed is presented in Figure 5.1 below.

***Figure 5.1**: The process followed in developing the framework*



Conclusions will be made from the Delphi study results on the management principles required to lean manage projects in additive manufacturing. The results and consensus from the questionnaire were studied extensively in Chapter Four, to provide the researcher with critical project success factors (CPSF's) criteria as listed below in Table 5.1. A summary of the project process groups and their knowledge areas, as influenced by additive manufacturing, is listed below in Table 5.2. The findings for the lean CPSF's will then be integrated into the mapped project management process groups and knowledge areas (PMI, 2013:61), to develop a framework for lean project management in additive manufacturing.

5.2. Critical project success criteria

Often the importance of project management is underestimated, and challenges exist in regard to the implementation and adoption of additive manufacturing. Therefore, an organisation needs to look at what changes are required in a business to be successful (Niaki & Nonino, 2014:1431). Projects often are managed successfully, even though scope, schedule, cost and quality constraints were compromised. The process of lean management entails more than just the use of example, tools, but requires the understanding of lean as an entire system which influences an organisations' whole culture. In order to develop the best possible framework to lean manage projects in additive manufacturing, it is necessary to gain an overall view of the factors critical to the success of projects in this manufacturing environment.

Therefore, the key findings from the research in Chapter Four, will aim to summarise and represent findings, as critical project success factors (*cf.* Table 5.1).

Table 5.1: Critical lean project success criteria

	Management principles in lean (Liker, 2004: 35-41)	**Critical project success factors**
Philosophy	1. Base management decisions on a long-term philosophy, even at the expense of short-term financial goals.	-Management must be concerned with the daily operations and continuous improvement efforts.

Processes	2. Create a continuous process flow to bring problems to the surface. 3. Use pull systems to avoid overproduction. 4. Level out the workload. 5. Build a culture of stopping to fix problems, get the quality right the first time. 6. Standardised tasks and processes are the foundation for continuous improvement and employment empowerment. 7. Use visual control so that no problems are hidden. 8. Use only reliable tested technology that serves your people and processes.	-Manage flow and waste, focusing on overproduction, excess inventory and unused creativity. -Plan production according to customer demand and treat projects, focusing on specific tasks and the scheduling of those tasks. -Employ pull and provide the link for the flexible management of customer and supplier demands. -Plan and manage efficient resource usage. -Build in quality evaluating technology and manage resource technology and perceptions. -Manage lead times. -Focus on flexible production. -Standardise processes and tasks. -Manage communication and place added focus on visual controls to highlight problems or standard deviation. -Focus on quality. -Control cost. -Adapt and apply supportive technology.
People & Partners	9. Grow leaders who thoroughly understand the work, live the philosophy and teach it to others. 10. Develop exceptional people and teams who follow your company's philosophy. 11. Respect your extended network of partners and suppliers by challenging them and helping them to improve.	-Build continuity in an organisation and focus on a long-term philosophy. -Develop and build on peoples' knowledge. -Develop and look after employees, as quality will ultimately come from them. -Look after customers and keep them in the loop through all stages of developments. -Ensure effective communication channels and cooperation between organisation and suppliers.
Problem Solving	12. Go and see for yourself to fully understand the situation. 13. Make decisions slowly by consensus, considering all options; implement rapidly. 14. Become a learning organisation through relentless reflection and continuous improvement.	-Analyse and understand flow in depth. -Standardise and critically evaluate work. -Analyse shortcomings and clarify skills and knowledge for further development. -Build consensus with teams and outside partners. -Use efficient communication vehicles. -Learn from mistakes, determine root causes, put countermeasures in place. -Empower people to implement measures.

The above summary, according to this study, highlights the factors critical to the management of lean projects in additive manufacturing. This study has found that there is little evidence or no defined essential set of project success factors relevant to the specific lean management of projects in additive manufacturing. It makes it thus appropriate to apply a combination of traditional project management principles, as prescribed by PMBOK (2013:50-60), with those principles, as championed by lean. The views from respondents regarding the application of these lean principles is seen as beneficial to the development of such a framework. The summarised lean principles, which supports the five project management process groups, are highlighted briefly in the following four categories. The summary of the lean principles is followed by the response in the Delphi study, on the project management process groups and knowledge areas.

5.2.1. Philosophy

Additive manufacturing, although viewed by some as a new technology, are already well-established and is having an impact on every major industry. Focussing on only certain aspects of the technology could be counterproductive, and it could be important not neglect less perceived elements, like an organisations' philosophy which is based on the conception of people and their motivation. Management must, therefore, be involved in the daily running of operations and ongoing improvement attempts of a business. This success ultimately is based on well-devised strategies, leadership, teams and culture, the build of client and supplier and customer relationships, and ongoing efforts of being a learning organisation. It is thus important to have a mission statement that explains how the organisation tends to stay in business long term.

5.2.2. Processes

Lean is effective, once all these four categories are implemented. The success is dependent on certain success factors as agreed upon by respondents. Processes need to be adequately managed as well as being standardised. All lean activities should be managed with the intent of generating continuous flow. It is thus good practice to identify problems and solving them, balancing the load and production lines (if large-scale AM manufacturing takes place), reducing all wasteful activities during and between process steps. The success factors identified in the study are applicable, as production often relies on a supply chain model where retail takes place electronically, manufacturing is initiated and where final distribution to the end customer takes place.

5.2.3. People and partners

It is important to employ the correct people that would share in the same company goals. If everyone's' objectives are aligned, as referred to in the mission statement, progress could be excelled, especially in a small to a medium sized additive manufacturing company. Good leaders from within a company can fulfil the company philosophy, teach it to others or lead by example. The optimisation of internal processes is reliant on the contribution of own employees and its management. Equally important is the contribution external partners can make in respect to what and when your own business need.

5.2.4. Problem solving

Data do not always present all the facts and it is more difficult to do a root cause analysis if you lack proximity. Solving problems can take time, and the collection of potential solutions needs time and all employees need to understand the impact of the problem and be part of the solution. Solving problems could only be beneficial if employees learn and reflection is drawn from the events.

5.3. Project management

This study as mentioned before uses the PMBOK guide (2013) as a basis for establishing a reference towards project management in additive manufacturing. The guide provides us with a foundation of the required project management knowledge areas to manage projects successfully. These knowledge areas deal with processes which accommodates different features of project management as it incorporates the processes and activities. They include the identification, definition, combination, unification and coordination of the various processes and project management activities within the project management process groups (PMI, 2013: 61). The reader of this research report might be familiar with the PMBOK guide, for those readers that are not, the research will aim to provide a framework based on the mapping of the essential project management knowledge areas and project management processes within the PMBOK guide as required by a lean approach. The required lean principles will be integrated, utilising the identified critical project success factors.

Table 5.2 below is a summary of the influence, specific project management knowledge areas have on the studied project process group areas, in additive manufacturing. This forms the basis on which the framework will be developed and include all the elements required to perform the project management process. The marked areas in colours are the mapped areas where consensus was reached in the study. The colour coding of the consensus reached does not mean that the fields not marked in colour are insignificant. The framework attempted to focus on areas of importance to lean and additive manufacturing.

Table 5.2.: Mapped AM influenced PM process group and knowledge areas

Knowledge Areas	Initiating Process Group	Planning Process Group	Executing Process Group	Monitoring and Controlling Process Group	Closing Process Group
Project Integration Management	- Develop Project Charter.	- Develop PM Plan	- Direct and Manage Project Work. - Manage Project Knowledge.	- Monitor and Control Project Work. - Perform Integrated Change Control.	- Close Project or Phase.
Project Scope Management		- Plan Scope Management. - Collect Requirements. - Define Scope. - Create WBS.		- Validate Scope. - Control Scope.	
Project Schedule Management		- Plan Schedule Management. - Define Activities - Sequence Activities - Estimate Activity Resources - Estimate Activity Durations -Develop Schedule		- Control Schedule	
Project Cost Management		- Plan Cost Management - Estimate Costs - Determine Budget		- Control Costs	
Project Quality Management		- Plan Quality Management	- Manage Quality	- Control Quality	
Project Resources Management		- Plan Resource Management - Estimate Activity Resources	- Acquired Resources - Develop Team - Manage Team	- Control Resources	
Project Communications Management		- Plan Communications Management.	- Manage Communications	- Monitor Communications	
Project Risk Management		- Plan Risk Management - Identify Risks - Perform Qualitative Risk Analysis - Perform Quantitative Risk Analysis - Plan Risk Responses	- Implement Responses	- Monitor Risks	

Project Procurement Management		- Plan Procurement management	- Conduct Procurements	- Control Procurements	- Close Procurements
Project Stakeholder Management	- Identify Stakeholders	- Plan Stakeholder Engagement	Manage Stakeholder Engagement	- Monitor Stakeholder Engagement	

Ini	**Initiation**
Pl	**Planning**
Ex	**Executing**
M	**Monitoring & Controlling**
Cl	**Closing**

Project Management Process Groups.

As highlighted before in this section, this research does not intend to change or modify the management processes and elements as outlaid in the PMBOK. It aims to focus the attention on areas of interest related to the use of lean management principles within an additive manufacturing environment. This approach might therefore be valuable in the development and use of a framework in the additive manufacturing environment and it might stimulate further interest and research into this field.

Each knowledge area with corresponding elements will be summarised, as per process group in the following ten points below. These elements include the required inputs, tools and techniques, as well as the outputs generated according to PMBOK (2013). These points are discussed within the framework of lean and additive manufacturing.

5.3.1. Project Integration Management

This knowledge area takes account of the development of the project charter and the PM plan. It deals with the direction and management of project work and project knowledge. Respondents identified these four areas as those areas which could have an influence in additive manufacturing. This Integration knowledge area includes the monitoring and controlling of project work; performing integrated change control and the closing of projects.

Table 5.3: Project integration management (PMBOK, 2013:63), (Hartney, 2016)

	Project integration management		
	Inputs	Tools & techniques	Outputs
Develop project charter	• Business documents • Agreements • Enterprise environmental factors • Organisational process assets	• Expert judgement • Data gathering • Interpersonal and team skills • Meetings	• Project charter • Assumption log
Develop project management plan	• Project charter • Outputs from other process • Enterprise environmental factors • Organisational process assets	• Expert judgment • Data gathering • Interpersonal and team skills • Meetings	• Project management plan
Direct and manage project execution	• Project management plan • Project documents • Approved change requests • Enterprise environmental factors • Organisational process assets	• Expert judgment • Project management information system • Meeting	• Deliverables • Work performance data • Issue log • Change requests • Project management plan updates • Project document updates • Organisational process assets updates
Manage project knowledge	• Project management plan • Project documents • Deliverables • Enterprise environmental factors • Organisational process assets	• Expert judgement • Knowledge management • Information management • Interpersonal and team skills	• Lessons learned register • Project management plan updates • Organisational process assets updates
Monitor and control project work	• Project management plan • Project documents • Work performance information • Agreements • Enterprise environmental factors • Organisational process assets	• Expert judgement • Data analysis • Decision making • Meetings	• Work performance records • Change requests • Project management plan updates • Project document updates
Perform integrated change control	• Project management plan • Project documents • Work performance information • Change requests • Enterprise environmental factors • Organisational process assets	• Expert judgement • Change control tools • Data analysis • Decision making • Meetings	• Approved changed requests • Project management plan updates • Project document updates

Close project or phase	• Project charter • Project management plan • Project documents • Accepted deliveries • Business documents • Agreements • Procurement documentation • Organisational process assets	• Expert judgement • Data analysis • Meetings	• Project documents updates • Final product, service or result transition • Final report • Organisational process assets updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

Approaching project management in an additive manufacturing environment requires the integration process to focus on the project charter which allows the researcher to announce the initiation of the project, background and purpose, the project manager and it is usually sent out to the sponsor of the project. The development of the project plan is undertaken, as this forms the backbone of the management process. The direction and management of the execution of the project are installed, and a good level of stakeholder involvement and consensus is needed. The management of project knowledge is vital, as all required decisions are based on the quality of information as supplied by employee knowledge and feedback and the lessons learned from current and past project experience. The quality level of employee is vital in the process of continuous improvement and philosophy development. The project charter and plan form an essential part of the integration process as all elements require feedback and input from these elements to progress.

