Development of a standardised lean design process for purpose-built machine tools

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PREFACE

Acknowledgements

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ABSTRACT

In the modern world, innovation and the incorporation of lean design processes are an effective way to develop automated machines that can contribute to increased profit margins. The unreliability and low skill level of the general South African workforce has created a need for automated machines that can produce products at high production rates, using a minimal amount of manpower. However, the design process of such automated machines, from concept phase to production phase, is experimental and time consuming; resulting in unnecessary costs and development time delays for the organisation.

The purpose of the research was to develop an artefact in the form of a standardised lean design process to improve the time frame within which purpose-built machine tools are designed by the machine tool industry in South Africa. The research incorporates existing design models and methods to optimise the design time frame in which purpose-built machines are designed by the South African machine tool industry. The novel research design consists of an integration of the *Design Science Research* paradigm, the *V-model* and the *Delphi technique* to generate prescriptive design of knowledge-building and evaluating the artefact.

The artefact that was designed consisted of an improved design process of the standardised lean design process. Various lean elements were used to verify and validate the artefact.

GLOSSARY OF TERMS

Lean manufacturing, machine design, process flow, design science research, Delphi technique, V-model.

ABBREVIATIONS

CAD	Computer Aided Design
CNC	Computer Numerical Control
DSR	Design Science Research
FAT	Factory Acceptance Test
JIT	Just in Time
MTP	Machine Tool Promotions
NC	Numerical Control
SAT	Site Acceptance Test
SOW	Scope of work
TPS	Toyota Production System
VSM	Value Stream Mapping
5S	Sort, straighten, shine, standardise, sustain.

JAPANESE WORDS AND TERMINOLOGY

The Japanese words associated with the Toyota Production System (also known as lean production) have been translated into English over the years. Some of the words could not be translated into English accurately and the Japanese terms are therefore still used today. Some of these words (used throughout this dissertation) are:

Andon cord:	A manufacturing term used as a visual control system to provide current status of production and signals possible problems to workers (Liker, 2004).
Gemba:	The source where value is created (Liker, 2004).
Genchi genbutsu:	To “go and see for yourself” or to visually inspect to be able to solve a problem (Liker, 2004).
Heijunka:	Evening out of production (Liker, 2004).
Jidoka:	An operating system that stops working as soon as a defect is detected and proceeds after the problem has been resolved (Automation that includes a human interface); (Womack *et al*., 1990).
Kanban:	A card system which holds important information and signals the activation of the pull system for upstream production (Kumar and Panneerselvam, 2007).
Kaizen:	Continuous process improvement (Brunet and New, 2003).
Poka-yoka:	Any error-proving mechanism in any process that helps avoid (yokeru) mistakes (poka) with the purpose of eliminating product defects during production (Bonnema, 2018).

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CHAPTER 1 - INTRODUCTION

In this chapter, a brief background to purpose-built machine tools and the current design process is given, to provide context to the research problem. The research aim, objectives and research questions are discussed, and a brief overview of the research design is given.

1.1 Background

Globally, new technologies are developing at an exponential rate which exacerbates the rise in national competitiveness in terms of the production of more sophisticated automated machine tools. As a result, local manufacturing companies are forced to embrace innovative and automated solutions, which deliver high performance and functionality, with fewer resources. The adoption of innovative and automated solutions aids in managing resource constraints, workforce restrictions, optimisation of manufacturing processes and limitations (Mukherjee and Ray, 2006). Competitiveness between manufacturing companies of machine tools is increased when resources and manufacturing processes are managed effectively.

Machine tools can be described as stationary power-driven machines used to shape or form parts made from metal or any other material. The shaping and forming can be accomplished by cutting, shaving, shearing or pressing parts into desired forms or shapes (De Lacalle and Mentxaka, 2008). Machine tools can be operated both manually and with automatic control (Altintas, 2012). The precision achieved by machine tools results in parts that are produced more economically. Modern day machine tools are used in various industries, from those used by the automotive industry to the purpose-built machines currently available, which include, gear cutting machines, screw lathes, boring machines, milling machines, turning lathes, surface, cylindrical and roll-grinding machines (Rentzsch *et al*., 2017).

Purpose-built machine tools are designed and manufactured for a specific purpose, which could typically include drilling and milling holes into material in a specific sequence and various other operations (Nathan, 2016). Every purpose-built machine tool is therefore unique and constructed according to a customer’s engineering specifications. For purpose-built machine tools, the entire product development process entails using new and agile methodologies, from the conception phase to the manufacturing phase (Germani *et al*., 2011, Fosse and Ballard, 2016, Franco and Picchi, 2016).

The nature of the design process for purpose-built machine tools is unique, as most purpose-built machine tools are prototypes or one-of-a-kind; therefore experimentation is required, which is costly and time-consuming (Reigeluth, 1983). Time spent on the experimental design and manufacturing translates directly into cost, and consequently, the time spent on the experimental design and manufacturing should be optimised (Germani *et al.,* 2011). Optimising the time spent on experimental design and manufacturing is a priority in the machine tool industry, as the demand for purpose-built machines has grown exponentially in recent years (Mekid *et al*., 2007).

The research problem emanated from a real-life design environment within the machine tool industry at a company which specialises in the design and development of purpose-built machine tools, based in South Africa. The current engineering design environment within this company includes common mistakes and rushed activities and as a result, makes the design and development process costly and time-consuming. With no actual machine design procedure, multiple problems keep arising during the manufacturing and assembly stages, which leads to re-work at the cost of valuable time and resources.

Establishing a systematic approach to designing solutions in the early phases of design, could improve the process, as solutions in the early design stages play a critical role in the competitiveness of product development (Hsieh *et al.*, 2015). Melton (2005) states that a company's competitiveness can be increased with the utilisation of standardised methods.

1.2 Case study

1.2.1 Case study organisation

This research was conducted at a machine tool company based in South Africa.

The company currently consists of three main divisions: each of them focusing on specific market-related areas of engineering. The workforce consists of 76 employees and varies from unskilled personnel to engineers who are specialists in the field of machine tools.

The continuous change in the industry over the last four decades has contributed to the growth, expansion and versatility of the company. Various specialists are continuously being introduced to a wider skills-set due to expansion. The Machine Development division of the company handles the modernisation of machine tools; performing all geometric rebuilding, mechanical upgrading and CNC and electronic work within the division. This division also develops industrial purpose-built machine tools, including the complete design, building, installation and commissioning of such machines; which normally includes a significant degree of automation. These machines consist of complex designs and can consume a lot of time and financial resources.

The development of purpose-built machine tools is a timely process that can consume a lot of time and resources. The development process includes brainstorming sessions with a multi-disciplinary team that consists of electrical engineers, machine tool artisans, machinists and mechanical and production engineers; the complex mechanical CAD design of the machine from concept phase to prototyping, and finally manufacturing the complete machine, which includes the incorporation of the electrical scope, as well as automation. The current process allows corrections, design updates and design changes to be made during the final phase of prototyping, which results in a lot of unnecessary waste of parts being manufactured, modified and re-manufactured due to design errors and concept alterations: this is in line with findings in literature as reported by Germani *et al. (*2011*)*.

1.2.2 The current design process

The current design process is described as follows:

1. An initial request to generate a cost estimation to design, manufacture and build a purpose-built machine tool;
2. The capturing of information on an official quote, which includes the basic scope of work (SOW) as well as the estimated time frame and the cost of the machine;
3. A technical review phase in which the functional and performance requirements of the machine are determined by the customer and designer;
4. The preliminary concept design review, which consists of a brainstorming session between the multi-disciplinary project team members to determine the best possible method to achieve the desired outcome;
5. Designing the machine, creating manufacturing drawings and initiating the manufacturing process for prototyping; and
6. Corrections, design updates and design changes which are only made during this final phase of prototyping.

The current design process is depicted in Figure 1. The red diamonds are decision blocks and the blue blocks represent the different phases of the design process. Multiple iterations may occur if the prototyping has not been deemed to be successful.

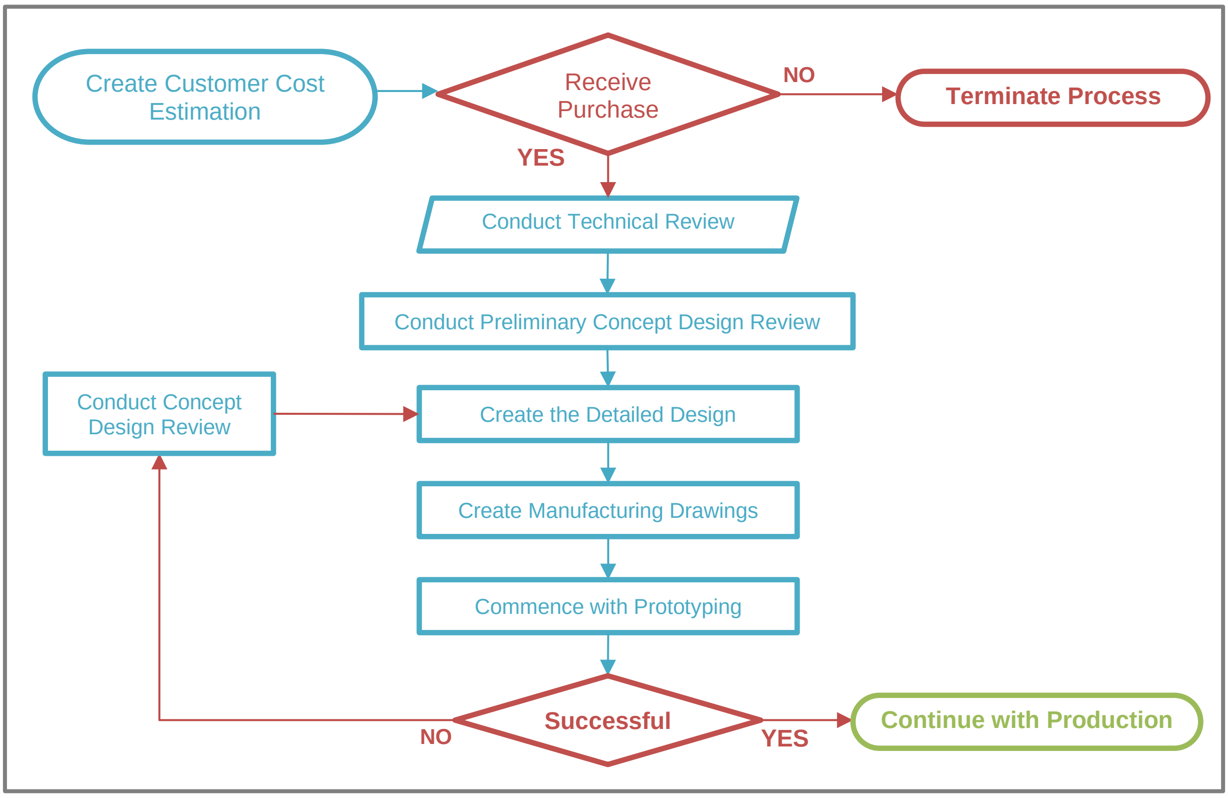

Figure 1: The current design process.

The flow chart starts with the initial interaction with the client who requests a quotation for the design, manufacture and building of a purpose-built machine tool. During the first step (quotation phase), an estimate of the cost is calculated by determining the cost of design, manufacturing, assembly and commissioning. This information is captured on an official cost estimate, which will include the basic scope of work (SOW). When the purchase order is received, the technical review phase - in which the functional and performance requirements of the machine tool are determined - will commence.

The next phase comprises the preliminary concept design review, which consists of a brainstorming session by the multi-disciplinary project team to determine the best possible method to achieve the desired outcome. Once this is determined, the designer will design the purpose-built machine, create manufacturing drawings and initiate the manufacturing process for prototyping. If prototyping is not successful, iterations of the process start again from the concept design review phase onwards.

In the current engineering design environment, design errors and concept alterations take place during the final prototyping phase. Any common mistakes and rushed activities will eventually make the design process costly and time-consuming. This results in waste in the form of multiple changes to designs, drawings and modifications to the actual parts, which would have to be re-manufactured if not correct. It also creates frustration for the artisan building the machine as well as the machinist, who has to do all the rework on the manufactured parts.

1.3 Problem statement

From the background presented, it is evident that the design process at a machine tool manufacturing company based in South Africa, requires costly and time-consuming experimentation in the prototyping phase, which results in waste and constant rework with multiple iterations.

1.4 Research oportunity

Lean manufacturing can possibly provide the tools and techniques for addressing the research aim, as lean manufacturing focuses on the design of a reliable production operation that is responsive, flexible, predictable, and consistent (Liker, 2004). This creates an operation that is dedicated to continuous improvement and which is driven by customer specifications (Feld, 2000). By applying the lean principles to the current design processes, the productivity of a design process can be improved.

1.5 Research aim

Due to the increased demand for purpose-built machine tools, a reduction in the time taken from design to production is a priority in the machine tool industry.

Therefore, the purpose of the research was to develop an artefact in the form of a standardised lean design process to improve the time frame within which purpose-built machine tools are designed by the machine tool industry in South Africa.

1.6 Research objectives

To achieve the aim of this research, the following research objectives were set:

- Conduct a literature study on existing design processes and clarify any abstruse concepts and terminology of lean engineering and manufacturing.
- Determine an appropriate research design to achieve the research aim.
- Develop a standardised lean design process, incorporating lean tools and techniques alongside existing design models, to achieve an optimal conceptual design time frame.
- Verify that the artefact adheres to the design requirements.
- Validate the research problem, the research design and the research output.

1.7 Research questions

The problem statement, research aim and objectives led to the following research questions that are answered through this study:

Research question 1: What are the existing machine design processes?

Research question 2: What are the current processes and systems in the machine tool design and development environment?

Research question 3: What are the applicable research designs used to achieve the research aim?

Research question 4: What are the requirements of a standardised lean design process, incorporating existing design models, to achieve an optimal conceptual design time frame?

Research question 5: Does the artefact adhere to the specified design requirements?

Research question 6: Has a valid research problem been identified?

Research question 7: Was a valid research design followed?

Research question 8: Does the research output address the research problem?

1.8 Research design

In order to design a standardised lean design process for purpose-built machine tools, a combination of different methods was used, as indicated in Figure 2. The design was set within the Design Science Research paradigm (purple), while the V-model (turquoise) was used for the design, development, verification and validation of the artefact (the standardised lean design process). To ensure continuous verification and validation, the Delphi technique (green) was used as a practical means of gathering data. This combined method will be referred to as the DSR-Delphi-V-method (DDV-method).

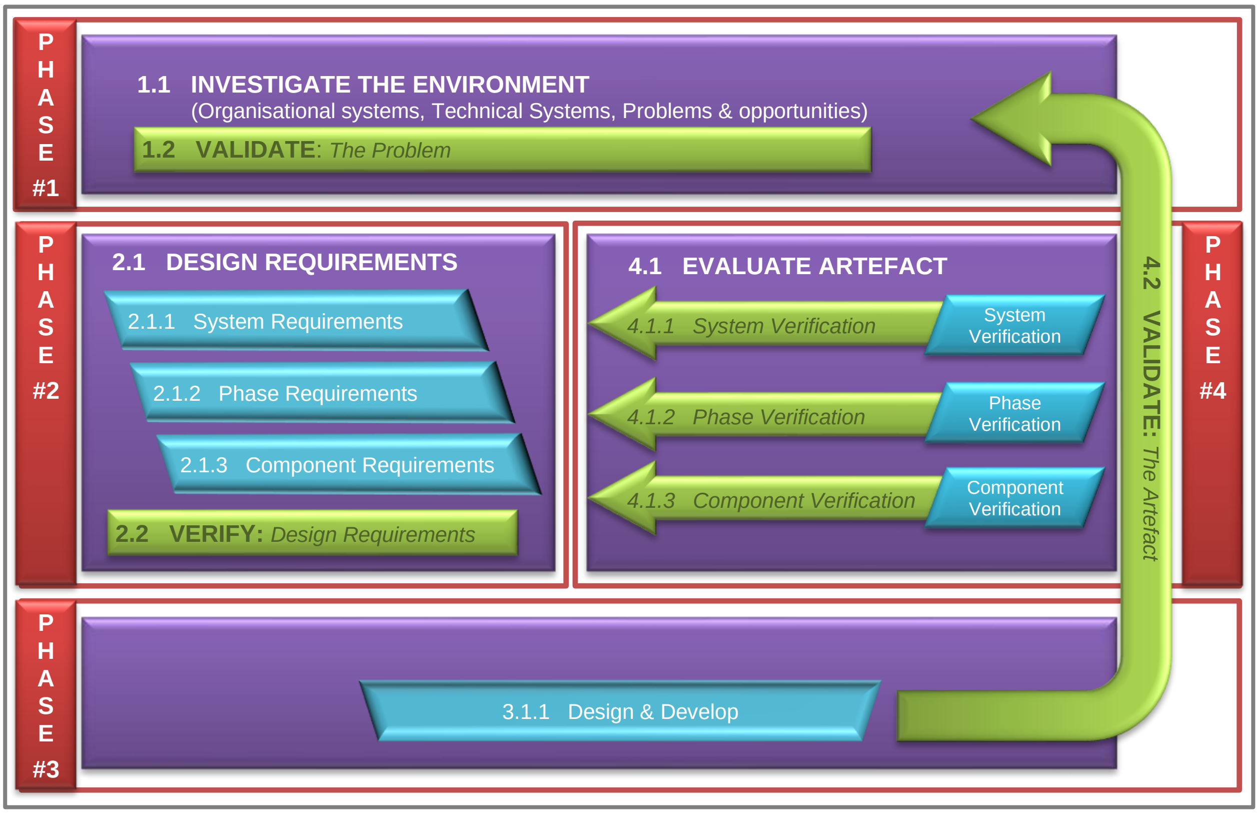

Figure 2: DDV-method.