5.3.2. Project Scope Management

This knowledge area incorporates all the processes that are responsible for controlling project scope. It consists of scope planning, requirements, definition, work breakdown system, verification, validation, and control. The focus from an additive manufacturing perspective concentrates mainly on the planning processes and includes scope planning, requirements, definition, work breakdown system, as labelled with the green background. The validation and control of the scope could be less influential in additive manufacturing, although added interest around the Initiating Process could be promulgated.

Table 5.4: Project scope management (PMBOK, 2013:105), (Hartney, 2016)

	Project scope management		
	Inputs	Tools & techniques	Outputs
Plan scope management	• Project charter • Project management plan • Enterprise environmental factors • Organisational process assets	• Expert judgement • Data analysis • Meetings	• Scope management plan • Requirements management plan
Collect requirements	• Project charter • Project management plan • Project documents • Business documents • Agreements • Enterprise environmental factors • Organisational process assets	• Expert judgment • Data gathering • Data analysis • Decision making • Data representation • Interpersonal and team skills • Data context diagram • Prototypes	• Requirements documentation • Requirements traceability matrix
Define scope	• Project charter • Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgment • Data analysis • Decision making • Interpersonal and team skills • Product analysis	• Project scope statement • Project documents updates
Create work breakdown system (WBS)	• Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgement • Decomposition	• Scope baseline • Project document updates
Validate scope	• Project management plan • Project documents • Verified deliverables • Work performance data	• Inspection • Decision making	• Accepted deliverables • Work performance information • Change requests • Project document updates
Control scope	• Project management plan • Project documents • Work performance data • Organisational process assets	• Data analysis	• Work performance information • Change requests • Project management plan updates • Project documents updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

Focus around the planning of the scope of all projects are essential. If all requirements are clearly identified, the planning towards the breakdown of work can commence. Although additive manufacturing provides the researcher with flexibility towards changes and customer requirements, the scope requires validation from an early stage of the project management process. This scope still needs to be controlled, and reference to the project plan is essential during the execution of projects.

5.3.3. Project schedule management

Project schedule management includes processes concerning the time or schedule constraints of the project. It provides a plan with detailed information on how and when the project will deliver products and results as defined in the project scope and serves as a communication vehicle to manage stakeholders' expectations. It deals with planning, definition, sequence and duration estimating of activities, the development and control of schedules. The focus is mainly focussed around the planning process (marked in green background); and monitoring and controlling (labelled with a blue background) process groups. Project management in additive manufacturing focuses on all the process groups in schedule management.

Table 5.5: Project schedule management (PMBOK, 2013:141), (Hartney, 2016)

	Project schedule/time management		
	Inputs	Tools & techniques	Outputs
Plan schedule management	• Project charter • Project management plan • Enterprise environmental factors • Organisational process assets	• Expert judgement • Analytical techniques • Meetings	• Schedule management plan
Define activities	• Schedule management plan • Enterprise environmental factors • Organisational process assets	• Expert judgement • Decomposition • Rolling wave planning • Meetings	• Activity list • Activity attributes • Milestone list • Change requests • Project management plan updates
Sequence activities	• Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Precedence diagramming method- PDM • Dependency determination • Applying leads and lags • Project management information system	• Project schedule network diagrams • Project documents updates

Estimate activity durations	• Project management plan • Project documents • Enterprise environmental Factors • Organisational process assets	• Expert judgement • Analogous estimating • Parametric estimating • Three-point estimates • Bottom-up estimating • Data analysis • Decision making • Meetings	• Duration estimates • Basis of estimates • Project document updates
Develop schedule	• Project management plan • Project documents • Agreements • Enterprise environmental factors • Organisational process assets	• Schedule network analysis • Critical path method • Resource optimisation • Data analysis • Applying leads and lags • Project management information system • Agile release planning	• Project schedule • Schedule baseline • Schedule data • Project calendars • Change requests • Project management plan updates • Project documents updates
Control schedule	• Project management plan • Project documents • Work performance data • Organisational process assets	• Data analysis • Critical path method • Project management information system • Resource optimisation • Adjusting leads and lags • Schedule compression	• Work performance information • Schedule forecasts • Change requests • Project management plan updates • Project document updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

Schedule management in additive manufacturing focusses like most other project environments, on the successful scheduling of projects. The planning, definition and the sequence of activities are vital in the eventual execution of projects. In additive manufacturing, this will assist the management of flow and waste, and production can be done according to customer demand. Pull initiatives and activity resources can support this demand, and durations can be adapted accordingly to develop the final schedule. During the management and execution of the scheduling process, activities and tasks need to be standardised and lead times managed efficiently to ensure one of additive manufacturing's core values, namely flexible production. Controlling the schedule is vital in delivering customer demand, and it is useful to evaluate and analyse the flow continually. Focus on the closing of the schedule management process could point at the on-time completion of the project. The project management plan and the communication process play a significant role in the schedule management process.

5.3.4. Project cost management

This knowledge area is concerned with all the processes necessary to manage the cost constraints of projects. It deals with the planning, cost estimation, budget and the control of costs. The focus is on four of the process groups, excluding the executing process group.

Table 5.6: Project cost management (PMBOK, 2013:193), (Hartney, 2016)

	Project cost management		
	Inputs	Tools & techniques	Outputs
Plan cost management	• Project charter • Project management plan • Enterprise environmental Factors • Organisational process assets	• Expert judgement • Data analysis • Meetings	• Cost management plan
Estimate costs	• Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgement • Analogous estimating • Parametric estimating • Bottom-up estimating • Three-point estimates • Data analysis • Project management information system • Group-decision making techniques	• Cost estimates • Basis of estimates • Project documents updates
Determine budget	• Project management plan • Project documents • Business documents • Agreements • Enterprise environmental factors • Organisational process assets	• Expert judgment • Cost aggregation • Data analysis • Historical relationships • Funding limit reconciliation • Financing	• Cost baseline • Project funding requirements • Project document updates
Control costs	• Project management plan • Project documents • Project funding requirements • Work performance data • Organisational process assets	• Expert judgment • Data analysis • To complete performance index (TCPI) • Project management information systems	• Work performance information • Cost forecasts • Change requests • Project management plan updates • Project document updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

Ultimately, most project management efforts relate to the management of cost. Additive manufacturing allows an organisation to efficiently manage cost, for instance through the limiting of waste. The project management and cost management plans are essential and effective updates and communication plays an integrated role. Good and regular reporting which provides accurate information is required to make informed decisions so that consensus can be reached in the controlling of costs. Closing cost will indicate the accomplishment of one of project management's three constraints.

5.3.5. Project quality management

Project quality management describes the processes which ensures that the project reached its quality requirements and consists of the planning of quality management, and the management and control of quality.

Table 5.7: Project quality management (PMBOK, 2013:227), (Hartney, 2016)

	Project quality management		
	Inputs	Tools & techniques	Outputs
Plan quality management	• Project charter • Project management plan • Project documentation • Enterprise environmental factors • Organisational process assets	• Expert judgement • Data gathering • Data analysis • Decision making • Data representation • Test and inspection planning • Meetings	• Quality management plan • Quality metrics • Project management plan updates • Project document updates
Manage quality	• Project management plan • Project documents • Organisational process assets	• Data gathering • Data analysis • Decision making • Data representation • Audits • Design forx • Problem-solving • Quality improvement methods	• Quality report • Test and evaluation documents • Change requests • Project management plan updates • Project document updates
Control quality	• Project management plan • Project documents • Approved change reports • Deliverables • Work performance data • Enterprise environmental factors • Organisational process assets	• Data gathering • Data analysis • Inspection • Testing/product evaluations • Data representations • Meetings	• Quality control measurements • Validated deliverables • Work performance information • Change requests • Project management plan updates • Project document updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

Ensuring quality within additive manufacturing might require a different mindset, as quality sometimes need to be checked and verified based on the design and observations and corrections during the manufacturing process. This process differs from conventional manufacturing where quality is usually checked after fabrication. The project management plan is again of importance during all the management processes and elements. Quality reports, including test and evaluation documents, are useful in the quality management process, as this supports the production/build planning, monitoring and feedback control. Good communication and information technology systems are essential as high levels of data can be generated. The closing of quality could indicate the accomplishment of one of project management's three constraints.

5.3.6. Project resource management

This knowledge area includes the processes that deal with obtaining and managing the project team. Processes include planning, activity estimation, resource acquiring, team development and managing, and control of resources. The focus in this knowledge area applies mainly to the executing process group, including the acquiring of resources, the development and management of teams.

Table 5.8: Project resource management (PMBOK, 2013:255), (Hartney, 2016)

	Project resource management		
	Inputs	Tools & techniques	Outputs
Plan resource management	• Project charter • Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgment • Data representation • Organisation theory • Meetings	• Resource management plan • Team charter • Project documents updates
Estimate activity resources	• Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgement • Analogous estimating • Parametric estimating • Bottom-up estimating • Data analysis • Project management information system • Meetings	• Resource requirements • Basis of estimates • Resource breakdown system • Project documents updates

Acquire resources	• Project management plan • Project documents • Enterprise Environmental Factors • Organisational process assets	• Decision making • Interpersonal and team skills • Pre-assignment • Virtual teams	• Physical resource assignments • Project team assignments • Resource calendars • Change requests • Project management plan updates • Project document updates • Enterprise environmental factors • Updates • Organisational process assets updates
Develop team	• Project management plan • Enterprise environmental factors • Project documents • Organisational process assets	• Colocation • Virtual teams • Communication technology • Interpersonal and team skills • Recognition and rewards • Training • Individual and team assessments • Meetings	• Team performance assessments • Change requests • Project management plan updates • Project document updates • Environmental enterprise factor updates • Organisational process assets updates
Manage team	• Project management plan • Project documents • Work performance reports • Team performance assessments • Enterprise environmental factors • Organisational process assets	• Interpersonal and team skills • Project management information system	• Change requests • Project management plan updates • Project document updates • Enterprise environmental factors updates
Control resources	• Project management plan • Project documents • Agreements • Work performance data • Organisational process assets	• Data analysis • Problem-solving • Interpersonal and team skills • Project management information system	• Work performance information • Change requests • Project management plan updates • Project document updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

Building continuity in an organisation and the investment in training is important in keeping employees additive manufacturing skills current and engaged. The strengthening of employees' skills levels will ultimately allow employees to oversee suppliers and meet customer and quality demands. Skills gaps must be identified and closed, and the build-in of evaluating technology is required. A collaborative approach can be taken to resource planning to cover these skills gaps, enabling the organisation to focus on high priority segments so that resources are not wasted. This manufacturing environment needs efficient resource planning, and employees need to be in a position to make informed decisions and implement measures as required. Apart from the technical skills required by employees, the focus must be on the philosophy of the business, as a change in culture and innovation can make technical staff more able to adopt the technology and changes and instil a culture of creativity. Regular reference to the project management plan and a robust and well-coordinated team effort is required.

5.3.7. Project communications management

Project communication management describes the processes concerning communication mechanisms of a projectThe focus is on all three of the process groups.

Table 5.9: Project communications management (PMBOK, 2013:287), (Hartney, 2016)

	Project communications management		
	Inputs	Tools & techniques	Outputs
Plan communication management	• Project charter • Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgements • Communication requirements analysis • Communication technology • Communication models • Communication methods • Interpersonal and team skills • Meetings	• Communications management plan • Project management plan updates • Project document updates
Manage communications	• Project management plan • Project documents • Work performance reports • Enterprise environmental factors • Organisational process assets	• Communication technology • Communication methods • Communication skills • Project management information system • Project reporting • Interpersonal and team skills	• Project communications • Project management plan updates • Project document updates • Organisational updates
Monitor communications	• Project management plan • Project documents • Work performance data • Enterprise environmental factors • Organisational process assets	• Expert judgment • Project management information systems • Data representation • Interpersonal and team skills • Meetings	• Work performance information • Change requests • Project management plan updates • Project document updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

Strong communication management is required, and focus is placed around planning, executing and monitoring and controlling processes. The elements required includes the planning, managing and monitoring of communications. Good communication skills and technology is required with frequent reference to the project management plan. Customers and suppliers need to be kept in the loop and the management of data needs to be supported by the right adopted technology. Data volumes can be extremely high, especially if certain communication and visual controls are used, like video monitoring data for in-situ manufacturing.