The detailed phases of the DDV-method are described in detail in Chapter 3.

1.9 Chapter divisions

An overview of the research questions and objectives that are discussed in each of the chapters are shown in Table 1.

Table 1: Research question and objectives according to chapters.

CHAPTER	RESEARCH OBJECTIVE	RESEARCH QUESTION	Method
1. Introduction			
2. Literature study	Conduct a literature study on existing machine design processes and clarify any abstruse concepts and terminology.	1. What are the existing machine design processes? 2. What are the current processes and systems in the machine tool design and development environment?	Literature review
3. Research design	Determine applicable research design to achieve the research aim.	3. Which are the applicable research designs used to achieve the research aim?	DDV-Method

4. Research findings	Develop a standardised lean design process, incorporating existing design models, to achieve an optimal conceptual design time frame	4. What are the requirements of a standardised lean design process, incorporating existing design models, to achieve an optimal conceptual design time frame?	Delphi
5. Verification	Verification of the design requirements, as well as the artefact.	5. Does the artefact address the specified design requirements?	V-model
6. Validation	Validation of the research problem, the research design and the research output.	6. Has a valid research problem been identified? 7. Was a valid research design followed? 8. Does the research output address the research problem?	Delphi
7. Conclusion			

1.10 Summary

In this chapter, the background to the research and the research problem were provided. The research questions and objectives were formulated, and the research design was outlined.

The following chapter provides a review of the literature that supports this research.

CHAPTER 2 - LITERATURE STUDY

This chapter discusses the relevant literature on lean definitions and the various types of lean techniques. The machine tool industry will be discussed, as well as design and lean design methods. Figure 3 provides an outline of the relevant literature. The lean philosophy and the research problem overlap to form the newly designed artefact.

The research design consists of three sections: investigate, design and evaluate. These three sections and their sub-sections overlap to form the research design and are summarised as follows:

- Investigate: A Literature review on existing machine design processes and to clarify any abstruse concepts and terminology.
- Design: The research design used for this research is a combined method that incorporates design science research and the V-model.
- Evaluate: The Delphi technique is used for the verification and validation of the design requirement and the artefact.

The lean philosophy from the Toyota Production System (TPS) is used to reduce waste by optimising and improving the design process.

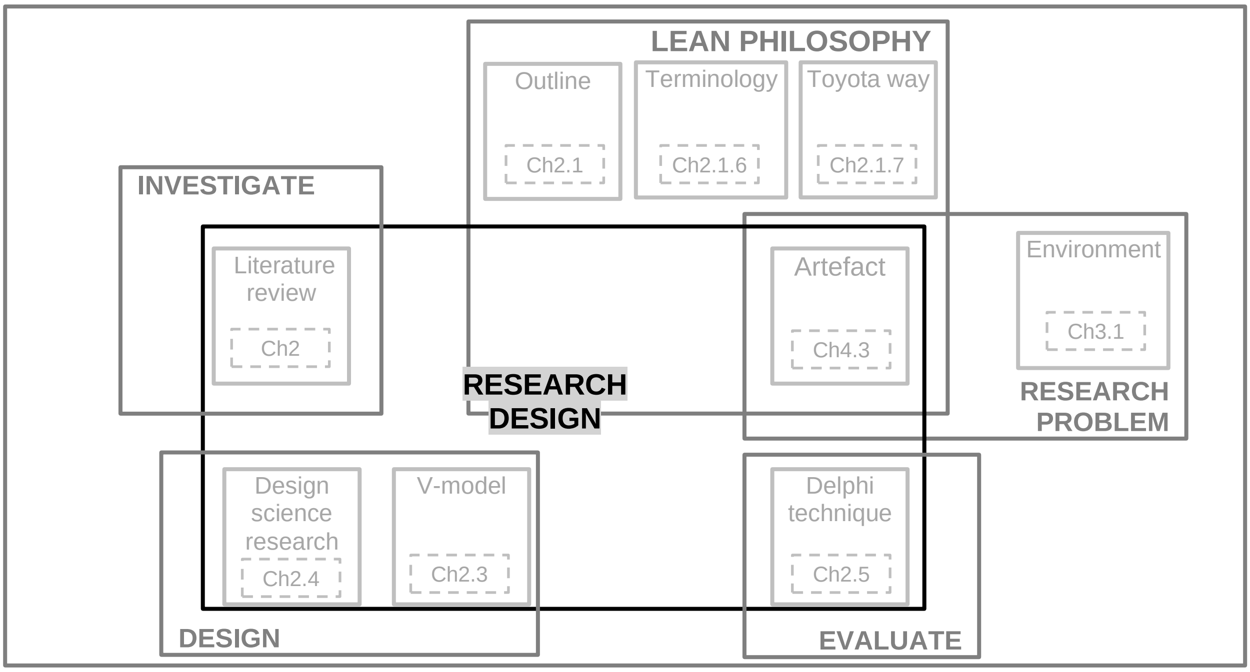

Figure 3: Literature review outline.

The following sections within this chapter elaborate on each of the literature aspects of Figure 3.

2.1 Lean manufacturing

The expression ‘lean manufacturing’ was introduced by the scientific environment in the book *The machine that changed the world* (Womack *et al.*, 1990). Lean manufacturing is an amendment to the Toyota Production System (TPS) (Womack and Jones, 1997), with its origins in Japan within Toyota (Melton, 2005). The focus of lean manufacturing is to design a reliable production operation that is responsive, flexible, predictable, and consistent. This creates an operation that is dedicated to continuous improvement and which is driven by customer specifications (Feld, 2000). The lean objectives of waste elimination and eliminating defects during lean manufacturing, as stated by Anand and Kodali (2009), can be achieved through:

- making employees aware of ‘lean’;
- identifying the lean barriers and overcoming them;
- changing the overall culture of the organisation;
- changing the responsibilities of management;
- layering the organisation;
- creating a team with multiple functionalities;
- motivating employee’s commitment level by rewarding them;
- creating an integrated supply chain from supplier to customer;
- including the need for innovation;
- changing in the organization;
- utilising lean principles in conjunction with information systems within the organisation.

Due to shortages of material, the financial crisis and the shortage of human resources caused by World War II, Japanese manufacturers were forced to create the ‘lean’ manufacturing concept (Abdulmalek and Rajgopal, 2007, Womack *et al*., 1990). The competitive market forced manufacturers to improve quality, reduce delivery times and most importantly, reduce costs. The core of lean manufacturing is to create greater productivity with shorter delivery times that will in turn lower costs, improve quality and ultimately increase customer satisfaction (Schroer, 2004).

The Japanese manufacturing industry provided the lean principles (Krafcik, 1988). The lean production system creates value-added work and eliminates waste (Womack *et al.*, 1990). When waste is removed, quality improves. This also helps to improve production time and reduce cost (Hoseus and Liker, 2008). Continuously reducing cost through waste elimination was the main objective of Kichiro Toyoda, founder of the Toyota Motor Corporation (Wee and Wu, 2009). Lean manufacturing is relevant to this research as various lean tools and methods, as described previously, are used to simplify the manufacturing process to save time and money. Waste, often called *muda* in Japanese, comprises seven types of common waste: overproduction, excess inventory, waiting, unnecessary motion, excess transportation, rejections/rework, and over processing (Barbosa and Carvalho, 2014).

The effective application of lean principles in manufacturing processes development - which includes the design process from the concept phase to the manufacturing phase - is necessary to enable the attractiveness, competitiveness, and perpetuity of manufacturers' businesses (Barbosa and Carvalho, 2014).

Results from the application of white-collar lean methodology can validate and enable its application in the development phases as follows (Barbosa and Carvalho, 2014):

- Processes that can help the implementation of automation in manufacturing;
- Value addition in manufacturing processes;
- Possible reduction/elimination of waste;
- Optimization of production environment physical arrangement (design process in this study);
- Improvement in the movements and flows of the design process;
- Technological innovation;
- Increased competitiveness.

Barbosa & Carvalho (2014) also mention that potential benefits of being lean may include:

- Financial benefits - by decreasing operating costs which allows potential capital gains and financial savings;
- Having a better understanding of a customer's needs;
- Better quality and robust processes leading to fewer errors, leading to less rework;
- Empowering multi-skilled teams, by increasing process understanding;
- Knowledge, with increased understanding of the whole supply chain, including all the processes within the value stream.

2.1.1 Toyota Production System

The Toyota Production System (TPS) started in Japan in the 1940s within the Toyota Company. TPS is a lean management philosophy applied to efficiently create organised manufacturing within the motoring industry (Melton, 2005).

The Toyota Production System (TPS) can be described as a unique approach to manufacturing and Toyota's lean manufacturing philosophy, and is the foundation for the international movement to "think lean"(Liker, 2004). The theory behind TPS can be represented as a house, as shown in Figure 4.

The main pillars in the TPS house focus on the technical concepts of the lean philosophy: just-in-time and *jidoka* (automation that includes human interface).

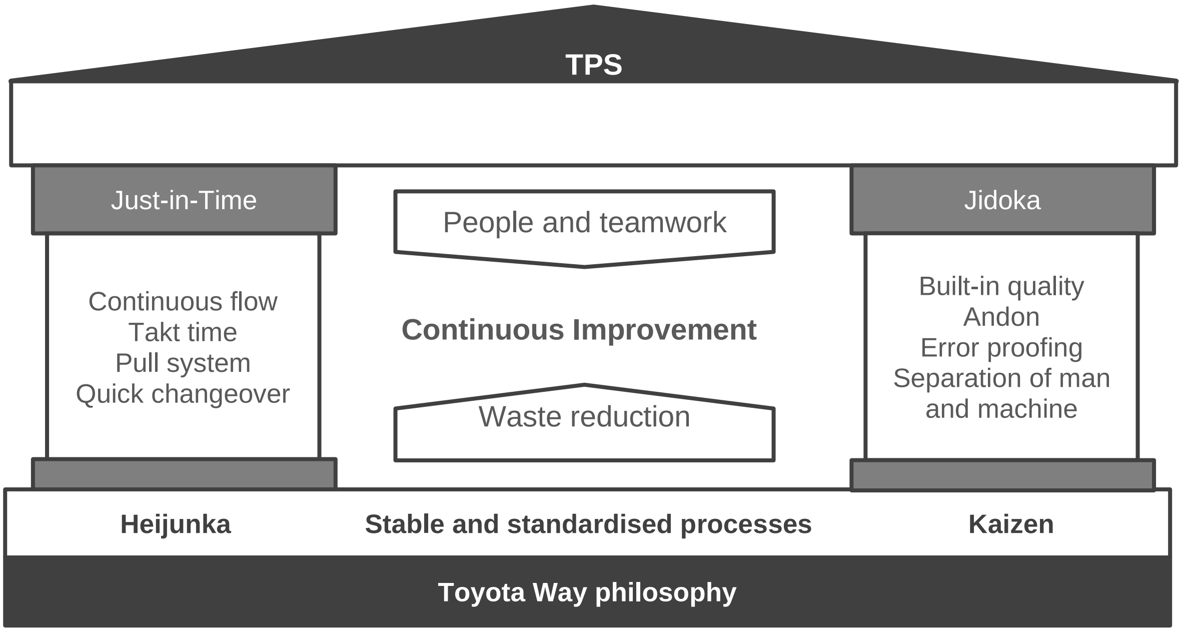

Figure 4: The TPS house (Adapted from Liker (2004)).

2.1.2 5S

Al-Aomar (2011) states that 5S is a lean technique that is used to reduce waste, clean a workplace, and increase efficiency. This strategy was used as a design requirement during the design and development phase of the artefact.

A 5S system consists of five key elements (Chapman, 2005) and these relate to the design requirements of the artefact as follows:

- **Sort (Seiri)**: removing as much as possible waste from the design process;
- **Set in order (Seiton)**: identifying and labelling locations for designs and documentations;
- **Shine (Seiso)**: improving the visual appearance of the design process;
- **Standardise (Seiketsu)**: using a standardised design process;
- **Sustain (Shitsuke)**: continuous improvement and incorporating 5S into the culture of designers.

If all five of these elements are implemented it should create a disciplined, clean and well-organised design environment. Filip and Marascu-Klein (2015) concurred that the 5S lean method consists of sorting, organising, cleaning, developing and sustaining a production system in a workplace.

2.1.3 Lean engineering

The term lean engineering was used by Garcia and Drogosz (2007) to describe Toyota's product development. Toyota created a sustainable lean culture by fulfilling the desire to create continuous flow throughout the production plant. Lean engineering promotes continuous improvement to increase the productivity and efficiency of engineering departments. This relates back to the research aims and objectives of this study, and forms part of the design requirements of the artefact.

The three goals of lean engineering that represent the different areas of process improvement include creating the correct product, with effective lifecycle and enterprise integration, and utilising innovative engineering processes (McManus *et al*., 2005).

2.1.4 Lean implementation restrictions

From previous studies conducted by Jasti and Kodali (2016), it was found that a barrier to the implementation of lean principles in an organisation was employee resistance, also known as "resistance to change" (Sim and Rogers, 2008); and the lack of understanding of the lean principles amongst the managers who delegate to the employees (Jina *et al.,* 1997). For future implementation of the artefact designed and developed in this research, the designer will need a clear understanding of lean principles to be able to successfully utilise the artefact.

With reference to this research, job security will not be a concern, as the implementation of the lean artefact will provide a road map and a standardised process to ultimately simplify the design process to create less waste, that will in turn provide better job satisfaction and less frustration (Sim and Rogers, 2008). Various sub-cultures may appear as a form of conflict after an attempt to implement lean principles in organisations as a result of not representing a consistent lean culture (Bhasin, 2012).

2.1.5 Japanese terminology

Most of the words used by the Japanese motor manufacturer Toyota have been translated into English, but some of the words cannot be directly translated. One of the terms used in this research is *Genchi genbutsu* which implies to physically observe something for oneself, or to visually inspect the situation to be able to make an assessment to facilitate the solving of the problem (Liker, 2004). In the context of this research, *Genchi genbutsu* is a part of the lean principles used as design requirements to design and develop the artefact.

2.1.6 The Toyota Way

The Toyota Way can be described as a comprehensive management philosophy that is based on the two key principles of continuous improvement, and respect for people (Liker, 2004). This philosophy is illustrated as a house (Figure 5). The house is built upon the foundation, which includes; challenge, *Genchi genbutsu, kaizen,* teamwork, and respect. It consists of two main pillars: continuous improvement, and respect for people (Ito, 2016). In this research, some of these principles are used as design requirements to develop and design the artefact.