5.3.8. Project risk management

The project risk management knowledge area describes the processes involving communication mechanisms of a project. These include planning, risk identification, qualitative and quantitative risk analysis, risk response planning, monitoring and implementation. No specific process area was identified, although reference was made to the initiation process.

Table 5.10: Project risk management (PMBOK, 2013:309), (Hartney, 2016)

	Project risk management		
	Inputs	Tools & techniques	Outputs
Plan risk management	• Project charter • Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgment • Data analysis • Meetings	• Risk management plan
Identify risks	• Project management plan • Project documents • Agreements • Procurement documentation • Enterprise environmental factors • Organisational process assets	• Expert judgement • Data gathering • Data analysis • Interpersonal and team skills • Prompt lists • Meetings	• Risk register • Risk report • Project documents updates
Perform qualitative risk analysis	• Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgement • Data gathering • Data analysis • Interpersonal and team skills • Risk categorisation • Data representations • Meetings	• Project documents updates

Perform quantitative risk analysis	• Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgment • Data gathering • Interpersonal and team skills • Representations of uncertainty • Data analysis	• Project document updates
Plan risk responses	• Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgment • Data gathering • Interpersonal and team skills • Strategies for threats • Strategies for opportunities • Contingent response strategies • Strategies for overall project risk • Data analysis • Decision making	• Change requests • Project management plan updates • Project document updates
Implement risk responses	• Project management plan • Project documents • Organisational process assets	• Expert judgement • Interpersonal and team skills • Project management information system	• Change requests • Project document updates
Monitor risks	• Project management plan • Project documents • Work performance data • Work performance reports	• Data analysis • Audits • Meetings	• Work performance information • Change requests • Project management plan updates • Project document updates • Organisational process assets updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

The purpose of an organisations risk management plan is to determine and establish the framework in which the project team will be able to identify and develop approaches to avoid these risks. Various types of risks exist within additive manufacturing, relating to material, systems and technologies, and technical knowledge. Risks can be identified through multiple qualitative and quantitative risk analysis efforts and these influential risks can be added to the project schedule. Once identified, the risk response must be planned, and mitigation must be implemented during the schedule. Risks should then be monitored, and regular status updates must be provided. During the closing process, the project manager needs to analyse each risk and the risk management process. This analysis will guide the project manager to identify additional improvements, required to manage the risk management process in future. This approach will tie in with leans' approach to an organisation's ability to learn from mistakes, to determine the root causes and development.

5.3.9. Project procurement management

The main focus from additive manufacturing is on the planning managing of procurement, although conducting and controlling of procurements included is in this knowledge area. The processes in this knowledge area deal with the obtaining of products, materials and services required to complete a project.

Table 5.11: Project procurement management (PMBOK, 2013:355), (Hartney, 2016)

	Project procurement management		
	Inputs	Tools & techniques	Outputs
Plan procurement management	• Project charter • Business documents • Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgment • Data gathering • Data analysis • Source selection analysis • Meetings	• Procurement management plan • Procurement strategy • Bid documents • Procurement statement of work • Source selection criteria • Make-or-buy decisions • Independent cost estimates • Change request • Project document updates • Organisational process assets updates
Conduct procurements	• Project management plan • Project documents • Procurement documentation • Seller proposals • Enterprise environmental factors • Organisational process assets	• Expert judgement • Advertising • Bidder conferences • Data analysis • Interpersonal and team skills	• Selected sellers • Agreements • Change requests • Project management plan updates • Project document updates • Organisational process assets updates

Control communications	• Project management plan • Project documents • Agreement • Procurement documentation • Approved change results • Work performance data • Enterprise environmental factors • Organisational process assets	• Expert judgment • Claims administration • Data analysis • Inspection • Audits	• Closed procurements • Work performance information • Procurement documentation updates • Change requests • Project management plan updates • Project documents updates • Organisational process assets updates

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

As mentioned earlier in this research, additive manufacturing relies on a different manufacturing supply chain. Compared to traditional manufacturing, which involves the following elements in order of production, distribution and retail; additive manufacturing follows a pattern of retail, production and lastly distribution. Additive manufacturing enters a digital phase (CAD, STL), manufacturing phase (machine setup, production part) and a post-process phase (cleaning and finishing). The planning and conducting of procurement need to take cognisance of the fact that retail will eventually focus on electronic platforms and that regional supply chains might expand at the expense of global chains. In a future manufacturing environment where the focus will be on customised and Internet-based products, the control of communication will be crucial. The planning and execution of procurement need to follow the project management plan and production closely.

5.3.10. Project stakeholder management

This knowledge area includes the Identification; the Planning, Managing and Monitoring of Stakeholder Engagement. The focus is on the planning process groups.

Table 5.12: Project stakeholder management (PMBOK, 2013:391), (Hartney, 2016)

	Project stakeholder management		
	Inputs	Tools & techniques	Outputs
Identify stakeholders	• Project charter • Business documents • Project management plan • Project documents • Agreements • Enterprise environmental factor	• Expert judgment • Data gathering • Data analysis • Data representation • Meetings	• Shareholder register • Change request • Project management plan updates • Project document updates
Plan stakeholder engagement	• Project management plan • Project documents • Procurement documentation • Seller proposals • Enterprise environmental factors • Organisational process	• Expert judgement • Data gathering • Data analysis • Decision making • Data representation • Meetings	• Stakeholder engagement plan
Manage stakeholder engagement	• Project management plan • Project documents • Enterprise environmental factors • Organisational process assets	• Expert judgment • Communication skills • Interpersonal and team skills • Ground rules • Meetings	• Change requests • Project management plan updates • Project documents updates
Monitor stakeholder engagement	• Project management plan • Project documents • Work performance data • Enterprise environmental factors • Organisational process assets	• Data analysis • Decision making • Data representation • Communication skills • Interpersonal and team skills • Meetings	• Work performance information • Change request • Project management plan/document update • Project documents

PM process groups focus areas

Initiating	Planning	Executing	Monitoring, Controlling	Closing

In additive manufacturing or any other business, it is important to determine which groups or individuals are stakeholders and who is not. It therefore becomes important to plan and manage the interest and needs of stakeholders. It is important to monitor the stakeholder engagement, as the primary stakeholders are crucial to the success and survival of an organisation. Reference to the project management plan is important as well as the stakeholder engagement plan. These engagements and interfaces might create value potential and show an organisation where and how value is created.

5.4. Lean project management framework for additive manufacturing

In reference to the definition of a framework in Chapter One (*cf.* 3.3), a framework is prescribed as a set of things to do, which helps to translate theory into practice through some systematic means. Table 5.13 illustrates the framework as developed through this Delphi study. The basis for the development was adopted from the PMBOK (2013) and the lean management principles as prescribed by Liker (2004: 35-47). A list of critical project success factors (CPSF's) was developed from the Delphi study in Chapter Four and integrated into the project management process groups and project management knowledge areas. These CPSF's are highlighted on the table in blue, using arrows and rectangles. The main areas of influence as suggested by respondents in terms of the mapped elements are highlighted in colours; initiation (yellow), planning (green), execution (orange), monitoring and controlling (blue) and closing (red). These processes interact through the course of the project via inherent inputs and outputs. Each of these processes serves as an informative guide to the project manager and project team, and **it is essential that the project management process should be adapted to the needs of each additive manufacturing project**.

Each project management knowledge area was discussed in the previous section, detailing the input, tools and techniques and the outputs. Most projects use the same set of processes to manage projects, and project managers are tasked to select the appropriate processes to comply with project requirements and balance the project constraints of schedule, scope and cost.

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Table 5.13: Lean project management framework for addditive manufacturing

Knowledge Areas	Initiating Process Group	Planning Process Group	Executing Process Group	Monitoring and Controlling Process Group	Closing Process Group
Project Integration Management	- Develop Project Charter.	- Develop PM Plan	- Direct and Manage Project Work. - Manage Project Knowledge.	- Monitor and Control Project Work. - Perform Integrated Change Control.	- Close Project or Phase.
Project Scope Management		- Plan Scope Management. - Collect Requirements. - Define Scope. - Create WBS.		- Validate Scope. - Control Scope.	
Project Schedule Management		- Plan Schedule Management. - Define Activities - Sequence Activities -Estimate Activity Resources - Estimate Activity Durations -Develop Schedule	Flow, Pull, Demand Manage Lead times, Flexible Production Standardised Production & Tasks	- Control Schedule Analyse Flow	
Project Cost Management		- Plan Cost Management - Estimate Costs - Determine Budget		- Control Costs	
Project Quality Management		- Plan Quality Management	- Manage Quality	- Control Quality	
Project Resources Management		- Plan Resource Management - Estimate Activity Resources Efficient Resource planning & usage, Continuity	- Acquired Resources - Develop Team Develop People - Manage Team Empower People	- Control Resources Evaluate Technology	
Project Communications Management		- Plan Communications Management.	- Manage Communications Supportive Technology; Organisation & Suppliers	- Monitor Communications Develop People	
Project Risk Management		- Plan Risk Management - Identify Risks - Perform Qualitative Risk Analysis - Perform Quantitative Risk Analysis - Plan Risk Responses	- Implement Responses Shortcomings & Consensus Efficient Communication & Root Causes	- Monitor Risks	
Project Procurement Management		- Plan Procurement management	- Conduct Procurements	- Control Procurements	
Project Stakeholder Management	- Identify Stakeholders	- Plan Stakeholder Engagement	Manage Stakeholder Engagement	- Monitor Stakeholder Engagement	

5.5. Summary

In this chapter the summary of the lean management principles, as analysed and discussed in Chapter Four, lead to the formulation of our critical project success factors (CPSF's). The project management process groups and project management knowledge areas were discussed and summarised, and the findings were used to deliver a project management framework within additive manufacturing. The CPSF's were integrated into the mapped project management process groups and knowledge areas to form the foundation of a lean project management framework for additive manufacturing.

In Chapter Six, the findings will be discussed in relation to the research objectives, as stated in Chapter One. The limitations, contributions will be considered, and recommendations will be made for future research.

6. Chapter Six: Conclusions and recommendations.

6.1. Introduction

In this chapter, the objective is to present the reader with conclusions that were drawn from this research regarding the development of a lean project management framework in additive manufacturing. In Chapter Six the researcher reviews the research questions as highlighted in the research and it will aim to answer the questions, based on the feedback provided in Chapters Four and Five. The feedback and answers to the questions will then be applied to the objective of this study, and it will be followed by a discussion on the Delphi technique which was applied in this research. The discussion will end with recommendations and potential follow-up research, as drawn from the feedback and results of this research.

6.2. Research objectives

The objective of this research was to analyse two important questions. The results acquired from the Delphi study were applied to these two questions to achieve a conclusion on the overall research objective of this study. Both statements and their results from this Delphi study are presented in the following.

1) To define and analyse to what degree, additive manufacturing (AM) can be described as a lean manufacturing technology.

This Delphi study presented several detailed designed questions to address the question above. It was found during this study that respondents agreed upon the topic, that additive manufacturing can be classified as a lean manufacturing technology.

2) To define and analyse what project management (PM) process groups and knowledge areas, influences the identified lean management principles, to create a framework for future project management in additive manufacturing.

Respondents agreed upon the process groups and knowledge areas and their contribution towards the development of a successful lean management framework for additive manufacturing.

6.3. Conclusions of the research

The research questions highlighted in the above, provided the necessary context and background to meet the objective of this research. The aim of this research was to determine what management principles are needed if the technology is classified as lean and what project management processes and knowledge area elements are required to develop a framework. Based on the answers provided by these two questions, the respondents in this Delphi study believes, that:

1) The management approach in additive manufacturing favours that of lean. Therefore, it can be classified as a lean technology. However, it is a technology which requires reliance on an organisation's philosophy, processes, people and partners; and the ability to solve problems.
2) A successful lean framework can be prescribed and utilised to manage projects in an additive manufacturing environment, but it is essential that the project management process should be adapted to the needs of each project.

It is the opinion of the researcher, that the statements drawn from the experts in this Delphi study, satisfy the research objectives.

6.4. Delphi application

The application of the Delphi technique proved to be successful in this research. This research method was chosen for its effectiveness to predict future alternatives or possibilities, and at the same time obtaining the views from a diverse panel of industry experts from around the world. This technique was instrumental in bringing the views together from participants and experts in the field of additive manufacturing, including those from industry and the academic environment. Although the panel of experts in this field was geographically separated, the study could analyse and generate a comprehensive opinion on the objectives of this study. Additionally, verbal responses from respondents regarding the topic and questionnaire affirmed the applicability of this subject knowledge in their particular technology environments. All the various feedback provided by respondents in this study therefore substantiated the use of the Delphi technique in this research.

6.5. Contribution of the research

This research, according to the researchers' knowledge, might be the first of its type to investigate the application of specific lean management principles in the management of projects in an additive manufacturing environment. The study appears to support the need for a comprehensive lean management approach to projects in additive manufacturing, and it could provide a baseline for further research. The knowledge provided through this research, could be used by additive manufacturing project managers to understand and promote the importance of lean as a management approach.

Chapter Two of this study contains a literature review on current additive manufacturing technologies and lean project management. This review confirms additive manufacturing as a disruptive technology and that technological changes should be developed in parallel with managerial changes and development.

Additionally, this research focussed on the need for an AM organisation to have a lean-based philosophy. This understanding of lean should be part of the whole organisation's culture, and that management should be actively involved in all daily operations and continuous improvement efforts. Being lean is all about how raw material is turned into the final product, the illumination of all non-value-added steps, and the reduction in value-added time.

Lastly, the research emphasised the importance of the ability to continually learn as an AM organisation, and it underscores the importance of teamwork and external partnerships with suppliers and clients.

6.6. Limitations of research

As with any research technique, including this Delphi study, this research was limited by the number of feedbacks it received from the original list of potential respondents. These experts were approached because of their proximity and expertise in the additive manufacturing environment. The researcher can, therefore, not claim the representativeness of the sample set, and it is pointed out that the applicability of the findings and conclusions are limited. The researcher, however, has full confidence in the design and execution of the study, and in the quality of experts and their responses.

6.7. Recommendations and future research

After having summarised the findings and conclusions, the following section highlights recommendations, based on the conducted research results and framework as supplied in Chapter Five. This research has produced several items for future research, and further analysis could expand upon the results of this study. The recommendations are discussed below, starting with the philosophy, initiation, planning, executing, monitoring and controlling, and closing processes.

Recommendation 1: "Philosophy"

Respondents agreed, having a solid company culture, which is based on simple achievable values, the understanding of people and their motivation, is important. Small AM start-up companies might feel that this step could be arbitrary, but it is an important function which should filter through the entire project management process of any size of business. It is therefore recommended that AM businesses should have well-devised strategies, good teamwork, solid culture, the ability to create leadership and continuity, always learn as accompany and maintain good client and customer relationships. Therefore, one of the main goals of an AM organisation should be one of firm survival, rebuking from to only concentrate on making money.

Recommendation 2: "The initiation process of AM projects"

The process of initiating projects focusses on the processes required to define and authorise new projects. The study shows that apart from focussing on the integration and stakeholder management alone, it might be beneficial if an additional degree or earlier focus is placed on the scope, schedule, cost, quality and risk management of projects in AM. Some of the important elements as highlighted in the planning process group could be integrated into this earlier stage of the initiation process. Consensus must be reached through informed decisions, and management need to be part of this process. It is recommended that project managers, management and employees place more focus during the initiation process, on elements connected with the scope, schedule, cost, quality and risk management. The aforementioned recommendation, however, can only be recommended and confirmed, by future research.

Recommendation 3: "The planning process of AM projects"

The planning process of projects provides project managers with guidelines to combine all the details necessary to complete projects phases. The study has demonstrated that the planning process in additive manufacturing is vitally important, as it is in any other manufacturing industry. The project management plan and the definition of the scope plays an important role, along with the schedule, cost and quality management. Additionally, the focus was placed on communications, procurement and stakeholder management. The study has revealed that during schedule management additional focus has to be placed on the demands from customers and during the planning process cognisance must be taken of the continuous flow of processes and activities. Additive manufacturing lends itself to a one-piece flow production cell, and looking at pull, it will create an ideal just-in-time manufacturing environment. According to respondents, a one-piece flow production cell is vital to cut out any wasted efforts which are not contributing to the end product. Attempts to pre-determine any pre-empt waste efforts, could be discussed and implemented during the planning process. It is therefore recommended that incorporating these lean elements into the main planning processes of additive manufacturing, be investigated in future research. Although less focus from the response was placed on the resource and risk management of projects, resource management still required the planning and efficient utilisation of resources, and continuity must be seen as part of an organisations' future resource planning efforts.

Recommendation 4: "The executing process of AM projects"

The execution of projects consists of the processes defined in the project management plan. These completed projects need to satisfy planned specifications, and it involves integration and coordination of people and all other resources. The study revealed that this process group focused on the integration, schedule, quality, resources and communications management in additive manufacturing. Project schedule management, as in planning, required an integrated look at flow, customer demand and pull. It is recommended that the importance of standardised production and tasks be highlighted, with emphasis on the management of lead times and flexible production during schedule management. Feedback has revealed that additive manufacturing allows itself to be seen as a one-piece-flow production system, producing according to customer demand, ensuring flexibility, while reducing the risk of unsold goods. Although the public image of additive manufacturing might be such, that it is viewed as a manufacturing technology, requiring minimal human interventions, the management of resources was highlighted as important. Therefore, it is recommended that employees must be developed to such a level, where they are empowered to find the root cause of problems, make decisions and implement important solutions. The study also revealed that to execute project management, efficient communication and supportive technology is recommended during the executing process.

Recommendation 5: "The monitoring and controlling process of AM projects"

The aim of monitoring and controlling projects is to track, review and regulate the progress and performance of projects. The results delivered from this study revealed that focus needs to be placed on the control of schedules, cost and quality and that communications need to be monitored. It is recommended that flow is analysed during the scheduling process and it requires the support of standardised production and tasks in the organisation. The study revealed that quality is similarly dependant on the monitoring and controlling process of products in additive manufacturing. It is recommended that built-in quality mechanisms should be employed and that problems should be immediately solved as they occur to save time, eliminate waste and increase productivity. It is recommended that employed technology always be evaluated to support this effort and that employees are developed to give the organisation the necessary support to focus on any shortcomings and root causes of problems.

Recommendation 6: "The closing process of projects"

The closing process' purpose is to close or complete a project formally, and although PMBOK (2013) only prescribes one element in this process, feedback from the study indicated that closing a project or phase relies on the schedule, cost, quality, communications and stakeholder engagements. It is recommended that each of these elements warrants future research and analysis.

6.8. Conclusion

The research has determined that additive manufacturing can be classified as a lean manufacturing technology and that it requires a different approach to project management, compared to traditional or conventional manufacturing.

The product of this research study is a framework, and it is essential to note that the detail for each project environment can differ radically. The framework details for individual project environments, however, falls outside of the scope of this research study.

This application of the prescribed framework is currently untested, but the conclusions made from the respondents' feedback, is that it would be beneficial for an additive manufacturer to apply the recommendations into their project management process. The recommendations are open for further research to refine and verify the results.

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Appendix

Appendix A: Delphi questionnaire

The aim of this study is to present a lean project management framework for the additive manufacturing industry (AM). This framework will contain critical elements of project management (PM) and will intend to add value to an organisation by outlining a body of knowledge, processes, skills, tools, and techniques. This will aim to improve the efficiency and performance within an AM organisation.

The PM framework will be developed from a lean perspective and focusses on the core idea of maximising customer value while minimising waste. The fundamental purpose is to improve productivity, improve the quality of products, to make production more flexible and to essentially reduce waste within an AM environment. This all will be defined within the main constraints of time, cost, scope, quality and good customer relationships.

The study will focus on the primary question, that if AM is identified as a lean manufacturing technology, how do AM organisations manage their design and development projects. The research will focus on the development of a framework, using the Delphi method, for the implementation of lean principles to AM project management.

The following research sub-questions are highlighted:

1) Research sub-question 1: To what degree, as agreed upon by the experts, can AM be described as a lean manufacturing technology?

2) Research sub-question 2: What PM processes and knowledge areas, influences the identified lean management principles, to create a framework for future project management in AM.?

1. Please indicate the type of organisation in which you currently work primarily (that is, 50% or more of your time).

2. Please specify your role; that is, the one in which you currently work primarily (that is, 50% or more of your time).

3. Indicate the country in which your work is based. (Drop-down menu)

4. T**he mission** of a company should never be focused on making money or KPI performance (short-term) but should consist of three parts: contribute to the growth of the economy, the well-being of employees and the growth of the company. Making money is just a requirement to achieve these three.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

5. To what extent, in your opinion, does the following PM knowledge areas play a significant role in the Initiation process of AM projects?

Influence / PM Area	Best Practice (5)	Very Good (4)	Good (3)	Fair (2)	Weak (1)	Non (0)
Integration						
Scope						
Time						
Cost						
Quality						
Human Resources						
Communication						
Risk						
Procurement						
Stakeholders						

6. To what extent, in your opinion, does the following PM knowledge areas play a significant role in the Planning process of AM projects?

Influence / PM	Best Practice	Very Good	Good	Fair	Weak	Non

Area	(5)	(4)	(3)	(2)	(1)	(0)
Integration						
Scope						
Time						
Cost						
Quality						
Human Resources						
Communication						
Risk						
Procurement						
Stakeholders						

7. Flow is a way in which all types of waste are defined, and the creation of a continuous process flow system is advised. To what extend does the following types of waste occur in an AM environment?

Type of Waste / Extend	Excessive (5)	Very Large (4)	Large (3)	Low (2)	Very Low (1)	Non (0)
Overproduction						
Waiting (time-on-hand)						
Unnecessary Transport						
Over or incorrect processing						
Excess inventory						
Unnecessary movement						
Defects						
Unused employee creativity						

8. Not every part of a process can be done as a one-piece flow. To avoid overproduction, pull systems should be used, ensuring that material should only be delivered exactly what, when and in the correct amount.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

9. It is often best to level out the work load or production schedule to create a true balanced flow of work. Levelling out work schedules are easier in high-volume manufacturing compared to low-volume service environments. To what extend are the benefits below applicable in AM?

Extend / Benefits	Excessive (5)	Very Large (4)	Large (3)	Low (2)	Very Low (1)	Non (0)
Flexibility to make for the customer, what and when they want it.						
Reduced risk of unsold goods.						
Balanced use of labour and machines.						
Smoothed demand on upstream processes and suppliers.						

10. Overburdening of people and/or equipment, or unevenness (over or under allocation of work to people and equipment are applicable in AM.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

11. Quality should be a built-in mechanism and defects detected immediately when they occur.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

12. Problems should be anticipated as early as possible and countermeasures should be put in place before problems occur.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

13. To what extent, in your opinion, does the following PM knowledge areas play a significant role in the Execution process of AM projects?

Influence / PM Area	Best Practice (5)	Very Good (4)	Good (3)	Fair (2)	Weak (1)	Non (0)
Integration						
Scope						
Time						
Cost						
Quality						
Human Resources						
Communication						
Risk						
Procurement						
Stakeholders						

14. To build in quality, any process needs to be standardised and stable. How important are the following elements?

Extend / Elements	Excessive (5)	Very Large (4)	Large (3)	Low (2)	Very Low (1)	Non (0)
The time required to complete one job according to customer demand.						
The sequence of processes or of doing things						
The inventory on hand needed to accomplish the required standardised work.						