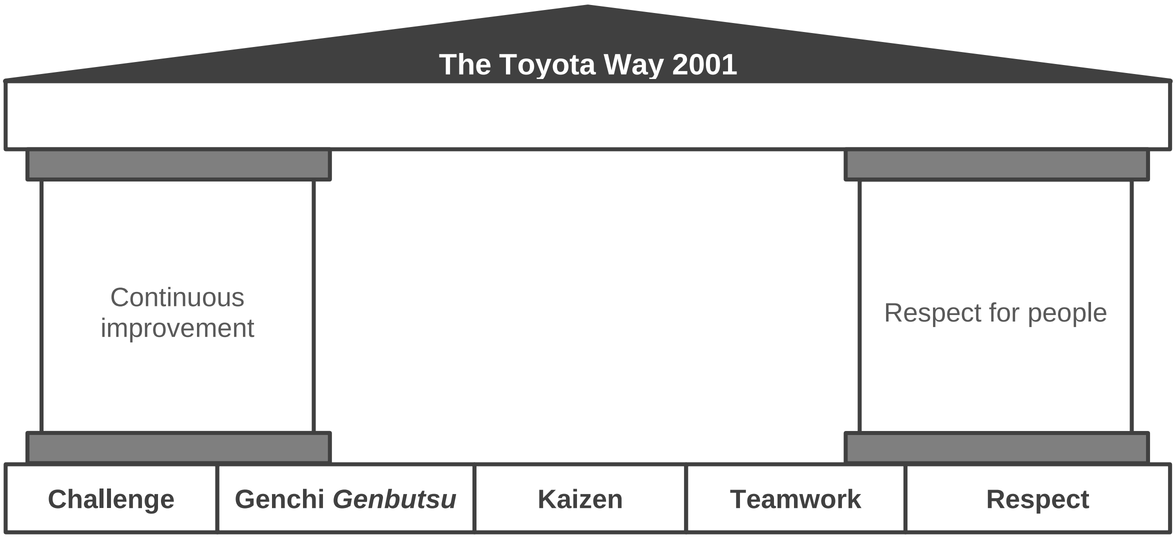

Figure 5: The Toyota Way (Adapted from (Ito, 2016)).

The 14 management principles of the Toyota Way are a unique approach to lean management of a production system. These 14 principles are divided into four categories and are summarised in the following subsections (Liker, 2004).

1P: Long-term philosophy

Principle 1: Management decisions are based on a long-term philosophy, even at the cost of short-term financial goals.

2P: The correct process will product the right results.

Principle 2: Create continuous flow by redesigning work process to highlight problems or defects.

Principle 3: Use *kanban* (pull system) to avoid overproduction and utilise just-in-time manufacturing.

Principle 4: Level out the workload (*heijunka)* of all the processes in batches.

Principle 5: Get the quality of the product right by creating a culture of stopping to fix problems.

Principle 6: Standardise tasks to promote continuous improvement.

Principle 7: Use visual indicators to identify problems.

Principle 8: Use reliable technology to support your employees, not replace them.

3P: By developing your people and partners you are adding value to your organisation.

Principle 9: Grow your management from within the company to understand the work, live the philosophy and educate other employees.

Principle 10: Develop your team of people who adhere to your organisation’s culture and philosophy.

Principle 11: Respect your partners and suppliers by challenging them and helping them to improve.

4P: Continuously solving root problems motivates organisational education.

Principle 12: Attend to the problem yourself to better understand the problem (*Genchi Genbutsu)*.

Principle 13: Consider all the options and make decisions slowly; but implement these decisions rapidly.

Principle 14: Become a learning organisation through reflection (*hansei*) and continuous improvement (*kaizen*).

2.1.7 The lean design process

The lean philosophy will be considered during the steps of the design process. Therefore, the in- and outputs of each design step are focused on lean philosophies. Various techniques and methods should be considered at the various design steps to ensure that the output created for each step is considered as lean as possible (de Kogel and Becker, 2016).

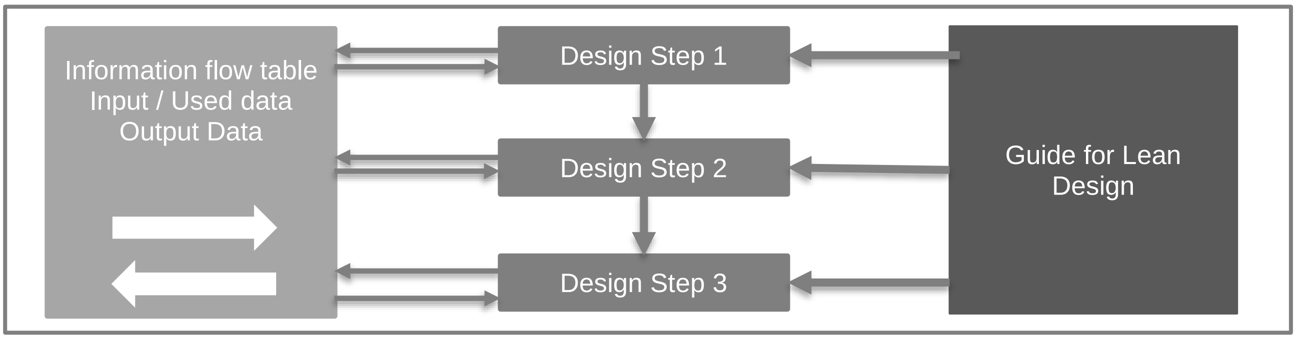

Figure 6: Three elements of a design support tool (Adapted from (de Kogel and Becker, 2016)).

By applying the lean principles of the TPS to design processes, the productivity of a design process can be improved. The ultimate goal of the lean design process is to eliminate waste and to improve delivery and profitability (Khanzode *et al.*, 2006).

Tilley (2005) states that poor design quality is one of the factors in reduced efficiency and productivity and in the overshooting of project timelines, due to a large amount of rework. By implementing lean production principles to the design process, these forms of waste can be eliminated.

2.2 Machine design processes

> *The importance of design, in particular, as an industrial and increasingly complex and dynamic context in which it takes place, has led to the wish to improve the effectiveness and efficiency of design practice as well as education (Blessing and & Chakrabarti, 2009).*

Blessing and & Chakrabarti (2009) also state that design can be defined as the activities that generate and develop products for specific needs. Design is a purposeful, knowledge-intensive, social and cognitive activity undertaken in a self-motivated setting.

Ullman and Dietterich (1987) describe mechanical design as "… the creative decision-making process for specifying or creating physical devices to fulfil a stated need".

Machine design can be defined as the art of devising new or improved machines to accomplish a specific purpose, and as a subsection of mechanical design in which the focus is on structures and motion only (Ugural, 2015). Mechanical engineering design refers to the conception, design, development and application of machines and mechanical components, which involves various disciplines of mechanical engineering (Ugural, 2015).

According to Ugural (2015), system requirements should meet performance, safety, reliability, aesthetic and cost goals.

Furthermore, Ugural (2015) states that there are five phases of design. These phases were used as design requirements to create the artefact and are summarised as follows:

- **Identification of need:** The design process is initiated by identifying the problem and deciding to do something about it.
- **Defining the problem**: Considering all the mechanisms, component and sub-assembly arrangements that will perform the required functions.
- **Synthesis and analysis:** The synthesis (ideation and invention), is where the most possible creative solutions are originated. This phase is also known as the concept design phase.
- **Testing and evaluation:** Prototyping is the result of the first working design. Product evaluation is the final proof of a successful design and can be done by CAD simulation and evaluation.

Ullman and Dietterich (1987), describe mechanical design as "… the creative decision-making process for specifying or creating physical devices to fulfil a stated need".

In the current worldwide manufacturing industry, changes and alterations are unavoidable. Every organisation should take advantage of these changes and apply continuous improvement principles to their process or model (Womack *et al.,* 1990).

2.3 V-model validation

The V-model plays a significant role in the research design of this study, as it provides an integrated step-by-step method to ultimately design and develop an artefact. The V-model is an elaborated version of the waterfall method and is based on the association of verification for each corresponding development stage. This means that for each section in the development cycle, there is a directly associated verification section. The next section starts only after completion of the previous phase (Mathur and Malik, 2010, Balaji and Murugaiyan, 2012). The decomposition section of the V-model will define the design requirements addressed in a later chapter, while the integration and re-composition side will be covered during the test chapter - where the quality research matrix and questionnaire are used (Forsberg and Mooz, 1991).

In this study, the V-model will mainly be used for the verification and validation of the design process. The V-model is a life cycle with a developing path of execution of processes. The next phase cannot be started if the previous phase has not been completed. The verification of the product is done with a corresponding phase of development of the V-model.

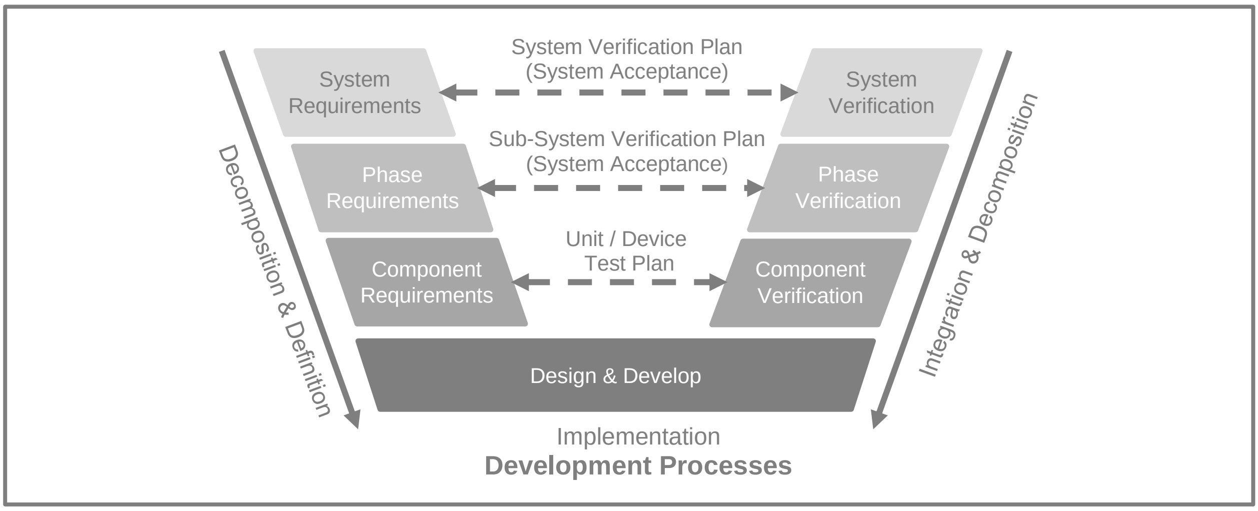

Figure 7: The V-Model (Adapted from (Malaek et al., 2015)).

The various phases of the V-model as shown in Figure 7 can be explained as follows:

Requirements such as concept operation, layout and design requirements begin the life cycle model. Within this model, a system test plan is created before the development is started. The main function of the test plan is to meet the specific functionality requirements that have been gathered. The phase design focuses on system planning and design. It provides the outline of solutions, platforms, systems and processes; after which an integrated test plan is created. This also contributes to the testing of the system to ensure that the components are able to work together. During the component design phase, the actual detail is designed. It describes the actual reasoning for each component of the system. Component testing can also be developed during this phase (Balaji and Murugaiyan, 2012).

During the design and development phase, prototyping also begins. Once the prototyping is complete, the path of completion continues up the right side of the V-model where the design requirements are verified (Clark, 2009).

The advantages of the V-model outnumber the disadvantages by far: another reason why this is a good method to use. The advantages and disadvantages are shown in Table 2 (Mathur and Malik, 2010).

Table 2 : Advantages and Disadvantages of the V-Model.

ADVANTAGES	DISADVANTAGES
Simple and easy to use. Planning and concept designing occurs well before prototyping. Higher chance of success because of proactive defect tracking. Defects detected at early stages. Avoids downwards flow of defects.	Very rigid structure which is not very flexible. If any changes occur midway through the process, the assessment documents along with requirement documents have to be updated continuously.

The V-model can be used for various sized projects, where specifications are clearly described and when sufficient technical resources are available, along with the required technical expertise. In this study, to find a solution for a mechanical system, the V-model, as discussed in previous sections, is used to represent the systems engineering process (Clark, 2009).

2.4 Design science research

Design science research (DSR), is a research paradigm that connects scientific precision, various design theories and real-world application with the focus on useful artefacts (Hevner *et al*., 2018). The paradox between theory and practice can be eliminated by finding solutions to the problems at hand, instead of creating explanations for the problems (Dresch *et al.,* 2014): which is one of the main reasons why design science research (DSR) was chosen.

Takeda *et al.* (1990) explain that DSR models can be used for high-level design processes, with only small variations in details as described in Figure 8. This design process proposes ways to develop artefacts in a strict way and capture the results.

> *”The mission of a design science is to develop knowledge for the design and realization of artefacts, i.e. to solve constructive problems, or to be used in the improvement of the performance of existing entities, i.e. to solve improvement problems” (Aken, 2004).*

Järvinen (2007) explains the steps as follows:

- All designs begin with the awareness of the problem.
- Suggestions for the solution are drawn from existing knowledge and theory.
- An attempt to implement the artefact according to the suggested solution is then made, which is shown as development in Figure 8.
- Implementations of the solution are evaluated.
- Development, evaluation and further suggestions are iterated during the research - as shown by the arrows under the knowledge flow column in the diagram.
- The conclusion shows the completion of the specific design project.

The theory construction opportunities are shown in the last column in the diagram. Each of these represents the outcome of a process step (Figure 8).

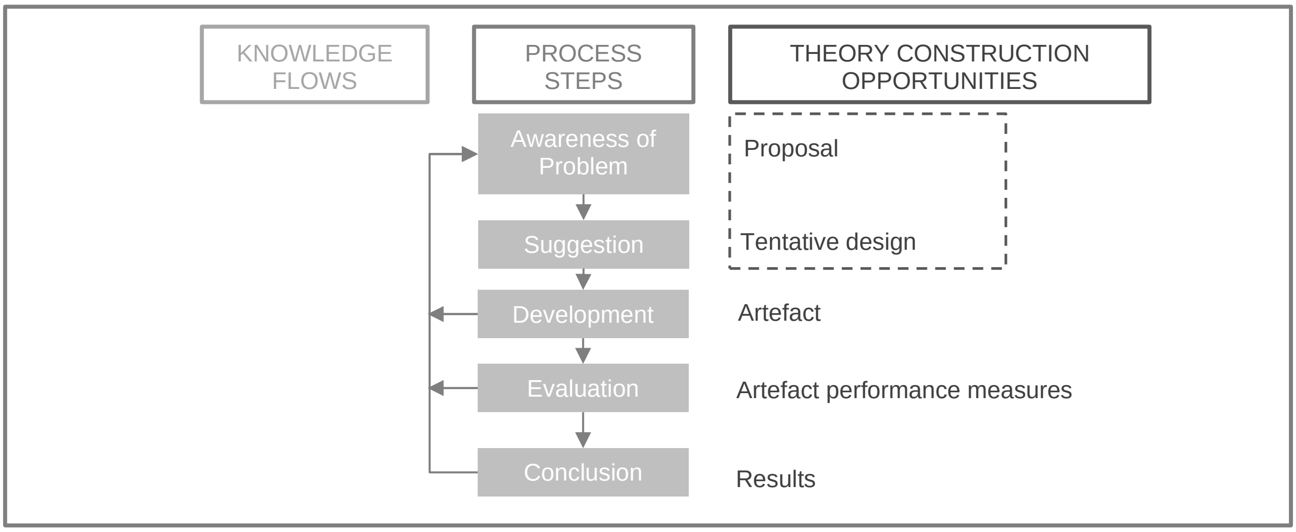

Figure 8: High Level Design Research Process (Adapted from (Takeda et al., 1990) and (Järvinen, 2007)).

Hevner (2007) focuses on three design cycles as shown in Figure 9 below.

- The Relevance cycle connects the background environment of the research project with the design science activities.
- The central Design cycle cyclically progresses between the main activities of building and evaluating the design artefacts, and the processes of the research.
- The Rigor cycle links the design science activities with the knowledge base of the scientific foundations, experience and expertise that inform the research project.

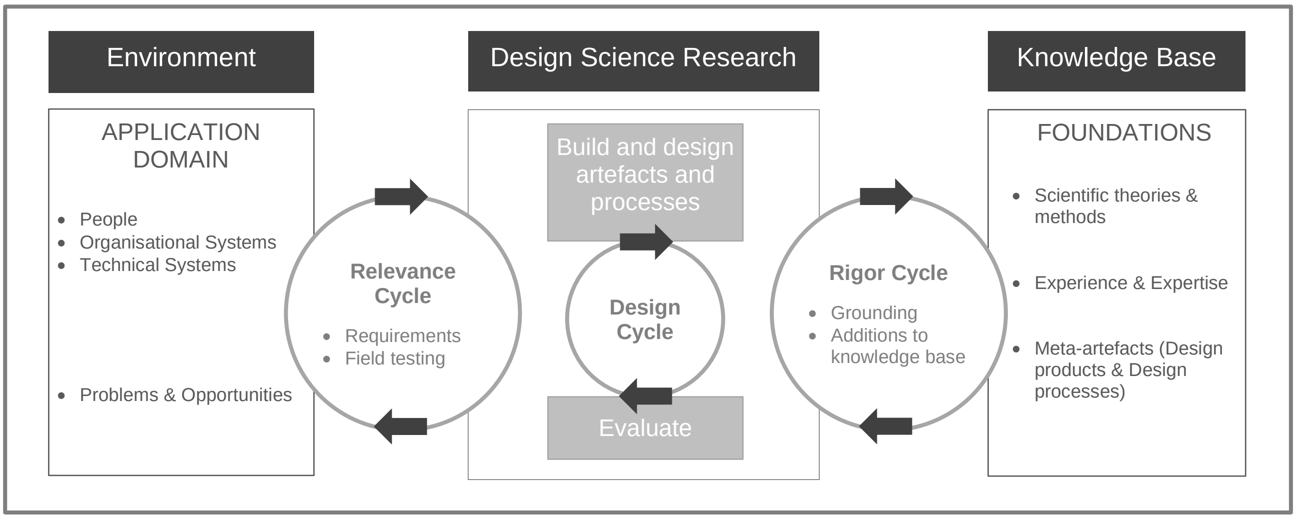

Figure 9: Design Science Research cycles (Adapted from (Hevner, 2007)).

The following subsection explains each of the three cycles in more detail. Depending on the specific design problem and possible solutions, relationships between these cycles, as well as the methodological design of research projects, can differ.

2.4.1 The relevance cycle

The relevance cycle institutes DSR with an implementation setting that provides the research requirements. In other words: the problem to be addressed, as well as defining the acceptance criteria for evaluating the results (Hevner, 2007).

Piirainen (2016) states that the relevance cycle also links the environment with the design. This is achieved by setting the problem domain and updating the design with the relevant requirements and constraints. Later in the process, the artefact will be presented and the results will be reported.

2.4.2 The design cycle

The design cycle is the center of the DSR project, where the problem domain and the solutions interface with the artefact (Martínez León and Calvo-Amodio, 2017). Simon (1988) and Hevner (2007) concur that this cycle can be described as the generating of design alternatives and the evaluation of the alternatives, against the design requirements, until a final design is reached. The design requirements are the inputs from the Relevance cycle and the design theories and methods are used from the Rigor cycle described below.

2.4.3 The Rigor cycle

The Rigor cycle uses previous knowledge and experience based on various scientific theories and multidiscipline engineering methods of the research project, to ensure innovation by informing the solution domain and contributing back to the knowledge, based on evaluation. Fallman (2008) maintains that this integrates the perspectives of different design practices, explorations and studies. The design produced from the project should contribute to the research and not be a "… routine design based upon the application of well-known processes", as stated by Hevner *et al.* (2004).

2.5 Validation by means of the Delphi technique

Validation is a term used to define whether a model is acceptable for its intended use by complying with the specified performance requirements (Rykiel Jr, 1996).

To validate a framework Inglis (2008) proposes six methods:

- reviewing the research literature related to success in learning;
- requiring input from an expert panel;
- conducting empirical research;
- conducting survey research;
- conducting experimental projects;
- reflecting on case studies.

For this research, inputs were obtained from a panel of experts by means of the Delphi technique (Turoff, 1977), using a validation framework as described by Nordin *et al*. (2012).

Nordin *et al*. (2012) states that the Delphi technique is a validation process by which a conclusion is made as to whether a tool is fit for purpose. According to Skulmoski *et al*. (2007), the Delphi technique consists of four phases. The Delphi technique is designed to acquire the most reliable consensus from a panel of experts by a series of questionnaires combined with optional feedback, with the results of each round being processed in the next round to find the most accurate outcome. The first phase is to select a team of experts to consult for their opinions on a specific real-world issue (Hsu and Sandford, 2007). This team of experts should meet the following requirements:

- Knowledge and experience of the issue under investigation;
- Capacity and willingness to participate;
- Sufficient time to participate;
- Effective communication skills.

The second phase is to develop the research questions. Numerous iteration rounds can occur for different studies. The first iteration of the questionnaire is usually unstructured and motivates an open response to identify the general issues, as suggested by Hsu and Sandford (2007). The questionnaire should consist of open-ended questions to obtain specific information with regard to the framework development. The results of the questionnaire are analysed to provide an improved framework that would also create the foundation for the second and third iteration: which will be more specific (Anand and Kodali, 2009). The results are verified after each questionnaire iteration. Only after the final iteration, is the artefact presented.

Hsu and Sandford (2007) state that the Delphi technique is a sufficient method for determining consensus, through its use of a series of questions to collect data from a panel of experts.

2.6 Conclusion

A literature study was conducted on the main components of this research.

In the following chapter the research design and the key components of the method used in this research are described.

CHAPTER 3 – RESEARCH DESIGN

3.1 Introduction

The purpose of the research was to develop a standardised lean design process to improve the design time frame within which purpose-built machine tools are designed by the machine tool industry in South Africa. The novelty of the research design explained in this chapter is specific and structured. Guidance is provided by a tailor-made V-model flowchart to guide the researcher through each of the phases of the research design. As a result, this specific research design contributes to assisting the engineers during project or process development. The improvement cycle is continuous and assists lean thinkers who are aiming for excellence (Melton, 2005).

The aim of this chapter is to describe the research design followed: the foundation of which is formed by the design science research (DSR) paradigm. The method used to answer the following research question is outlined in the following sections:

> **Research question 3:** What are the applicable research designs used to achieve the research aim?

3.2 Research Design Overview

In order to develop a standardised lean design process for purpose-built machine tools the DSR cycles, the V-model and the Delphi technique were combined within the lean philosophy, (discussed in Chapter 2), to form an integrated model that was used as the research design for this study. The detailed phases of the DDV-method are described in the following sections (Figure 10).

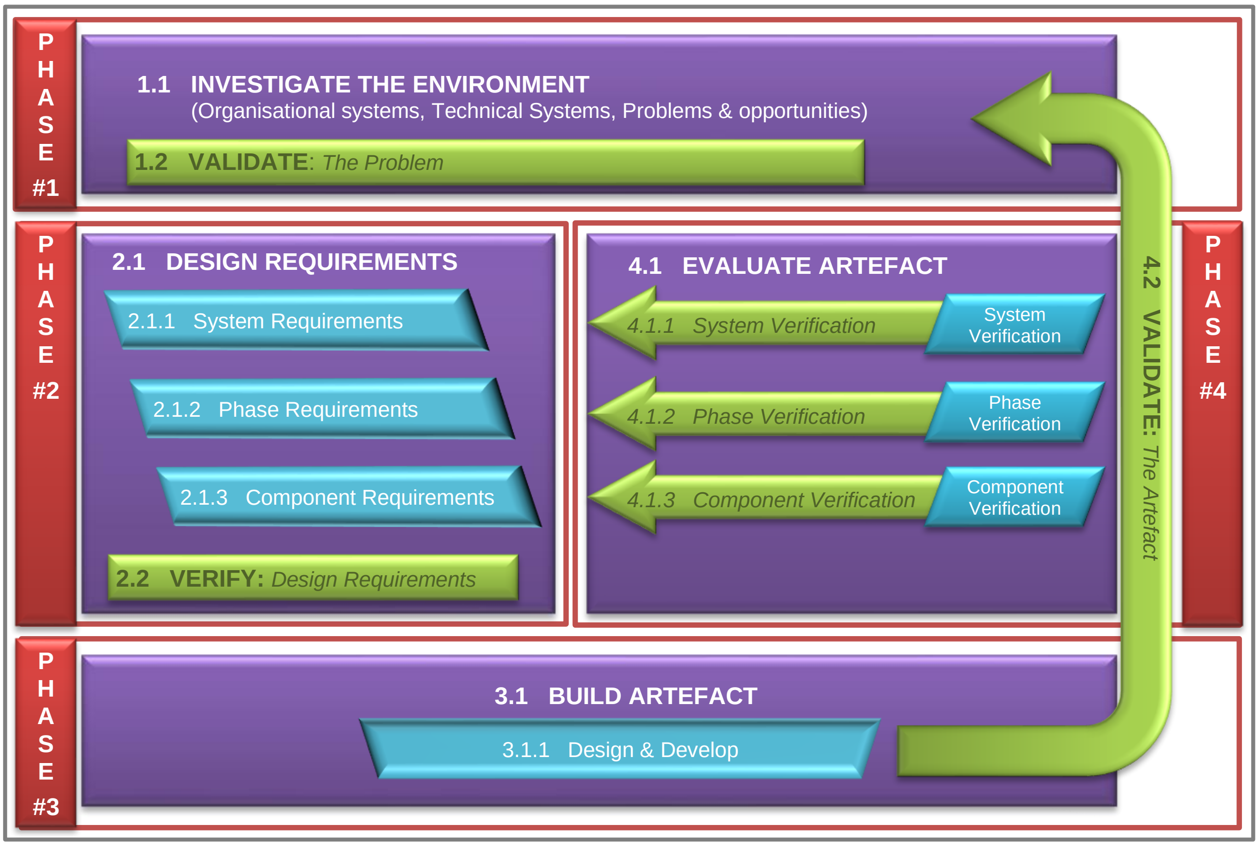

Figure 10: DDV-method.

- The purple section in Figure 10 represents the DSR paradigm of the research design, which includes a series of rigorous activities: designing, building and evaluating the artefact. The DSR paradigm was chosen as it combines scientific precision with various design theories and industrial real-world application, with the focus on useful artefacts as a result (Hevner *et al*., 2018). In addition, the DSR paradigm was used to find solutions to the problems at hand, instead of creating explanations for the problems (Dresch *et al*., 2014).
- The V-model with its activities is highlighted in the blue section. The V-model was used as a progressive path for executing every phase in the development cycle. For every phase in this cycle, there is also a directly associated testing phase (Mathur and Malik, 2010).
- The Delphi technique is highlighted in green. The Delphi technique was applied to various steps during the development of the artefact to verify and validate the model throughout.
- Finally, as an overview, each of the four phases of the DDV-method are grouped together in red.

3.2.1 Design Science Research

In Figure 11, the integrated part of the model in purple indicates the Design Science Research (DSR) paradigm that forms the basis of the research design.

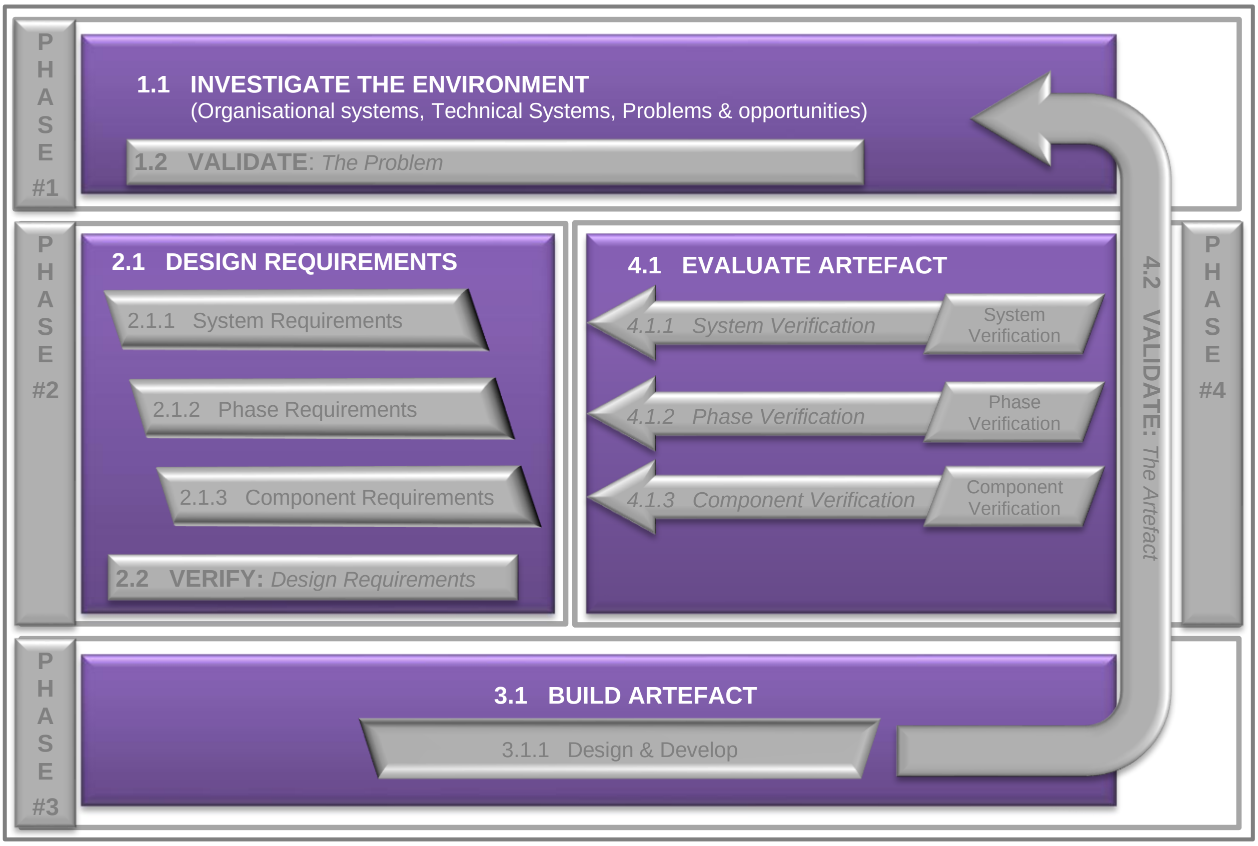

Figure 11: DSR section of DDV-method.

The top part of Figure 11 represents the *Investigation of the Environment* which contains the research problem - this consists of organisational systems, technical systems, problems and opportunities that interact with each other towards a common goal (Hevner, 2007).

The next phase (left-hand side of Figure 11), focuses on the *Design Requirements* of the artefact. The design requirements were provided by the relevance cycle of the DSR paradigm, which initiates design science research (Hevner, 2007).

The bottom section of Figure 11 represents the *Building of the Artefact*. The design requirements determined in the previous phase presented the information required to build the artefact. The process of developing a system or process to meet pre-determined needs can be described as engineering design (Ugural, 2015).

The *Evaluate* phase (right-hand side of Figure 11), drawn from the Rigor cycle from the DSR paradigm, was utilised to ensure that the design process stayed relevant (Hevner, 2007).

3.2.2 The V-Model validation

The prescribed design requirements were developed from the V-model validation method highlighted in Figure 12, in blue. The decomposition phase of the V-model, on the left-hand side, addressed the development part of the life cycle, and consists of the system requirements (DDV step 2.1.1) and phase requirements (DDV step 2.1.2). These requirements focused on the system planning as well as the design and provides possible solutions. Lastly, the component requirements (DDV step 2.1.3) focus on the possible solutions, as the focus is on the detail of the design.

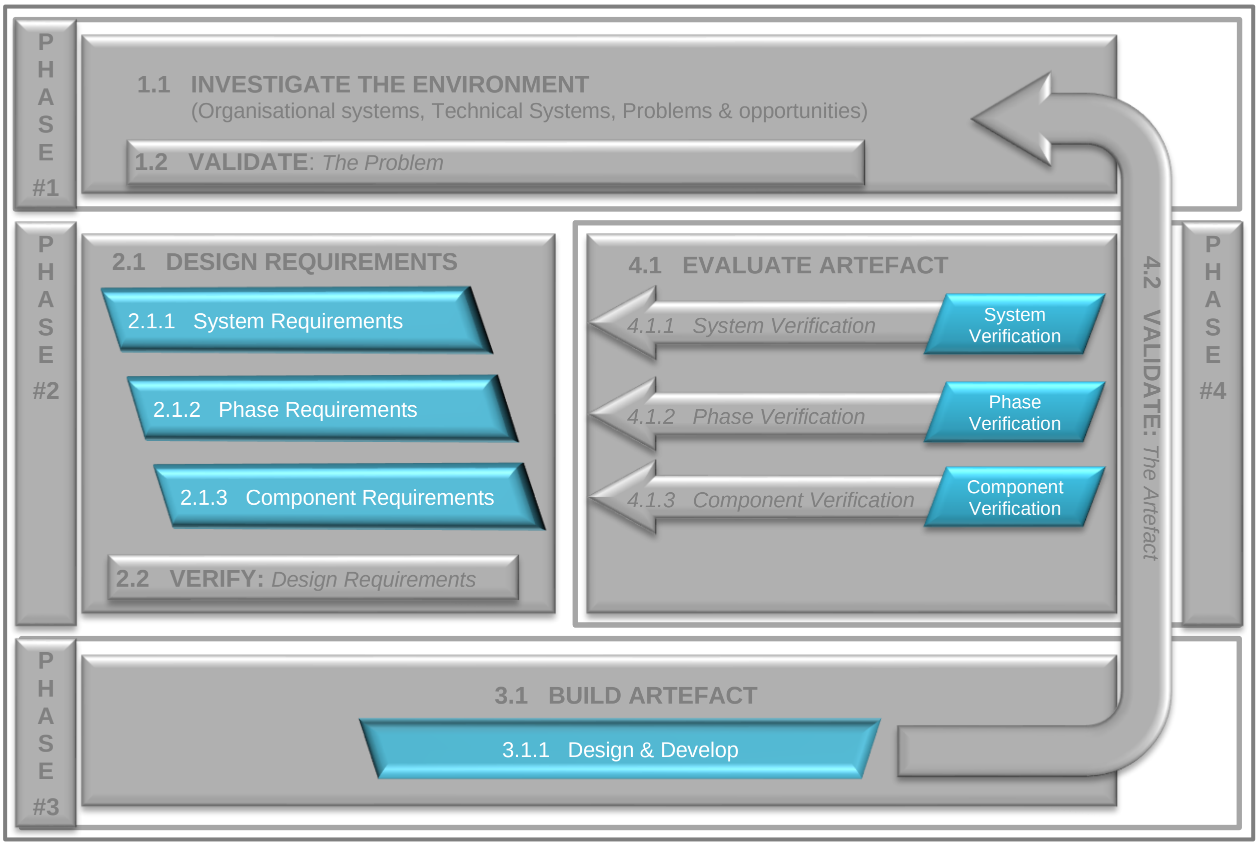

Figure 12: V-model section of DDV-method.