15. An employee is regarded as the most important valuable resource, analyst and problem solver, this ultimately forms the basis for flexibility and innovation.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

16. To avoid hidden problems visual controls should be integrated into processes of the value-added work. It should be able to visually inspect a process, a piece of equipment, inventory or a worker performing a job according to standards.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

17. Only reliable, thoroughly tested technology which works should be implemented without employee resistance and process disruption.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

18. Actual manufacturing situations should be observed in detail and it is necessary to understand how work gets done in the manufacturing environment. How important are the following elements?

Extend / Elements	Very Important (4)	Important (3)	Low Importance (2)	Very Low (1)	Non (0)
Focus on a long-term purpose for the company and add value to society.					
Never deviate from the company's principals.					
Work your way up doing the detailed work and always go where the work is being done.					
Saw problems as opportunities to train and coach people.					

19. To what extent, in your opinion, does the following PM knowledge areas play a significant role in the Monitoring and Controlling process of AM projects?

Influence / PM	Best Practice	Very Good	Good	Fair	Weak	Non

Area	(5)	(4)	(3)	(2)	(1)	(0)
Integration						
Scope						
Time						
Cost						
Quality						
Human Resources						
Communication						
Risk						
Procurement						
Stakeholders						

20. In industry a lot of focus is placed on how to streamline supply chains through advanced information technology and very little on how to forge relationships across firms and working together towards a common goal. How important are the following elements in an AM environment?

Extend / Elements	Very Important (4)	Important (3)	Low Importance (2)	Very Low (1)	Non (0)
Creating partnerships with suppliers.					
Maintain internal capabilities.					
Core technology knowledge and responsibilities are not transferred to suppliers.					
Suppliers needs to be as competent as its own in delivering product, components and materials.					

21. True learning as an enterprise suggests that relationships between your own business and suppliers must be stabilised to the point where the business relationship is fair, processes are stable, and expectations are clear.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

22. What is seen first-hand on the manufacturing floor does not always show up in reports. Participants must be encouraged to see and experience problems on the production floor at first hand and have an open mind and ask the question “why” to every matter.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

23. The key to decision making is that a great deal of learning should take place upfront before a decision is made, planned or implemented. All relevant parties should get involved, all facts must be uncovered, and resistance worked out through consensus and support before anything is implemented.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

24. Adaptation, innovation and flexibility have become the necessary ingredients for survival and the hallmarks of a successful business. To sustain these elements of such organisational behavior, it requires one key component: the ability to learn.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

25. Most problems do not call for complex statistical tools, but requires detailed problem solving. This detailed thinking and analysis is a matter of discipline, attitude and culture. True problem solving requires finding the root cause rather than the source of the problem. The answer is achieved by searching deeper, by asking why the problem occurred.

Strongly Agree (5)	Agree (4)	Disagree (3)	Strongly Disagree (2)	No view (0)

26. To what extent, in your opinion, does the following PM knowledge areas play a significant role in the Closing process of AM projects?

Influence / PM Area	Best Practice (5)	Very Good (4)	Good (3)	Fair (2)	Weak (1)	Non (0)
Integration						

Scope						
Time						
Cost						
Quality						
Human Resources						
Communication						
Risk						
Procurement						
Stakeholders						

Appendix B: Accompanied letter

The application of AM technology in the early phases of development was limited to the production of prototypes. The real opportunity this technology provides us, is the replacement of conventional production technologies for serial manufacturing of components or products.

The dynamic nature of additive manufacturing affords it a level of flexibility unmatched by standard manufacturing processes; however, this advantage has historically been coupled with slow build times, limited material options, high costs, and poor quality. These characteristics largely restricted the use of additive manufacturing to low function prototyping and production of consumer trinkets.

The last few years, however, have been a period of additive manufacturing enlightenment as research in material science, innovation in additive manufacturing processes, and advances in additive manufacturing-related engineering software have converged to elevate additive manufacturing into the industrial manufacturing domain.

Although the focus may seem to be tilted towards small and medium design and development projects in AM organisations, this research is done against the backdrop of future mass additive manufacturing. Factors that are applied in a small manufacturing environment could well be applied in future mass AM environments. This survey is carried out to learn more about your opinion and/or experience with regard to the employed approach when managing projects in AM. The questionnaire focuses on the factors AM organisations require to manage projects.

The questionnaire is part of a research project conducted by Eugene Zeelie as part of his Masters Research Thesis at the Northwest University, South Africa. The project is supervised by Prof. Harry Wichers, Director, School of Mechanical and Nuclear Engineering, Potchestroom Campus. Please answer the questions freely. **All data will be treated in the strictest confidence and you will not be identified from the information you provide.** Under no circumstances will your individual replies made available to anyone except the researcher.

The questionnaire should take about 10 minutes to complete. **Your answers are essential to build an accurate picture of the issues that are important for the research project and will contribute to the management process of projects in AM.**

Please return completed questionnaire via the provided online platform.

Thank you for your interest and participation in the study and assistance through completion of the questionnaire.

Appendix C: Survey feedback

A Lean Project Management Framework for Additive Manufacturing. SurveyMonkey

Q1 Please indicate the type of department within your organization in which you currently work primarily (that is, 50% or more of your time).

Answered: 12 Skipped: 0

Q2 Please specify your role; that is, the one in which you currently work primarily (that is, 50% or more of your time).

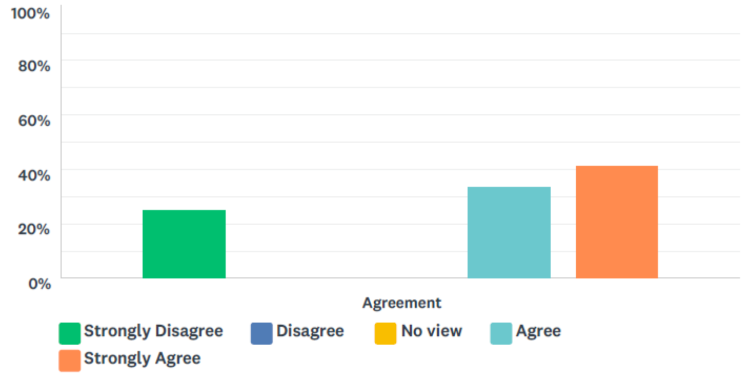
Answered: 12 Skipped: 0

Q3 Indicate the country in which your work is based

Answered: 12 Skipped: 0

Q4 The mission of a company should never be focused on profit making or KPI performance (short-term) but should consist of three parts: contribute to the growth of the economy, the well-being of employees and the growth of the company. Profit-making is a requirement to achieve these three.

Answered: 12 Skipped: 0

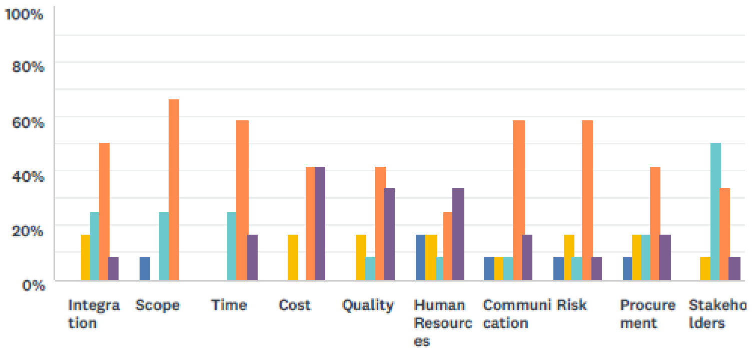


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	25% 3	0% 0	0% 0	33% 4	42% 5	12	3.67

BASIC STATISTICS				
Minimum 1.00	Maximum 5.00	Median 4.00	Mean 3.67	Standard Deviation 1.60

Q5 To what extent, in your opinion, does the following project management (PM) knowledge areas play a significant role in the Initiation (scope, deliverables, etc.) process of additive manufacturing (AM) projects?

Answered: 12 Skipped: 0



	NON (1)	WEAK (2)	FAIR (3)	GOOD (4)	VERY GOOD (5)	BEST PRACTICE (6)	TOTAL	WEIGHTED AVERAGE
Integration	0% 0	0% 0	17% 2	25% 3	50% 6	8% 1	12	3.50
Scope	0% 0	8% 1	0% 0	25% 3	67% 8	0% 0	12	3.50
Time	0% 0	0% 0	0% 0	25% 3	58% 7	17% 2	12	3.92
Cost	0% 0	0% 0	17% 2	0% 0	42% 5	42% 5	12	4.08
Quality	0% 0	0% 0	17% 2	8% 1	42% 5	33% 4	12	3.92
Human Resources	0% 0	17% 2	17% 2	8% 1	25% 3	33% 4	12	3.42
Communication	0% 0	8% 1	8% 1	8% 1	58% 7	17% 2	12	3.67
Risk	0% 0	8% 1	17% 2	8% 1	58% 7	8% 1	12	3.42
Procurement	0% 0	8% 1	17% 2	17% 2	42% 5	17% 2	12	3.42
Stakeholders	0% 0	0% 0	8% 1	50% 6	33% 4	8% 1	12	3.42

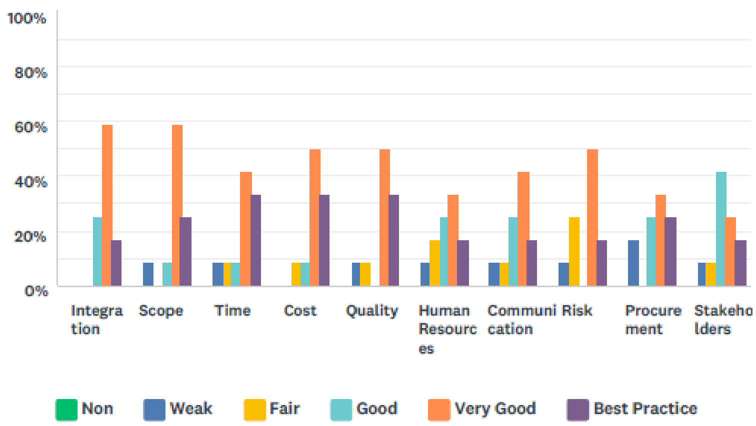
BASIC STATISTICS

	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION

Integration	3.00	6.00	5.00	4.50	0.87
Scope	2.00	5.00	5.00	4.50	0.87
Time	4.00	6.00	5.00	4.92	0.64
Cost	3.00	6.00	5.00	5.08	1.04
Quality	3.00	6.00	5.00	4.92	1.04
Human Resources	2.00	6.00	5.00	4.42	1.50
Communication	2.00	6.00	5.00	4.67	1.11
Risk	2.00	6.00	5.00	4.42	1.11
Procurement	2.00	6.00	5.00	4.42	1.19
Stakeholders	3.00	6.00	4.00	4.42	0.76

Q6 To what extent, in your opinion, does the following project management (PM) knowledge areas play a significant role in the Planning process of additive manufacturing (AM) projects?