The design and development, at the bottom of the V-model (DDV step 3.1.1), are based on the requirements determined in the previous phases. The integration and re-composition phase on the right-hand side of the V-model (Figure 12), focuses on the verification and validation of each of the phases on the left-hand side of the V-model. This verification and validation is done to ensure that the information remains relevant in accordance with the system requirements. DDV step 4.1.1 refers to the overall system requirements, DDV step 4.1.2 refers to the various phase requirements and DDV step 4.1.3 refers to the component requirements of the standardised lean design process for purpose-built machine tools.

3.2.3 The Delphi Technique

The Delphi technique was applied throughout the research to cyclically verify and validate the different phases of the DDV-method, as shown in Figure 13. The Delphi technique was used to verify that a valid problem was identified in phase one and that it complies with the design requirements in phase two, to prove that a valid artefact was designed during phase four.

Prior to the application of the Delphi Technique, a panel of experts needed to be selected. The selection was based on their expertise in the field of engineering design. Based on Skulmoski *et al.* (2007), the three main characteristics of the selected of the panel needed to be: (1) a minimum of three years' known experience in the field of machine tool design; (2) capacity and willingness to participate; (3) effective communication skills.

The panel of experts consisted of employees from a South African based machine tool company, ranging from executive management to machine tool fitters who were familiar with the current design process; as well as other industry experts ranging from engineers to top-level managers within the local machine tool industry in South Africa. Participants from the company were selected as they have vast experience relating to past and current design processes. Experts were also recruited from other companies to ensure that various perspectives were taken into consideration for this research.

The panel consisted of fifteen experts. Twelve participants responded by completing the questionnaire, which provided an 80% response rate. Table 3 shows the frequency distribution of the level of experience of the participants.

Table 3: Frequency distribution of level of experience of Delphi panel.

Years of Experience	Frequency	%
0-5 years	3	25%
6-10 years	1	8.33%
11-15 years	3	25%
16-20 years	1	8.33%
21+ years	4	33.33%

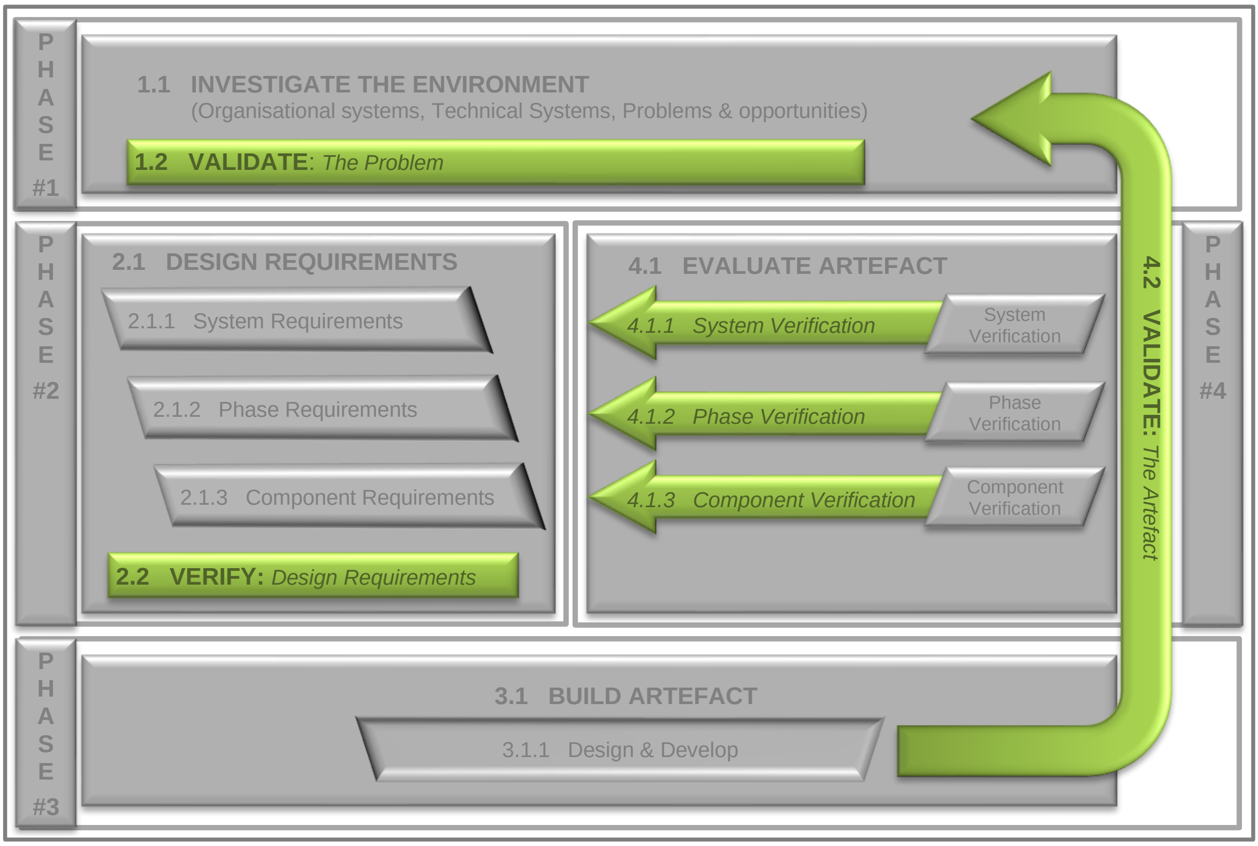

Figure 13: The Delphi technique highlighted in the DSR-Delphi-V-method.

Once the panel was selected, the research questions were developed with the purpose of confirming the relevance of each of the progressive steps in the DDV-Method.

Each questionnaire was set up according to a five-point Likert scale to measure the extent of agreement between the participants. The Likert scale consists of 5 points that range from strongly disagree (1) to strongly agree (5). During the response phase of the Delphi questionnaire, the experts were shown the results after each round, until consensus was reached (Nordin *et al*., 2012).

Consensus was defined as agreement between the experts on rating a particular item of the questionnaire. The minimum percentage of agreement on any particular question was set at 75% (Tigelaar *et al*., 2004). For this study, consensus was achieved when the experts rated each question with a score exceeding 3.7, which is 75% on a five-point Likert scale (Nordin *et al.,* 2012).

The first phase of the Delphi Technique (DDV step 1.2) was structured to seek agreement between the participants regarding the validation of the research problem. The results of the first phase were analysed to provide a foundation for the second phase of the questionnaire (DDV step 2.2), which was more specific.

The third phase (DDV steps 4.1.1 to 4.1.3) occurred during the evaluation of the artefact in Phase 4. During this phase, it was verified that the new artefact complied with all the design requirements that had been determined in Phase 2. Finally, the fourth phase (DDV step 4.2) focuses on validating the artefact to ensure that the artefact was fit for purpose.

3.3 Conclusion

This chapter elaborated on the research design that was followed for this study, with step-by-step instructions that enabled the successful application of the research design.

The DSR paradigm combined scientific precision with various design theories and industrial real-world applications to develop a useful artefact. The V-model provided a progressive path for completing every phase in the development cycle, with a directly associated verification phase. The Delphi technique, applied to the various phases during the development of the artefact, provided verification and validation of the artefact throughout.

The following chapters explain the application of the method and provide the results and/or findings of each research stage.

CHAPTER 4 – RESEARCH FINDINGS

In this chapter, the research findings are discussed through the application of the research design, described in the previous chapter.

The aim of the study was to design a standardised lean design process for purpose-built machine tools to improve the design time frame within which purpose-built machine tools are designed by the machine tool industry in South Africa. In this chapter the following research question is addressed:

> **Research question 4:** What are the requirements of a standardised lean design process, incorporating existing design models, to achieve an optimal conceptual design time frame?

The DDV-method (Figure 14) which was used to design a lean design process for purpose-built machine tools is shown below.

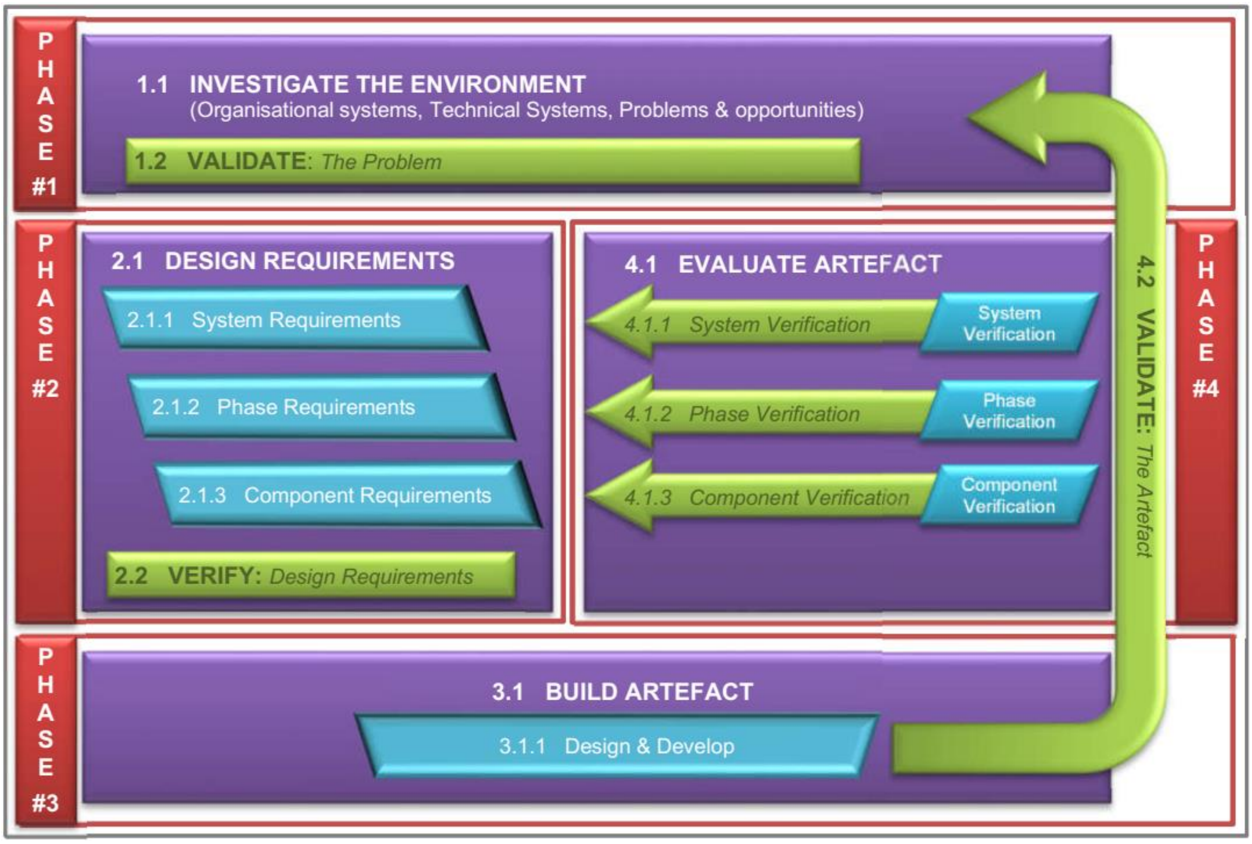

Figure 14: DDV-method.

The results of each of the four phases of the DDV-model is described in the sections below,

4.1 Phase 1: Investigating the environment

4.1.1 Current design process

During the execution of Phase 1 of the DDV-method (Figure 15), the Investigate the *Environment* phase of the DSR framework, the problem space in which the research problem lies was defined (as the V-model does not have an overlapping presence, it does not influence the first phase).

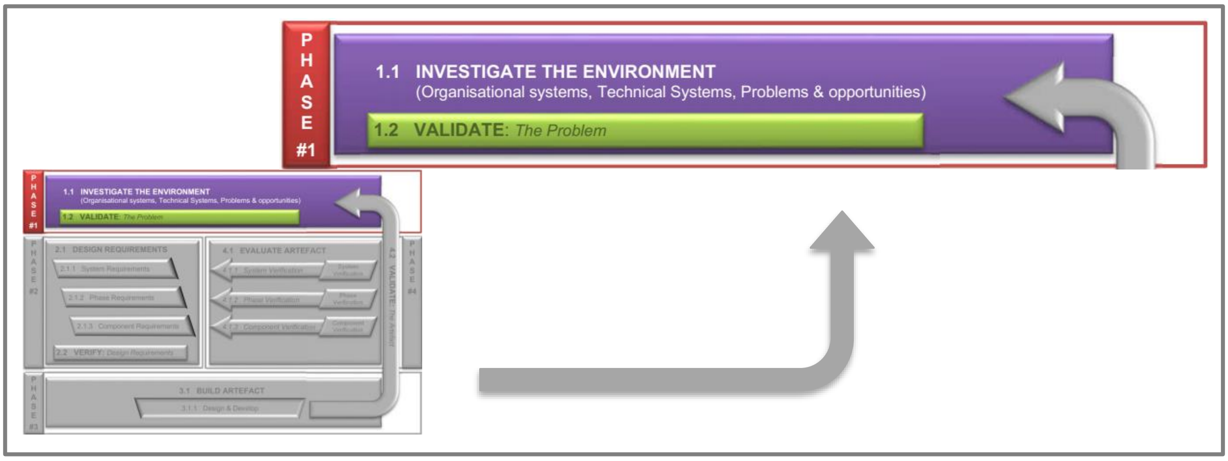

Figure 15: Phase 1 of DDV-method.

As shown in Figure 15, the first step (DDV step 1.1) was used to investigate the contextual environment in which the research project was undertaken. The application domain of the environment included an analysis of the organisational systems, technical systems, problems, and opportunities that currently exist within the research environment. The current design environment is shown in the flow chart (Figure 16), to represent the environment addressed by this research.

The flow chart represented in Figure 16 (discussed Section 1.2.2), represents the current engineering design environment where design errors, concept alterations and manufacturing changes takes place only during the final prototyping phase.