Answered: 12 Skipped: 0



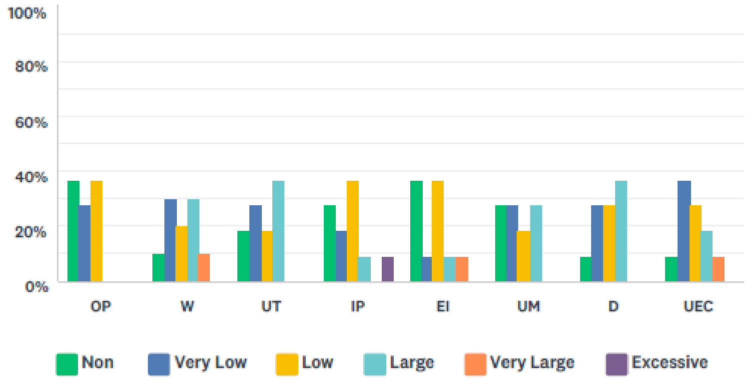
	NON (1)	WEAK (2)	FAIR (3)	GOOD (4)	VERY GOOD (5)	BEST PRACTICE (6)	TOTAL	WEIGHTED AVERAGE
Integration	0% 0	0% 0	0% 0	25% 3	58% 7	17% 2	12	3.92
Scope	0% 0	8% 1	0% 0	8% 1	58% 7	25% 3	12	3.92
Time	0% 0	8% 1	8% 1	8% 1	42% 5	33% 4	12	3.83
Cost	0% 0	0% 0	8% 1	8% 1	50% 6	33% 4	12	4.08
Quality	0% 0	8% 1	8% 1	0% 0	50% 6	33% 4	12	3.92
Human Resources	0% 0	8% 1	17% 2	25% 3	33% 4	17% 2	12	3.33
Communication	0% 0	8% 1	8% 1	25% 3	42% 5	17% 2	12	3.50
Risk	0% 0	8% 1	25% 3	0% 0	50% 6	17% 2	12	3.42
Procurement	0% 0	17% 2	0% 0	25% 3	33% 4	25% 3	12	3.50
Stakeholders	0% 0	8% 1	8% 1	42% 5	25% 3	17% 2	12	3.33

BASIC STATISTICS

	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION
Integration	4.00	6.00	5.00	4.92	0.64

Q7 Flow is a way in which all types of waste are defined, and the creation of a continuous process flow system is advised. To what extent do the following types of waste occur in an additive manufacturing (AM) environment?

Answered: 11 Skipped: 1

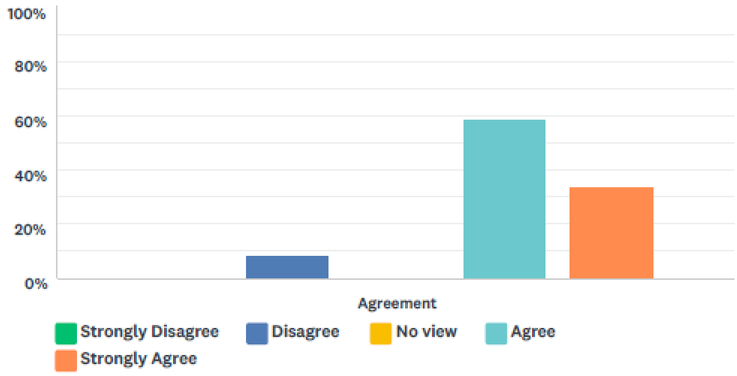


	NON (1)	VERY LOW (2)	LOW (3)	LARGE (4)	VERY LARGE (5)	EXCESSIVE (6)	TOTAL	WEIGHTED AVERAGE
OP	36% 4	27% 3	36% 4	0% 0	0% 0	0% 0	11	1.00
W	10% 1	30% 3	20% 2	30% 3	10% 1	0% 0	10	2.00
UT	18% 2	27% 3	18% 2	36% 4	0% 0	0% 0	11	1.73
IP	27% 3	18% 2	36% 4	9% 1	0% 0	9% 1	11	1.64
EI	36% 4	9% 1	36% 4	9% 1	9% 1	0% 0	11	1.45
UM	27% 3	27% 3	18% 2	27% 3	0% 0	0% 0	11	1.45
D	9% 1	27% 3	27% 3	36% 4	0% 0	0% 0	11	1.91
UEC	9% 1	36% 4	27% 3	18% 2	9% 1	0% 0	11	1.82

BASIC STATISTICS	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION
OP	1.00	3.00	2.00	2.00	0.85
W	1.00	5.00	3.00	3.00	1.18
UT	1.00	4.00	3.00	2.73	1.14
IP	1.00	6.00	3.00	2.64	1.43
EI	1.00	5.00	3.00	2.45	1.30
UM	1.00	4.00	2.00	2.45	1.16
D	1.00	4.00	3.00	2.91	1.00
UEC	1.00	5.00	3.00	2.82	1.11

Q8 Not every part of a process can be done as a one-piece flow. To avoid overproduction, pull systems can be used, ensuring that parts/products should only be delivered exactly what, when and in the correct amount.

Answered: 12 Skipped: 0

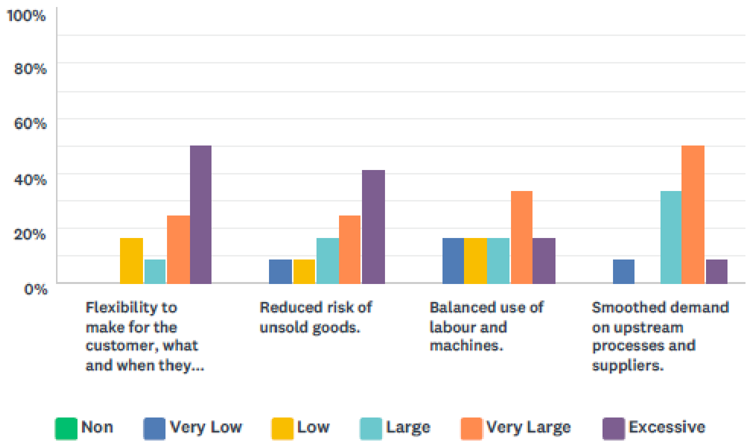


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	8% 1	0% 0	58% 7	33% 4	12	4.17

BASIC STATISTICS				
Minimum 2.00	Maximum 5.00	Median 4.00	Mean 4.17	Standard Deviation 0.80

Q9 It is often best to level out the workload or production schedule to create a true balanced flow of work. Leveling out work schedules are easier in high-volume manufacturing compared to low-volume service environments. To what extent are the benefits below applicable in additive manufacturing (AM)?

Answered: 12 Skipped: 0



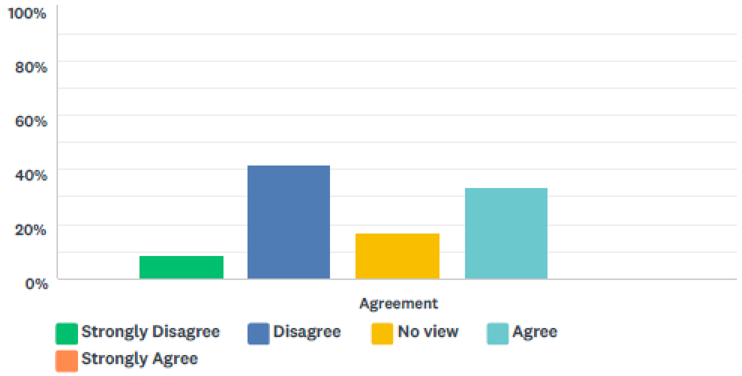
	NON (1)	VERY LOW (2)	LOW (3)	LARGE (4)	VERY LARGE (5)	EXCESSIVE (6)	TOTAL	WEIGHTED AVERAGE
Flexibility to make for the customer, what and when they want it.	0% 0	0% 0	17% 2	8% 1	25% 3	50% 6	12	4.08
Reduced risk of unsold goods.	0% 0	8% 1	8% 1	17% 2	25% 3	42% 5	12	3.83
Balanced use of labour and machines.	0% 0	17% 2	17% 2	17% 2	33% 4	17% 2	12	3.17
Smoothed demand on upstream processes and suppliers.	0% 0	8% 1	0% 0	33% 4	50% 6	8% 1	12	3.50

BASIC STATISTICS

	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION
Flexibility to make for the customer, what and when they want it.	3.00	6.00	5.50	5.08	1.11
Reduced risk of unsold goods.	2.00	6.00	5.00	4.83	1.28
Balanced use of labour and machines.	2.00	6.00	4.50	4.17	1.34
Smoothed demand on upstream processes and suppliers.	2.00	6.00	5.00	4.50	0.96

Q10 Overburdening of people and/or equipment, or unevenness (over or under allocation) of work to people and equipment are applicable in additive manufacturing (AM).

Answered: 12 Skipped: 0

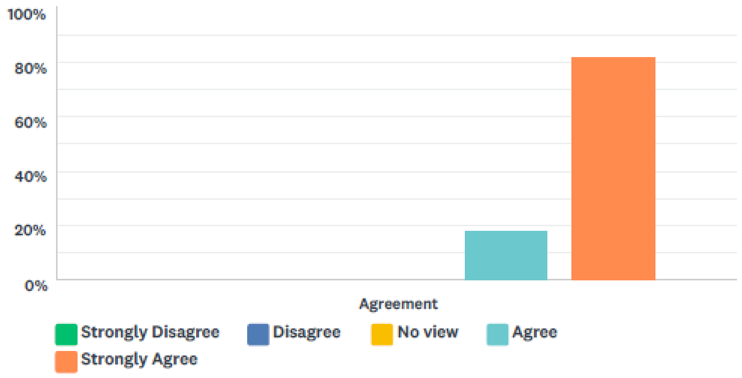


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	8% 1	42% 5	17% 2	33% 4	0% 0	12	2.75

BASIC STATISTICS				
Minimum 1.00	Maximum 4.00	Median 2.50	Mean 2.75	Standard Deviation 1.01

Q11 Quality should be a built-in mechanism and defects detected immediately when they occur.

Answered: 11 Skipped: 1

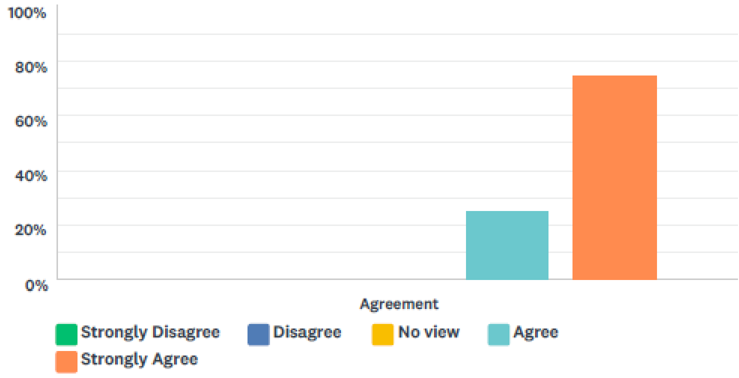


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	18% 2	82% 9	11	4.82

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 5.00	Mean 4.82	Standard Deviation 0.39

Q12 Problems should be anticipated as early as possible and countermeasures should be put in place before problems occur.

Answered: 12 Skipped: 0

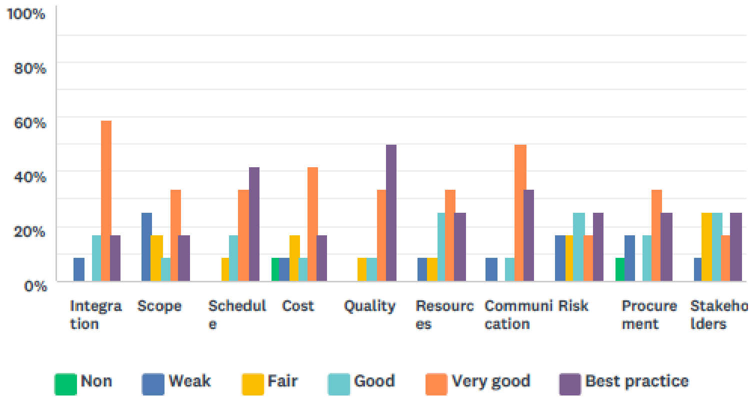


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	25% 3	75% 9	12	4.75

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 5.00	Mean 4.75	Standard Deviation 0.43

Q13 To what extent, in your opinion, does the following project management (PM) knowledge areas play a significant role in the Execution process of additive manufacturing (AM) projects?