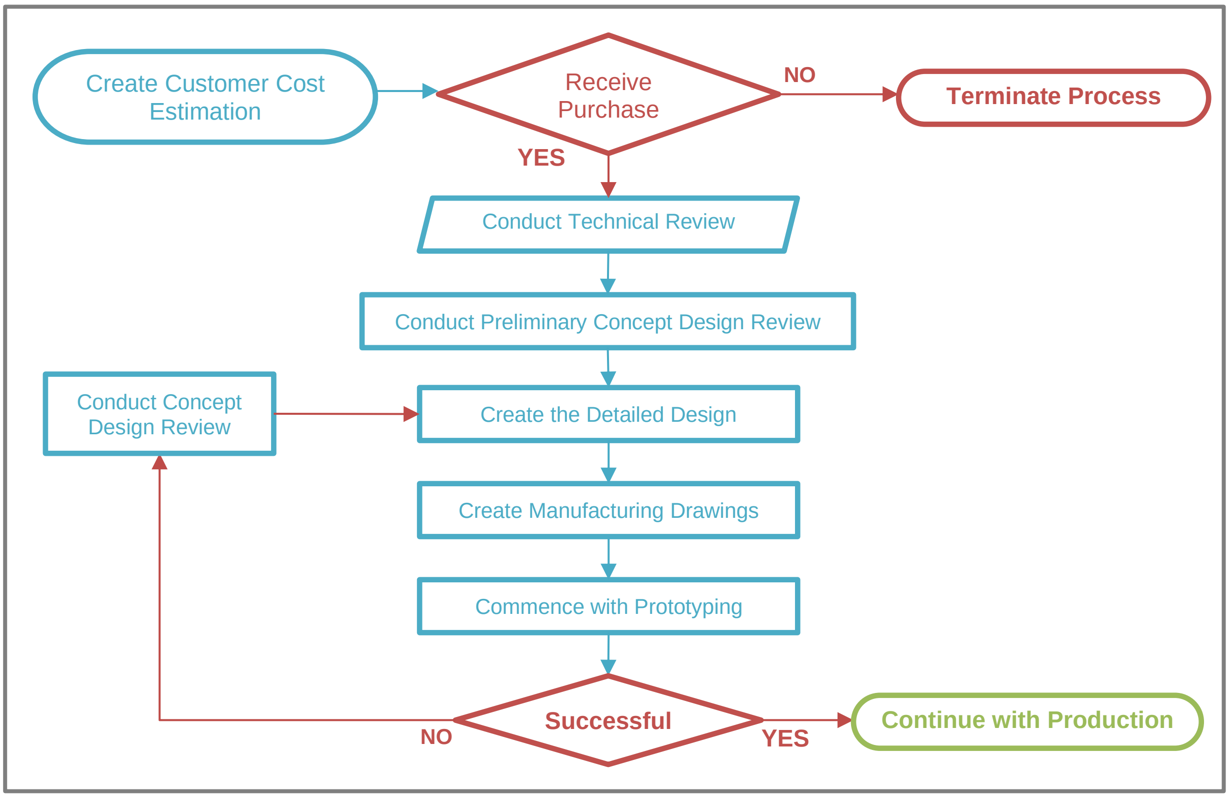

Figure 16: Flow chart of the current design process.

In Figure 16, an oval represents the start or end of a process, the parallelogram represents input, the rectangular blocks represent a process and red diamonds are decision blocks with a simple yes or no answer.

The current design process does not allow any review phases to ensure that the initial design requirements are met prior to manufacturing and prototyping. As a result, this process creates waste in the form of multiple changes to designs, revisions on manufacturing drawings and modifications to the actual parts and re-manufactured as a result. This process frustrates the artisan building the machine, as well as the machinist, who must conduct the rework on the manufactured parts. Consequently, all these elements add to time constraints and cost accumulation as a result of the waste.

As an example, for the design and building of a purpose-built machine for a customer, the assigned man-hours for the project were allocated to be 105 hours. This included the design and manufacturing of all parts of the machine. At the assembly stages, design changes and rework would be required if some of the components were not functional and could not be assembled as per the initial design. The design of certain components would then have to be revised, modifications to parts done and, in some instances, new parts would need to be manufactured and the machine would have to be re-assembled. The repercussions of the rework caused the project to go beyond the initial time frame allocated, used more resources than originally estimated and an additional 20 man-hours were used to re-assemble all the new components.

This is only an example to give context to how a typical purpose-built machine tool project would be executed, based on the current design process. It is important to remember that purpose-built machine tools are never exactly alike, and each machine has its own challenges in terms of complexity and functionality.

4.1.2 Results: Validation of problems statement

The first step of the Delphi technique (DDV step 1.2) was used to validate the research problem with the use of a questionnaire answered by a selected team, which had knowledge of the design of purpose-built machine tools. These questions are stated in Table 4. The participants had to rank their agreement with the statements on a 5-point Likert scale, ranging from strongly disagree (1) to strongly agree (5).

Table 4: Validation of the research problem with Delphi questions.

VALIDATION OF ENVIRONMENT	QUESTIONNAIRE *(Strongly Disagree, Disagree, Don't Know, Agree, Strongly Agree)*
1.1 Validity of the research problem.	**1.2 This section relates to the validity of the research problem.**
a) **The research problem should be a valid problem.**	a) The current design process for purpose-built machine tools is inefficient.
	b) The current process is not cost effective.
	c) The current design process is time consuming.

Table 5 shows the average of the response rate per question for the first round of the Delphi Technique.

Table 5: Participants' responses to validate the research problem.

QUESTION	PARTICIPANT LIKERTS SCORE												
NUMBER	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**AVG**
1.2 a)	5	4	3	2	3	1	5	4	5	4	4	5	**3.75**
1.2 b)	5	3	5	1	4	1	4	4	4	4	5	5	**3.75**
1.2 c)	5	4	4	2	5	2	5	4	4	4	4	5	**4**

Reflecting on the responses received for the three questions as indicated in Table 5, the lowest ranked scores according to the Likert scale (1 and 2) were used to indicate the outlying responders. The participants who awarded either 1 ("Strongly disagree") or 2 ("Disagree") were requested to elaborate on their response with additional open-ended answers to enrich the data. The original statements for evaluation were:

Question 1: The current design process for purpose-built machine tools is inefficient.
Question 2: The current process in not cost effective.

Question3: The current design process is time consuming.”

Table 6 shows the participants (P4 and P6) with their low response (1 or 2) for each question, as well as their open-ended responses.

Table 6: Open-ended responses of participants with low scores.

ORIGINAL QUESTION 1:		
Participant #	Score	Response:
P4	2	*“It is not completely inefficient. Simple improvements can be made to create a more efficient process.“*
P6	1	*“For simple designs, the process can be efficient.”*
ORIGINAL QUESTION 2:		
Participant #	Score	Response:
P4	1	*“Cost can be managed in various ways, and the process itself is not necessarily the reason for going over budget with projects.”*
P6	1	*“For simple designs, the process can be cost effective.”*
ORIGINAL QUESTION 3:		
Participant #	Score	Response:
P4	2	*“Time can be managed efficiently if the purpose is defined clearly.”*
P6	2	*“The current design process is suitable for simple designs and would not be time-consuming.”*

The following histograms in Figure 17 indicate the spread and the centrality pertaining to each of the questions, relevant to the environment. A short description related to each question is listed on the right of the histogram. For the question relating to the inefficiency of the current design, one can see that there were deviations on the response; and for the second and third questions, the responses were more positive.

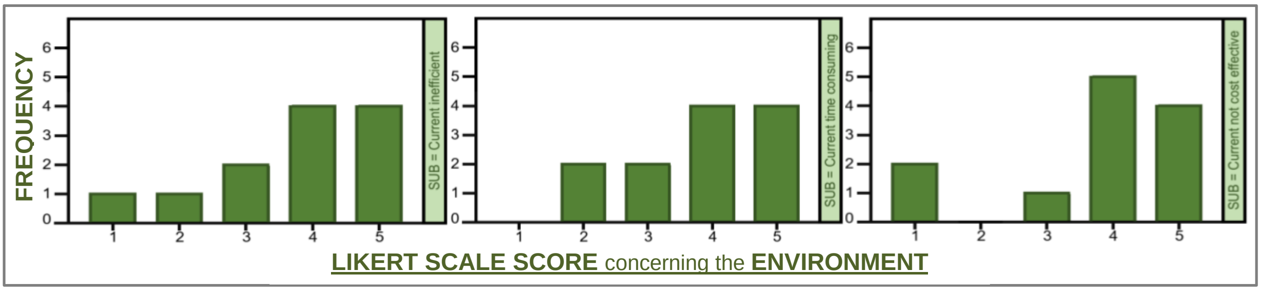

Figure 17: The spread and the centrality of the data for questions related to the environment.

The results of the first three questions are interpreted in the following section.

4.1.3 Discussion: Results for Phase 1

According to the feedback provided by the two participants that scored low on the Likert scale, when asked to motivate why they did not agree, the overall conclusion is that more focus should be given to project management. In addition, although the current process might be sufficient for a smaller project, an improved, more effective process will be required for more complex customer needs and for the design of complete purpose-built machine tools. Respondents did not indicate in their open-ended responses that the statements were incorrect: merely that they did not deem the problem as significant as indicated by the researcher and that there might possibly be other reasons for the problem.

The average scores of the Delphi panel (3.75 for question one and two, and 4 for the third question), confirmed that these problems are valid within the environment. Four of the participants indicated that they strongly agreed that the current design process for purpose-built machine tools is inefficient. In addition, four of the participants strongly agreed that the current design process is not cost-effective. Lastly, four of the participants strongly agreed that the current design process is time-consuming. From DDV step 1.2 it was confirmed that the main problem is that the process itself, from concept to production, is both costly and inefficient for the design of purpose-built machine tools.

The open-ended question results of the low responders give a broader prospective that gives future researchers an opportunity to investigate, apply and elaborate on future iterations of the DSR cycles used in this study.

4.2 Phase 2: Developing of design requirements

The second phase in the DDV-method (Figure 18) focused on the development of the *Design Requirements* for the artefact: the *System Requirements,* the *Phase Requirements* and lastly the *Component Requirements* of the artefact. These requirements are discussed in the sections below.

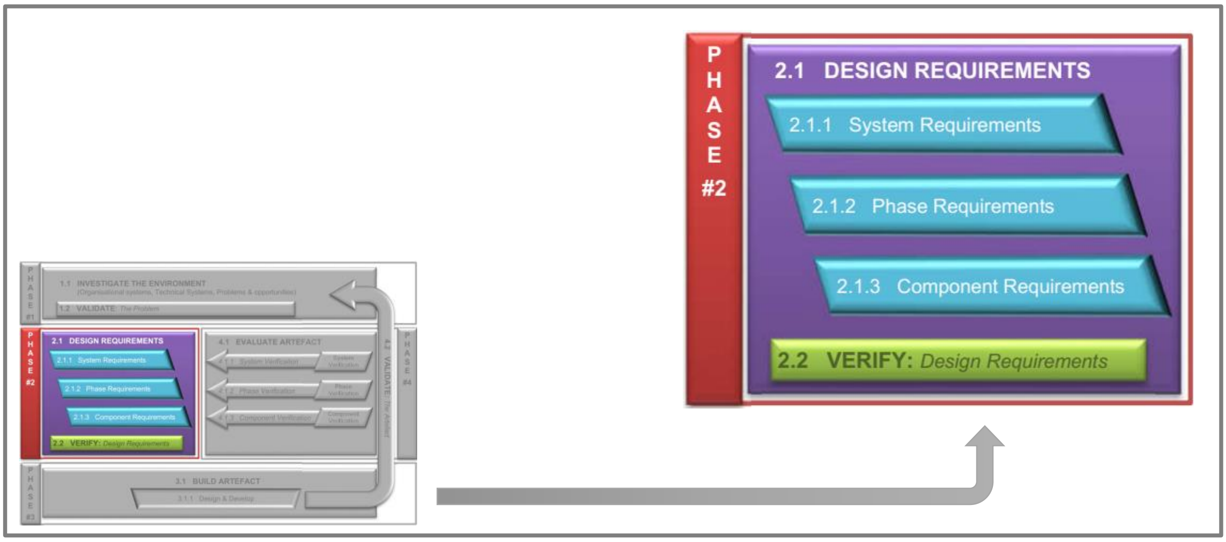

Figure 18: Phase 2 of DDV-method.

4.2.1 System requirements

The system requirements are the requirements of the entire system: in this case, the lean design process for purpose-built machine tools. The following inputs were used to determine the system requirements:

4.2.1.1 The lean philosophy

The following characteristics of the lean philosophy are important for lean implementation:

Respect for people is one of the key principles of the Toyota way and pillars of the TPS house respect each other. This includes making the effort to understand each other , taking responsibility and building mutual trust and good communication (Hoseus and Liker, 2008, Liker and Hoseus, 2008, Ohno, 1988).

Continuous improvement is Principle 6 of the Toyota way 2001. This principle is to standardise tasks to promote continuous improvement: continuous improvement initiatives that increase success and reduce failures (Hoseus and Liker, 2008).

Reduction of waste by utilising lean manufacturing processes (Ohno, 1988), is the third characteristic. Lean thinking is characterised as a powerful way to eliminate or to reduce rework to eliminate waste (Liker, 2004). *5S* consists of 5 elements that should create a disciplined, clean and well-organised design environment. These elements consist of sort, organising (set in order), clean (shine), standardise and sustain. By sorting and organising design requirements, an organised design environment is created, which assists machine tool designers to remove as much waste as possible from the design process. By using a standardised lean design process for purpose-built machine tools, continuous improvement and waste reduction comes naturally, but can only be sustained if the 5S is incorporated into the design (Chapman, 2005).

4.2.1.2 Implementation framework design criteria

The following criteria were considered as a guide for developing a sufficient framework (Baba *et al*., 2006). The framework should:

- Be organised and easy to interpret;
- Be simple in structure;
- Have clear links between the steps provided;
- Be general enough to suit different applications;
- Represent a road map and a planning tool for implementation.

According to Medori and Steeple (2000), the design requirements for developing a framework should be in agreement with company strategy and have a strong relationship with the six essential competitive priorities. These include quality, cost, flexibility, time, delivery and future growth. Ugural (2015) concurred that the system requirements should meet performance, safety, reliability, aesthetics and cost goals. Important concepts from the lean philosophy, such as waste reduction and continuous improvement, can be applied to the lean design process by analysing design in three different ways: (1) design as conversion of input to outputs; (2) design as a process of flow of information; and (3) design as a process of value-generation (Deshpande *et al*., 2011).

The system requirements from the lean philosophy and frameworks design literature, are summarised as follows:

System requirement (2.1.1a):	The model should include the following lean implementation principles: • Respect for people; • Continuous improvement; • Reduction of waste; • 5S.
System requirement (2.1.1b):	The model should consist of a simple structure.
System requirement (2.1.1c):	The sequence of the framework should be logical, systematic and easily understood.
System requirement (2.1.1d):	The model should be able to provide feedback on whether the outcomes of each phase were achieved.
System requirement (2.1.1e):	The model should save overall project cost and design time.
System requirement (2.1.1f):	The model should improve overall delivery.
System requirement (2.1.1g):	The model should be designed as a process or flow of information.

4.2.2 Phase requirements

Deshpande *et al*. (2011) stated that:

> *"The process of value generation depends on the quality of information available to the designers, as well as the ability of the design team to transform complex, uncertain, and conflicting requirements into solutions."*

The idea of making design decisions at the last possible moment is an important aspect of the design process used by Toyota - where the designers attempt to support numerous design solutions to a problem as late in the design process as possible (Ward *et al*., 1995). This philosophy eliminates the negative impacts of making a decision based on limited information early in the design process, which will eventually cause l modifications to the design and a negative ripple effect on the quality of design and the project schedule (Deshpande *et al*., 2011).

Waste can be eliminated from the design process by thoroughly reviewing the process to determine if the requirements provided by the client serve a specific applicable purpose in the project, or are just cosmetic features (Deshpande *et al*., 2011).

The 5S techniques are developed to ensure that the workplace is well-organised for best and most effective worker performance. These techniques include:

- Seiri (sort: the first step in making things organised);
- Seiton (set in order);
- Seiso (regular maintenance);
- Seiketsu (standardise);
- Shitsuke (sustain the improvements).

These techniques can be applied to the design environment and process to ensure effective organisation, to ensure work efficiency through improved organisation of the designer's workplace (documentation, filing systems, etc.) and the design process. It is important to find areas where work processes can be improved and improvements can be implemented (Deshpande *et al*., 2011).

The design process is based on the concept of the product life cycle. Every engineering design problem is unique to its environment, but the methodology for solving these problems is universal (Ugural, 2015). The phase requirements (DDV-method step 2.1.2) focus on the various phases within the lean design process. Each of these phases form a crucial part of the lean design process for the gathering of information. The phases are described in the following section.

Design input:	Design input is the physical and performance criteria, requirements and features of the product, which are used as a basis for design.
Concept design:	Concept design is the first phase in the design process. During this phase, the broad outlines of the design are articulated. Concept design can be presented as a sketch or model.

Detailed design (Sub-assemblies): Detailed machine design is the use of scientific principles and engineering techniques to create a machine economically, to meet the requirements of a client.

Final design: The final design incorporates all the factors that need to be considered to make the design a working model.

Manufacturing drawings: Manufacturing drawings are complete sets of drawings that detail the manufacturing and assembly of the product designed in the previous phases.

The phase requirements for the design processes are summarised as follows:

Phase requirement (2.1.2a): The model should have a phase in which design input information is determined.

Phase requirement (2.1.2b): The model should have a phase for ideation and invention (concept phase).

Phase requirement (2.1.2c): The model should have a phase for evaluating the concept design.

Phase requirement (2.1.2d): The model should have a phase for detailed design of sub-assemblies and components.

Phase requirement (2.1.2e): The model should have a phase for evaluating the design of the integration of the sub-assemblies prior to manufacturing.

Phase requirement (2.1.2f): The model should have a phase for the final design of the machine.

Phase requirement (2.1.2g): The model should have a phase for creating manufacturing drawings.

4.2.3 Component requirements

The component requirements consist of the design inputs that dictate the specifications and functionalities that the final product should adhere to. These are referred to as the functional and performance requirements, as well as the statutory and regulatory requirements. The statutory and regulatory requirements are the various ISO and safety standards from the OSH act that need to be considered when designing purpose-built machine tools. The component requirements

(DDV-method step 2.1.3) focus on the review and documentation of each of the requirements in the design phases. The component requirements are listed as follows:

Technical review:

During this review, all the functional and performance requirements, statutory and regulatory requirements are reviewed and documented.

Concept design review:

The concept review requirements include the method study as well as the feasibility of the concept. The requirements are documented and used to develop the detailed design.

Detailed design review:

During the detailed design review, requirements should be evaluated and documented. These include material specifications for specific applications, coupling methods and drive train specifications for the sub-assemblies.

Review of sub-assembly integration:

During this review, the integration of the sub-assemblies should be evaluated and documented to assist in the practical assembling of the sub-assemblies.

Final design review:

The final design review requirements are to evaluate the functionality of the design against the initial design inputs and to present the final design to the client.

Manufacturing drawing review:

The manufacturing drawings should contain the necessary information for the components to be accurately manufactured. All dimensions, material specifications, surface finishes and heat treatment information should be clearly indicated. Part names and drawing numbers on manufacturing drawings are also an essential requirement.

The component requirements for design processes, according to literature, are addressed as follows:

Component requirement (2.1.3a): The model should have a component for technical review.

Component requirement (2.1.3b): The model should have a component for concept review.

Component requirement (2.1.3c): The model should have a component for detailed design review of the sub-assemblies.

Component requirement (2.1.3d): The model should have a component for review of the integration of the sub-assemblies.

Component requirement (2.1.3e): The model should have a component for final design review of the complete machine.

Component requirement (2.1.3f): The model should have a component for manufacturing drawing review.

4.2.4 Results: Verification of Phase 2

During the second phase of the DDV-method, the Delphi questionnaire was presented to a panel of experts and applied to verify the set of design requirements developed in this phase (DDV step 2.2).

As described in section 4.2.1, to 4.2.3, there were three phases within the design requirements: system requirements, phase requirements and component requirements. The verification of these design requirements is discussed in the following sub-section.

4.2.4.1 Verification of Design requirements

The design requirements of the artefact consist of three subsections: system requirements, phase requirements and component requirements. The Delphi questions which focus on the system requirements of the artefact are stated in Table 7; and Table 8 represents the responses of the participants who participated in the questionnaire - with responses ranging from 1 (strongly disagree) to 5 (strongly agree), according to the Likert scale.

Table 7: Verification of system requirements as design requirements with Delphi questions.

VERIFICATION OF DESIGN REQUIREMENTS	QUESTIONNAIRE (Strongly Disagree, Disagree, Don't Know, Agree, Strongly Agree)
2.1.1 System requirements	**2.2.1 This section relates to the system requirements of the artefact**
a) The model should address lean implementation fundamentals	a) The model should include the following lean principles: ▪ Respect for people ▪ Continuous improvement ▪ Reduction of waste ▪ 5 S
b) Simple in structure	b) The design of the model should be simple in structure
c) The sequence of the framework should be logical, systematic, and easily understood.	c) The sequence of the model should be logical and easy to understand.
d) The model should be able to provide feedback on whether the outcomes have been achieved.	d) The lean design process should provide feedback on whether the outcome has been achieved.

e) The model should save overall project cost and design time.	e) The lean design process should save project cost and design time.
f) The model should improve overall delivery.	f) The lean design process should improve project delivery.
g) The model should be designed as a process of flow of information.	g) The lean design process should present a flow of information.

Table 8: Participants' responses to validate the system requirements as design requirements.

QUESTION	PARTICIPANT LIKERT SCORE												
NUMBER	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**AVG**
2.2.1 a)	5	5	4	4	4	4	4	5	3	5	5	4	4.33
	5	5	5	4	4	5	5	5	4	5	5	4	4.67
	5	5	5	4	5	4	5	4	4	5	4	4	4.50
	4	4	4	3	4	4	5	5	3	5	4	4	4.10
2.2.1 b)	4	5	4	5	1	4	4	4	3	4	3	4	3.75
2.2.1 c)	4	5	4	5	4	5	4	5	5	4	5	4	4.50
2.2.1 d)	4	5	4	5	2	5	4	4	5	4	4	4	4.16
2.2.1 e)	4	1	5	4	1	5	5	4	4	5	5	5	4.00
2.2.1 f)	3	5	4	5	5	5	3	4	5	4	4	5	4.33
2.2.1 g)	4	5	4	5	4	5	4	5	5	4	5	5	4.58

Only four low-scoring responses received for the seven questions are indicated in Table 9. This includes only the participants who awarded either 1 (Strongly disagree) or 2 (Disagree), and after the completion of the original questionnaire, these respondents were requested to elaborate on their response by means of specific additional open-ended questions, to enrich the data.

Table 9 shows the participants (numbered P2 and P5) with their low responses (1or 2) for each question as well as their open-ended responses.

Table 9: Open-ended responses of participants with low responses.

ORIGINAL QUESTION 2.2.1 b)		*The design of the model should be simple in structure*
Participant #	Likert score	Response
P5	1	*"At the first glance, the design of the model is not simple in structure. It is a busy flow chart with lots of information."*
ORIGINAL QUESTION 2.2.1.d)		*The lean design process should provide feedback on whether the outcome has been achieved.*
Participant #	Likert score	Response
P5	2	"*Depending on the type of design project, feedback might not always be necessary."*
ORIGINAL QUESTION 2.2.1 e)		*The lean design process should save project cost and design time.*
Participant #	Likert score	Response
P2	1	*"Any design process with step-by-step instructions would improve a design process."*
P5	1	*"Quality of the design is more important than the cost or time limitations in some instances."*

A sub-section of phase two is to verify the phase requirements as set design requirements developed in this phase 2 (DDV step 2.2). The Delphi questions are stated in Table 10 with the participants' responses presented in Table 11.

Table 10: Verification of phase requirements as design requirements with Delphi questions.

VERIFICATION OF DESIGN REQUIREMENTS	**QUESTIONNAIRE (Strongly Disagree, Disagree, Don't Know, Agree, Strongly Agree)**
2.1.2 Phase requirements	**2.2.2 This section relates to the phase requirements of the artefact**
a) The model should have a phase where design input information is determined.	a) The lean design process should have a phase to document design inputs.
b) The model should have a phase for ideation and invention (concept phase).	b) The lean design process should have a concept phase.
c) The model should have a phase for evaluating the concept design.	c) The lean design process should have an evaluation of the concept phase.
d) The model should have a phase for detailed design of sub-assemblies and components.	d) The lean design process should have a phase for detailed design of sub-assemblies and components.
e) The model should have a phase for evaluation of the design integration of the sub-assemblies.	e) The lean design process should have a phase for evaluating the design integration of the sub-assemblies.
f) The model should have a phase for final design review of the complete machine.	f) The lean design process should have a phase for final design of the machine.
g) The model should have a phase for creating and reviewing of manufacturing drawings.	g) The lean design process should have a phase for creating manufacturing drawings

Table 11: Participants' responses to validate the phase requirements as design requirements.

QUESTION	PARTICIPANT LIKERTS SCORE											
NUMBER	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**AVG**
2.2.2 a)	4	5	4	5	4	5	5	4	4	4	5	4	**4.42**
2.2.2 b)	4	5	4	5	4	5	5	4	4	4	5	4	**4.42**
2.2.2 c)	5	5	4	5	4	5	4	4	4	4	5	4	**4.42**
2.2.2 d)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.2 e)	5	5	4	5	4	5	4	4	4	4	5	4	**4.42**
2.2.2 f)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.2 g)	3	5	4	3	4	5	4	4	4	3	5	5	**4.10**

No significant low scoring responses were received for the seven questions, as indicated in Table 10. This includes only the participants who awarded either 1 (Strongly disagree) or 2 (Disagree). The average score of each of the questions was above 4: therefore, no additional open-ended questions were required to enrich the data.

The third sub-section of phase two is to verify the component requirements as part of the set design requirements developed in this phase 2 (DDV step 2.2). The Delphi questions and participants' responses are presented in Table 12 and Table 13 respectively.

Table 12: Verification of component requirements as design requirements with Delphi questions.

VERIFICATION OF DESIGN REQUIREMENTS	QUESTIONNAIRE (Strongly disagree, disagree, don't know, agree, strongly agree)
2.1.3 Component requirements	**2.2.3 This section relates to the component requirements of the artefact**
a) The model should have a component for technical review requirements.	a) The lean design process should have a component for technical review requirements.
b) The model should have a component for concept review.	b) The lean design process should have a component for concept review.
c) The model should have a component for detailed design review.	c) The lean design process should have a component for detailed design review.
d) The model should have a component for the integration of the sub-assemblies.	d) The lean design process should have a component for the integration of sub-assemblies.
e) The model should have a component for final design review.	e) The lean design process should have a component for final design review.
f) The model should have a component for manufacturing drawing review.	f) The lean design process should have a component for manufacturing drawing review.

Table 13: Participants' responses to validate the component requirements as design requirements.

QUESTION	PARTICIPANT LIKERTS SCORE											
NUMBER	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**AVG**
2.2.3 a)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.3 b)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.3 c)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.3 d)	5	5	4	4	4	4	4	4	4	4	5	4	**4.25**
2.2.3 e)	5	5	4	5	3	5	4	4	4	4	5	5	**4.42**
2.2.3 f)	3	5	4	3	3	4	4	4	4	3	5	4	**3.83**

No outlying responses were received for the seven questions, as indicated in Table 10. No additional open-ended questions were required to enrich the data.

Table 8 shows the questions and responses from the team of experts according to the Likert scale, for the first round of the Delphi Technique. The histograms in Figure 19, Figure 20,

Figure 21, Figure 22 and Figure 23 indicate the spread and the centrality pertaining to each of the questions relevant to the environment. A short description related to each question is listed on the right of the histogram. For the question relating to the inefficiency of the current design, one can see that there was not a clear-cut positive response. For the second and third question the responses were more positive.

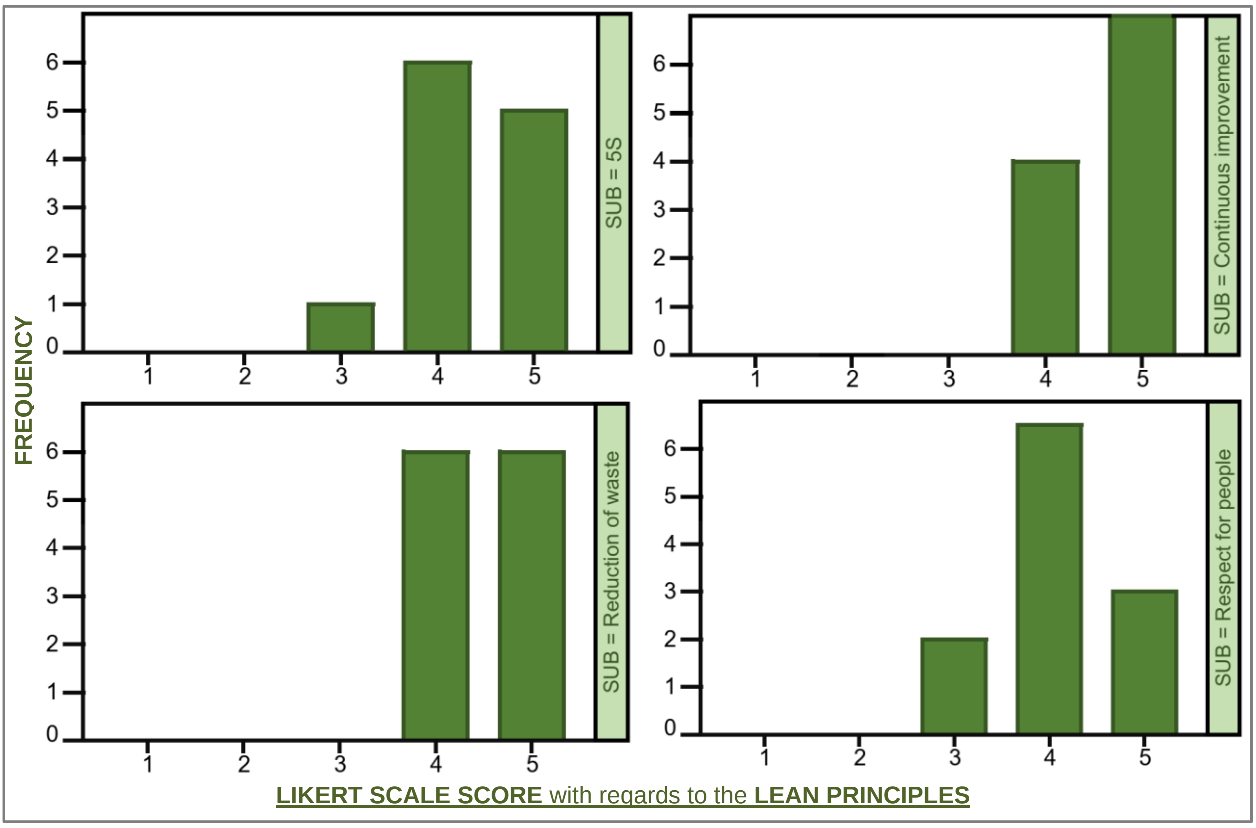

Figure 19: The spread and the centrality of the data for questions related to the lean principles.

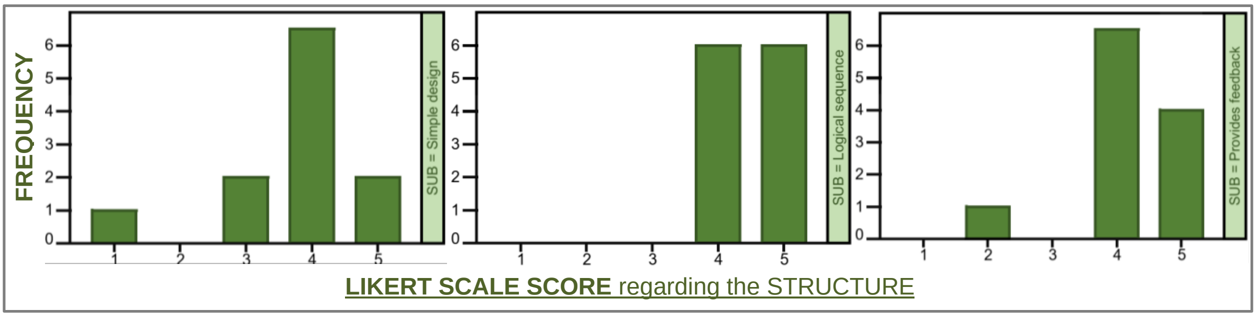

Figure 20: The spread and the centrality of the data for questions related to the structure of the improved flow chart.

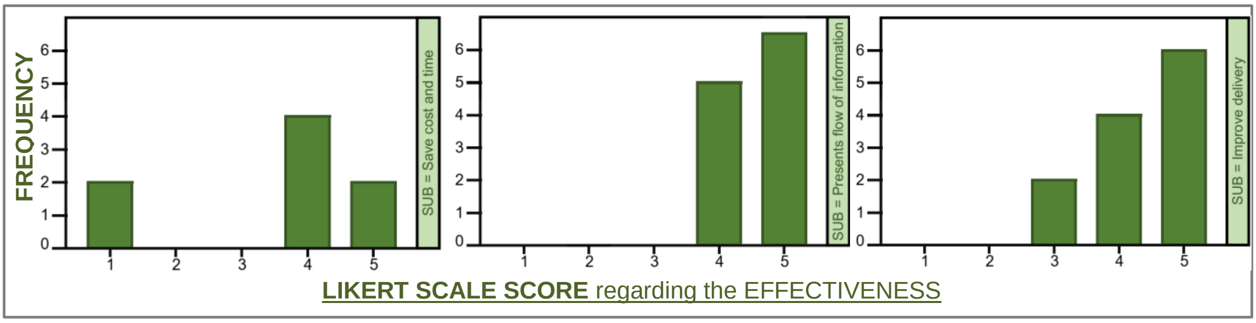

Figure 21: The spread and the centrality of the data for questions related to the effectiveness of the improved design process.