Answered: 12 Skipped: 0



	NON (1)	WEAK (2)	FAIR (3)	GOOD (4)	VERY GOOD (5)	BEST PRACTICE (6)	TOTAL	WEIGHTED AVERAGE
Integration	0% 0	8% 1	0% 0	17% 2	58% 7	17% 2	12	3.75
Scope	0% 0	25% 3	17% 2	8% 1	33% 4	17% 2	12	3.00
Schedule	0% 0	0% 0	8% 1	17% 2	33% 4	42% 5	12	4.08
Cost	8% 1	8% 1	17% 2	8% 1	42% 5	17% 2	12	3.17
Quality	0% 0	0% 0	8% 1	8% 1	33% 4	50% 6	12	4.25
Resources	0% 0	8% 1	8% 1	25% 3	33% 4	25% 3	12	3.58
Communication	0% 0	8% 1	0% 0	8% 1	50% 6	33% 4	12	4.00
Risk	0% 0	17% 2	17% 2	25% 3	17% 2	25% 3	12	3.17
Procurement	8% 1	17% 2	0% 0	17% 2	33% 4	25% 3	12	3.25
Stakeholders	0% 0	8% 1	25% 3	25% 3	17% 2	25% 3	12	3.25

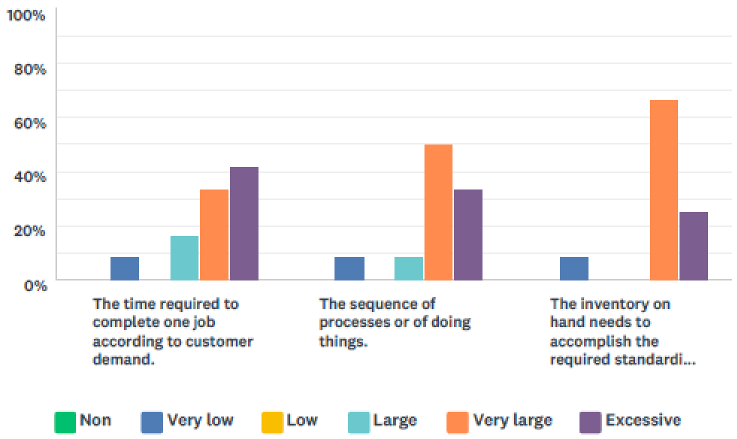
BASIC STATISTICS

	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION
Integration	2.00	6.00	5.00	4.75	1.01

Scope	2.00	6.00	4.50	4.00	1.47
Schedule	3.00	6.00	5.00	5.08	0.95
Cost	1.00	6.00	5.00	4.17	1.52
Quality	3.00	6.00	5.50	5.25	0.92
Resources	2.00	6.00	5.00	4.58	1.19
Communication	2.00	6.00	5.00	5.00	1.08
Risk	2.00	6.00	4.00	4.17	1.40
Procurement	1.00	6.00	5.00	4.25	1.64
Stakeholders	2.00	6.00	4.00	4.25	1.30

Q14 To build in quality, any process needs to be standardised and stable. What are the importance of the following elements?

Answered: 12 Skipped: 0

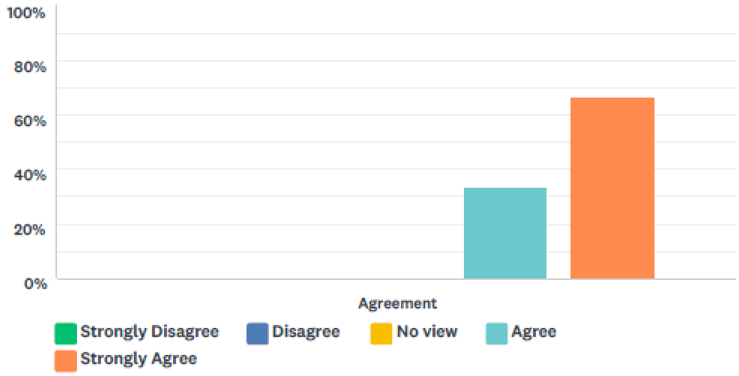


	NON (1)	VERY LOW (2)	LOW (3)	LARGE (4)	VERY LARGE (5)	EXCESSIVE (6)	TOTAL	WEIGHTED AVERAGE
The time required to complete one job according to customer demand.	0% 0	8% 1	0% 0	17% 2	33% 4	42% 5	12	4.00
The sequence of processes or of doing things.	0% 0	8% 1	0% 0	8% 1	50% 6	33% 4	12	4.00
The inventory on hand needs to accomplish the required standardised work.	0% 0	8% 1	0% 0	0% 0	67% 8	25% 3	12	4.00

BASIC STATISTICS	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION
The time required to complete one job according to customer demand.	2.00	6.00	5.00	5.00	1.15
The sequence of processes or of doing things.	2.00	6.00	5.00	5.00	1.08
The inventory on hand needs to accomplish the required standardised work.	2.00	6.00	5.00	5.00	1.00

Q15 An employee is regarded as the most important valuable resource, analyst and problem solver, this ultimately forms the basis for flexibility and innovation.

Answered: 12 Skipped: 0

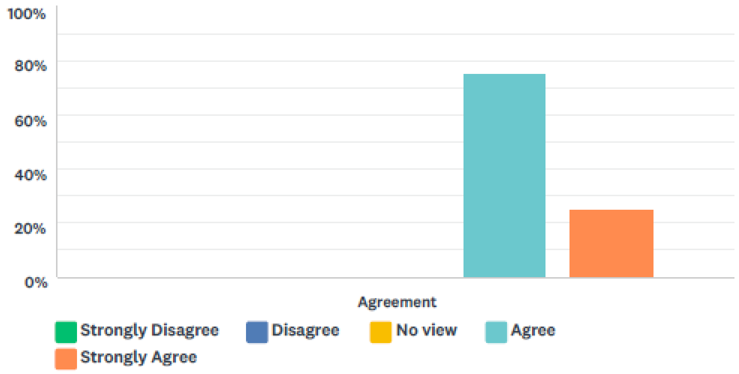


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	33% 4	67% 8	12	4.67

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 5.00	Mean 4.67	Standard Deviation 0.47

Q16 To avoid hidden problems visual controls should be integrated into processes of the value-added work. It should be able to visually inspect a process, a piece of equipment, inventory or a worker performing a job according to standards.

Answered: 12 Skipped: 0

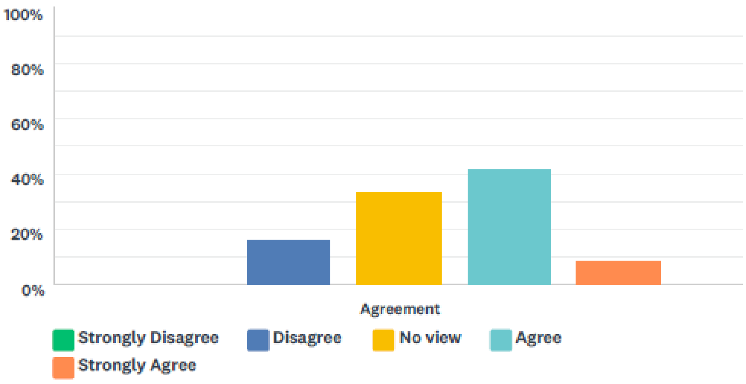


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	75% 9	25% 3	12	4.25

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 4.00	Mean 4.25	Standard Deviation 0.43

Q17 Only reliable and thoroughly tested technology should be implemented without employee resistance and process disruption.

Answered: 12 Skipped: 0

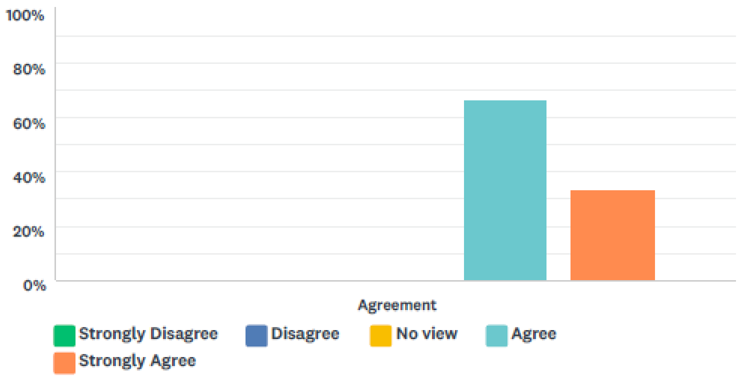


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	17% 2	33% 4	42% 5	8% 1	12	3.42

BASIC STATISTICS				
Minimum 2.00	Maximum 5.00	Median 3.50	Mean 3.42	Standard Deviation 0.86

Q18 Actual manufacturing situations should be observed in detail and it is necessary to understand how work gets done in the manufacturing environment.

Answered: 12 Skipped: 0

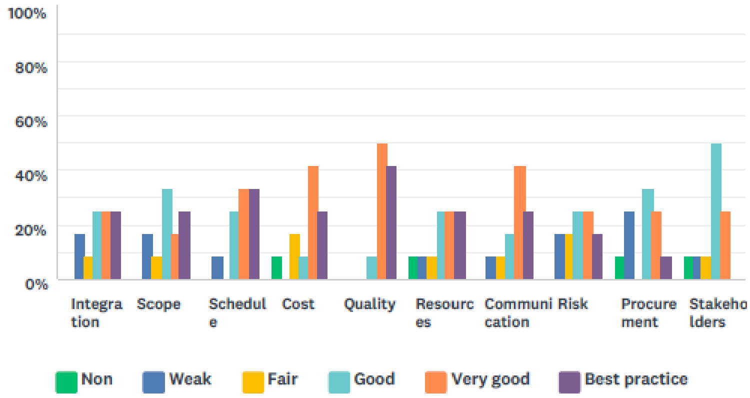


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	67% 8	33% 4	12	4.33

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 4.00	Mean 4.33	Standard Deviation 0.47

Q19 To what extent, in your opinion, does the following PM knowledge areas play a significant role in the Monitoring and Controlling process of AM projects?

Answered: 12 Skipped: 0



	NON (1)	WEAK (2)	FAIR (3)	GOOD (4)	VERY GOOD (5)	BEST PRACTICE (6)	TOTAL	WEIGHTED AVERAGE
Integration	0% 0	17% 2	8% 1	25% 3	25% 3	25% 3	12	3.33
Scope	0% 0	17% 2	8% 1	33% 4	17% 2	25% 3	12	3.25
Schedule	0% 0	8% 1	0% 0	25% 3	33% 4	33% 4	12	3.83
Cost	8% 1	0% 0	17% 2	8% 1	42% 5	25% 3	12	3.50
Quality	0% 0	0% 0	0% 0	8% 1	50% 6	42% 5	12	4.33
Resources	8% 1	8% 1	8% 1	25% 3	25% 3	25% 3	12	3.25
Communication	0% 0	8% 1	8% 1	17% 2	42% 5	25% 3	12	3.67
Risk	0% 0	17% 2	17% 2	25% 3	25% 3	17% 2	12	3.08
Procurement	8% 1	25% 3	0% 0	33% 4	25% 3	8% 1	12	2.67
Stakeholders	8% 1	8% 1	8% 1	50% 6	25% 3	0% 0	12	2.75

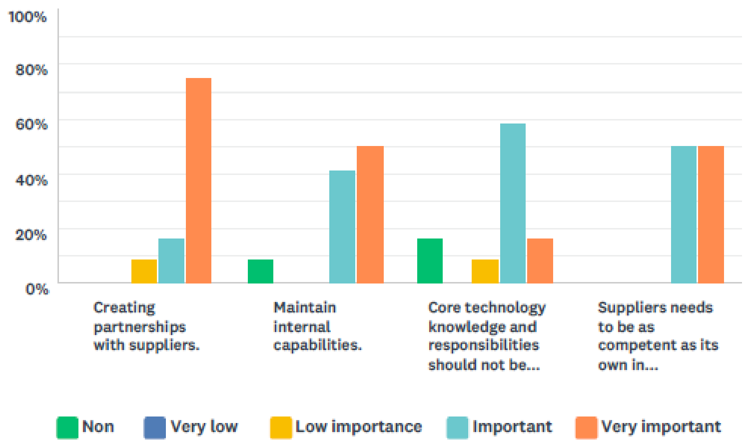
BASIC STATISTICS

	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION
Integration	2.00	6.00	4.50	4.33	1.37

Scope	2.00	6.00	4.00	4.25	1.36
Schedule	2.00	6.00	5.00	4.83	1.14
Cost	1.00	6.00	5.00	4.50	1.44
Quality	4.00	6.00	5.00	5.33	0.62
Resources	1.00	6.00	4.50	4.25	1.53
Communication	2.00	6.00	5.00	4.67	1.18
Risk	2.00	6.00	4.00	4.08	1.32
Procurement	1.00	6.00	4.00	3.67	1.49
Stakeholders	1.00	5.00	4.00	3.75	1.16

Q20 In industry, the focus is placed on how to streamline supply chains through advanced information technology and very little on how to forge relationships across firms and working together towards a common goal. What are the importance of the following elements in an additive manufacturing (AM) environment?

Answered: 12 Skipped: 0



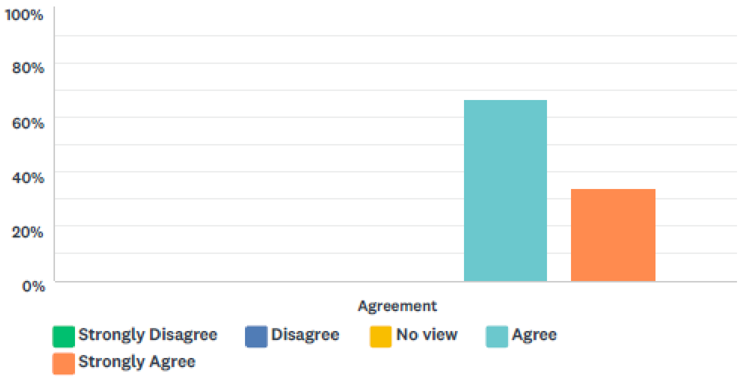
	NON (1)	VERY LOW (2)	LOW IMPORTANCE (3)	IMPORTANT (4)	VERY IMPORTANT (5)	TOTAL	WEIGHTED AVERAGE
Creating partnerships with suppliers.	0% 0	0% 0	8% 1	17% 2	75% 9	12	3.67
Maintain internal capabilities.	8% 1	0% 0	0% 0	42% 5	50% 6	12	3.25
Core technology knowledge and responsibilities should not be transferred to suppliers.	17% 2	0% 0	8% 1	58% 7	17% 2	12	2.58
Suppliers needs to be as competent as its own in delivering product, components and materials.	0% 0	0% 0	0% 0	50% 6	50% 6	12	3.50

BASIC STATISTICS

	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION
Creating partnerships with suppliers.	3.00	5.00	5.00	4.67	0.62
Maintain internal capabilities.	1.00	5.00	4.50	4.25	1.09
Core technology knowledge and responsibilities should not be transferred to suppliers.	1.00	5.00	4.00	3.58	1.26
Suppliers needs to be as competent as its own in delivering product, components and materials.	4.00	5.00	4.50	4.50	0.50

Q21 True learning as an enterprise suggests that relationships between your own business and suppliers must be stabilised to the point where the business relationship is fair, processes are stable, and expectations are clear.

Answered: 12 Skipped: 0

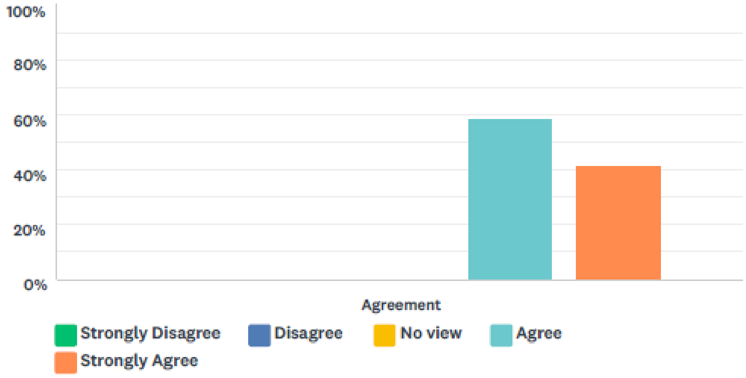


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	67% 8	33% 4	12	4.33

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 4.00	Mean 4.33	Standard Deviation 0.47

Q22 What is seen first-hand in the manufacturing environment does not always show up in reports. Participants must be encouraged to see and experience problems on the production floor at first hand and have an open mind and ask the question "why" to every matter.

Answered: 12 Skipped: 0

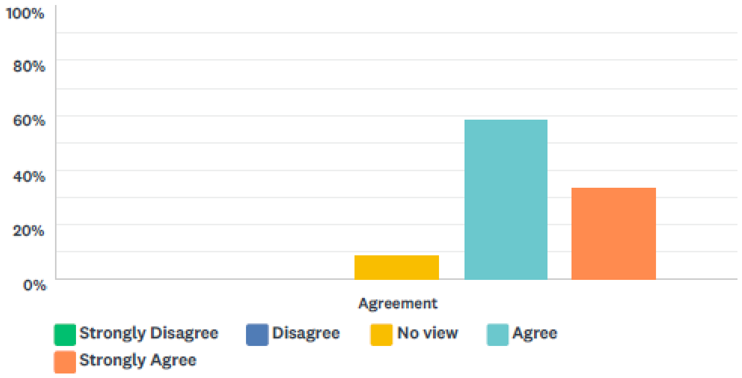


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	58% 7	42% 5	12	4.42

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 4.00	Mean 4.42	Standard Deviation 0.49

Q23 The key to decision making is that a great deal of learning should take place upfront before a decision is made, planned or implemented. All relevant parties should get involved, all facts must be uncovered, and resistance worked out through consensus and support before implementation takes place.

Answered: 12 Skipped: 0

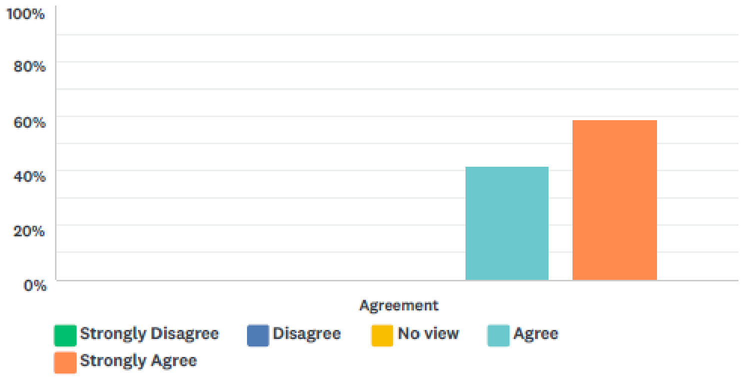


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	8% 1	58% 7	33% 4	12	4.25

BASIC STATISTICS				
Minimum 3.00	Maximum 5.00	Median 4.00	Mean 4.25	Standard Deviation 0.60

Q24 Adaptation, innovation, and flexibility have become the necessary ingredients for survival and the hallmarks of a successful business. To sustain these elements of such organisational behaviour, it requires one key component: the ability to learn.

Answered: 12 Skipped: 0

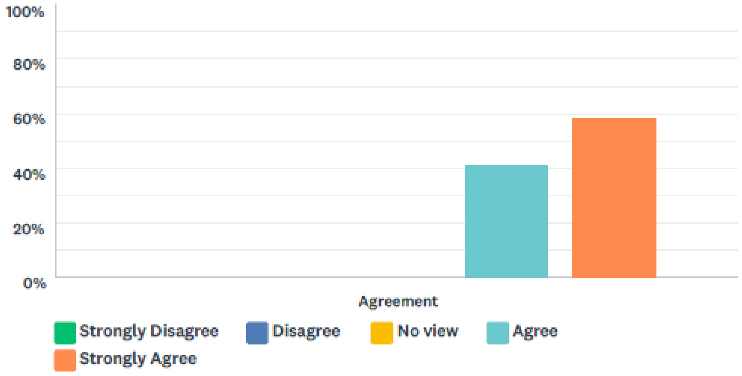


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	42% 5	58% 7	12	4.58

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 5.00	Mean 4.58	Standard Deviation 0.49

Q25 Many problems do not call for complex statistical tools but require detailed problem-solving. This detailed thinking and analysis is a matter of discipline, attitude, and culture. True problem solving requires finding the root cause rather than the source of the problem. The answer is achieved by searching deeper, by asking why the problem occurred.

Answered: 12 Skipped: 0

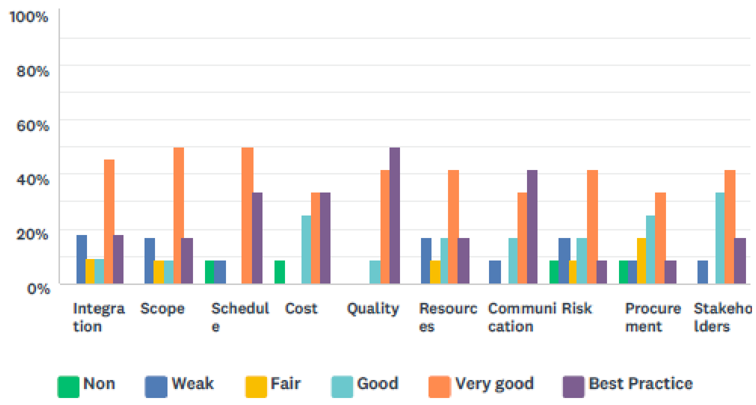


	STRONGLY DISAGREE (1)	DISAGREE (2)	NO VIEW (3)	AGREE (4)	STRONGLY AGREE (5)	TOTAL	WEIGHTED AVERAGE
Agreement	0% 0	0% 0	0% 0	42% 5	58% 7	12	4.58

BASIC STATISTICS				
Minimum 4.00	Maximum 5.00	Median 5.00	Mean 4.58	Standard Deviation 0.49

Q26 To what extent, in your opinion, does the following project management (PM) knowledge areas play a significant role in the Closing process of additive manufacturing (AM) projects?

Answered: 12 Skipped: 0



	NON (1)	WEAK (2)	FAIR (3)	GOOD (4)	VERY GOOD (5)	BEST PRACTICE (6)	TOTAL	WEIGHTED AVERAGE
Integration	0% 0	18% 2	9% 1	9% 1	45% 5	18% 2	11	4.36
Scope	0% 0	17% 2	8% 1	8% 1	50% 6	17% 2	12	4.42
Schedule	8% 1	8% 1	0% 0	0% 0	50% 6	33% 4	12	4.75
Cost	8% 1	0% 0	0% 0	25% 3	33% 4	33% 4	12	4.75
Quality	0% 0	0% 0	0% 0	8% 1	42% 5	50% 6	12	5.42
Resources	0% 0	17% 2	8% 1	17% 2	42% 5	17% 2	12	4.33
Communication	0% 0	8% 1	0% 0	17% 2	33% 4	42% 5	12	5.00
Risk	8% 1	17% 2	8% 1	17% 2	42% 5	8% 1	12	3.92
Procurement	8% 1	8% 1	17% 2	25% 3	33% 4	8% 1	12	3.92
Stakeholders	0% 0	8% 1	0% 0	33% 4	42% 5	17% 2	12	4.58

BASIC STATISTICS

	MINIMUM	MAXIMUM	MEDIAN	MEAN	STANDARD DEVIATION
Integration	2.00	6.00	5.00	4.36	1.37

Scope	2.00	6.00	5.00	4.42	1.32
Schedule	1.00	6.00	5.00	4.75	1.53
Cost	1.00	6.00	5.00	4.75	1.36
Quality	4.00	6.00	5.50	5.42	0.64
Resources	2.00	6.00	5.00	4.33	1.31
Communication	2.00	6.00	5.00	5.00	1.15
Risk	1.00	6.00	4.50	3.92	1.50
Procurement	1.00	6.00	4.00	3.92	1.38
Stakeholders	2.00	6.00	5.00	4.58	1.04