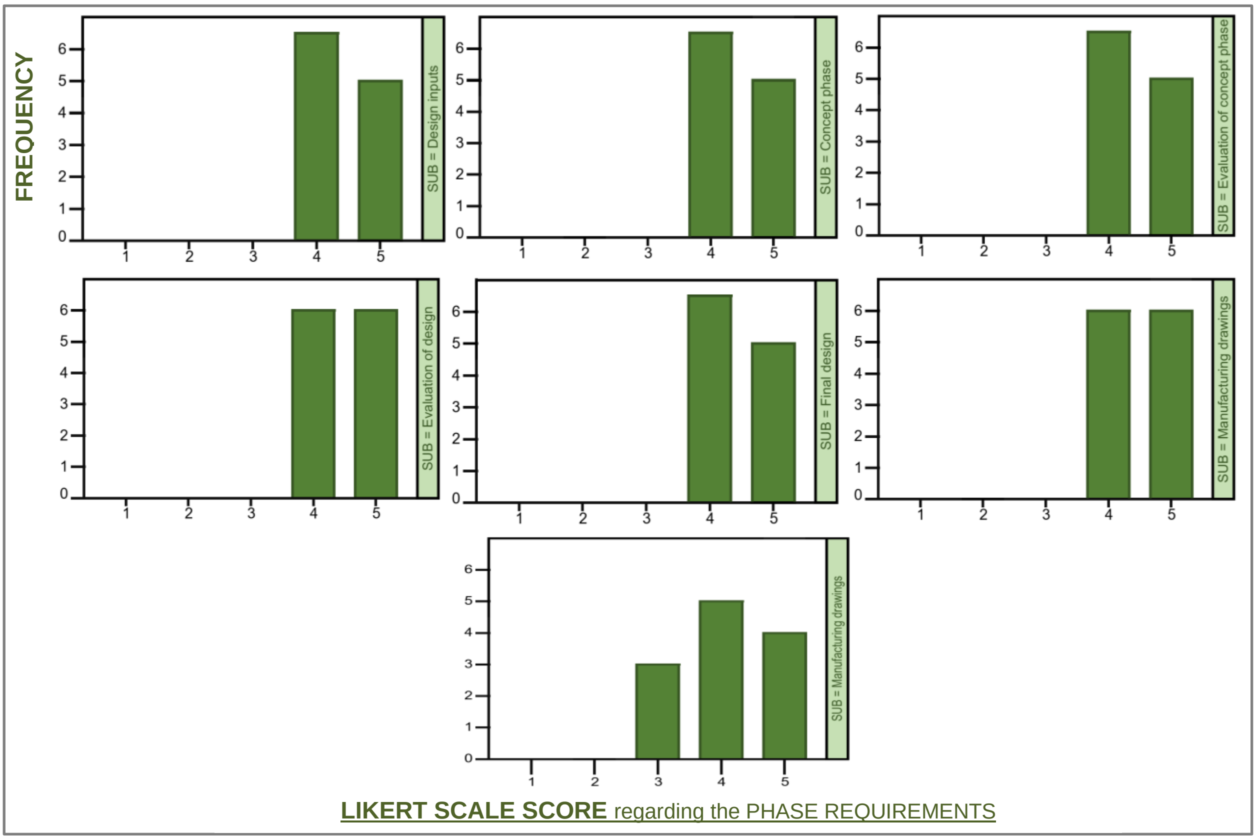

Figure 22: The spread and the centrality of the data for questions related to the phase requirements of the improved design process.

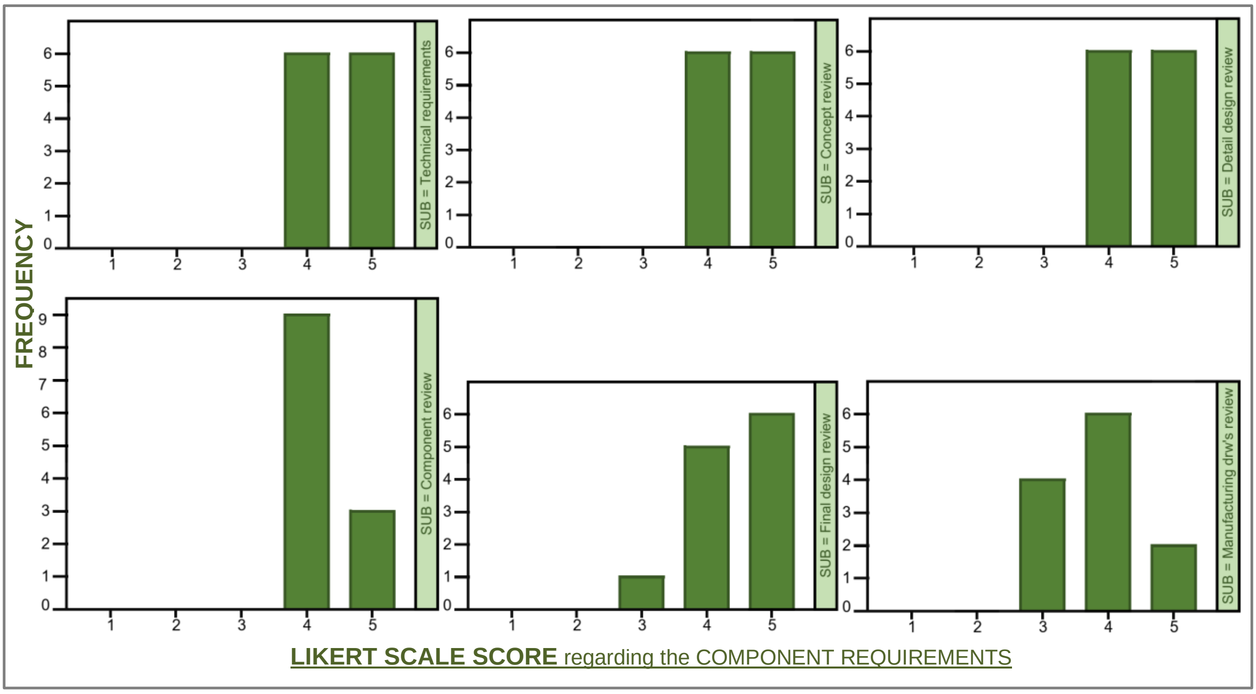

Figure 23: The spread and the centrality of the data for questions related to the component requirements of the improved design process.

The findings of phase two are presented next.

4.2.5 Discussion: Results for Phase 2

Reflecting on the low scoring responses received for the three questions as indicated in Table 8, the lowest ranked scores according to the Likert scale are used to indicate the outlying responders. The participants who awarded either 1 (Strongly disagree) or 2 (Disagree) were requested after the completion of the original questionnaire to elaborate on their response. These specific participants were asked to elaborate on their low scores.

The results of the questions and responses from the team of experts according to the Likert scale for the Delphi technique are provided in Table 8,Table 9, Table 11 and Table 13. The Delphi panel confirmed that the set design requirements developed in this phase, are valid.

The design requirements of the DDV-method step 2.1 were verified as the results from Table 8, Table 9, Table 11 and Table 13 have a score above 3.75. These requirements will be used in the following phase. The histograms (Figure 19 to Figure 23), provide a graphical representation of the frequency of reoccurrence of the results for easy interpretation.

4.3 Phase 3: Building of the artefact

DDV step 3.1 of the third phase of the DDV-method focused on *Building of the Artefact* from the DSR paradigm and the *Design and Develop* sections from the V-model. The artefact was the result of the design and development process, using the design requirements determined in the previous phase as shown in Figure 24.

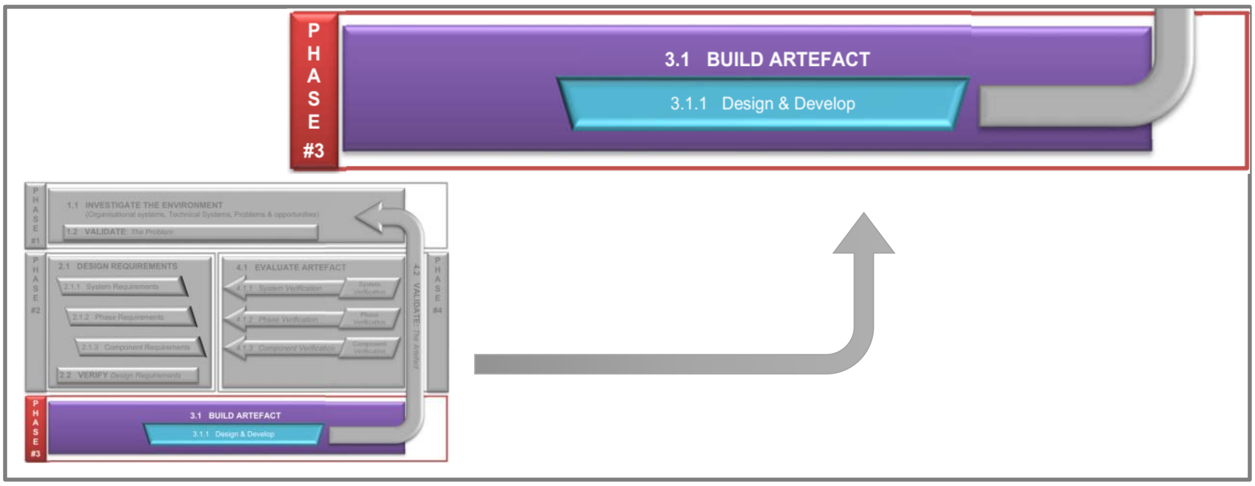

Figure 24: Phase 3 of DDV-method.

The artefact is considered as the future state process flow that will improve the design process for purpose-built machine tools, by using a more efficient design process that will consequently save time and money.

4.3.1 Findings for Phase 3

By utilising the design requirements determined in Phase 2, the improved design process was designed and developed to form the artefact (Figure 25). The aim of the process flow of the improved design process is to eliminate as much waste as possible, to contribute towards a lean culture and continuous improvement. The flow chart focuses on design reviews to eliminate waste prior to manufacturing. This alteration from the current design process to the improved design process has the potential to save time, reduce re-work and waste. For example: at the South Africa-based company involved in this research, a team consisting of various experts in the field, brainstormed the design during the design review phase before manufacturing, to eliminate possible assembly and manufacturing constraints. The goal of the artefact is to address the current problem of having multiple design iterations after manufacturing.

The first phase of the flow chart is to determine the design input. To initialise the process flow chart (Figure 25), a request is made by a client who requires a quote for the design, manufacture and building of a purpose-built machine tool. The first block (technical review) is the most important phase of the design process. During this phase, all technical information, including functional, performance and safety requirements, are specified by the client. The next block represents the compilation of the preliminary scope of work (SOW), which includes the technical specifications determined in the previous phase.

From the technical specifications, a preliminary concept design is prepared, either by making a sketch or a simple CAD model, to provide sufficient information to enable a detailed quotation to be compiled. This fixes the scope of work with a pricing element that includes the cost of design, manufacturing, assembly and commissioning of the machine. Before the final quote is submitted to the client, the client has to approve the competence of the concepts. Once the purchase order has been received, the actual CAD concept design phase will commence and the technical requirements - determined during the first phase - will be used as guidelines.

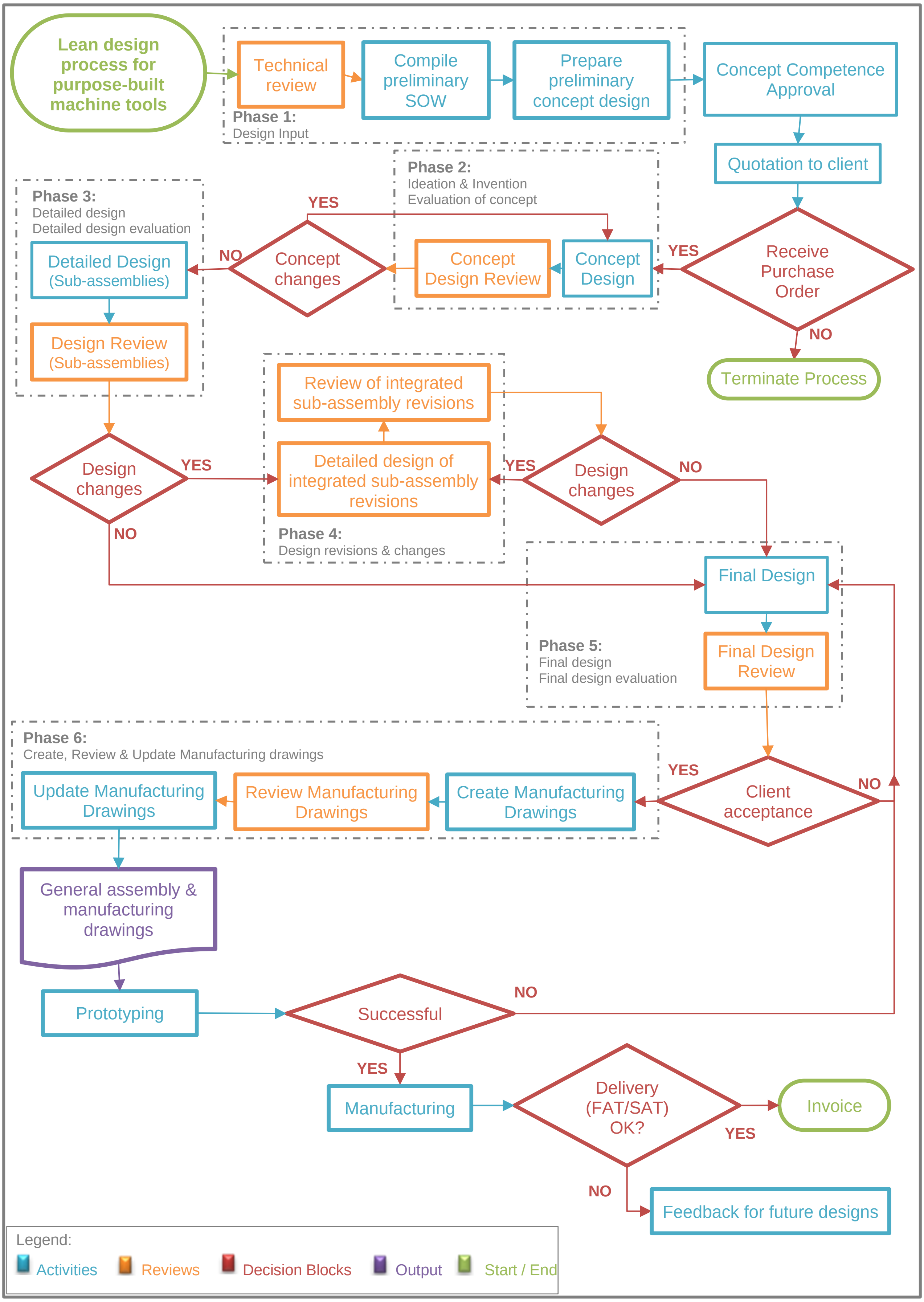

Figure 25: Flow chart for the lean design process for purpose-built machine tools.

The next phase is the concept design review, which consists of a session between the multi-disciplinary project team members to determine whether the concept is the best possible method of achieving the desired outcome. The decision block allows for conceptual changes to determine the best possible solution before continuing to the detailed design. Once the most feasible concept has been selected, the designer will then design the components and sub-assemblies.

The next decision block provides for continuous improvements by allowing design changes and updates for the integration of the components and sub-assemblies, and to flush out all possible obstructions that might influence the final design of the complete machine. The design review block (with the multi-disciplinary project team) focuses on the greater detail of the design, including functionalities and drive mechanisms. This process can be cyclical until the best version of the design emerges. This might add to design time, but it will eliminate the physical waste of parts in the manufacture for prototyping that will not be used due to design changes or extensive re-work. By eliminating as much waste as possible on the components and sub-assemblies of the CAD model, the final design will include a simulation of the moving parts of the machine as well as interference checks and possible finite element analysis, if required.

The next decision block is interaction with the client to ensure that they are satisfied with the design. Once the design has been accepted, the manufacturing drawings can be created, reviewed and updated (should there be any changes).

The design output is the set of manufacturing drawings as well as the general assembly of the machine on CAD. The manufacturing drawings are then used to initiate the manufacturing process for prototyping. If prototyping is not successful, iterations of the process can be done by revisiting the final design and following the cyclical process flow from there on. If the prototyping is successful, the machine is completed and delivered to the customer for commissioning into factory production.

The improved design process focuses more on various design and review phases to eliminate as much waste as possible and to use the lean philosophy of continuous improvement and the 5S method to standardise and continuously improve the design process, to finally obtain the best possible version of the CAD design, prior to manufacture.

4.4 Phase 4: Evaluating the artefact

The final phase of the DDV-method was to verify the artefact in terms of compliance with the design requirement and to validate that the artefact addresses the research problem, by ensuring that the underlying theoretical claim is true and that the artefact is relevant (Hevner *et al.*, 2018).

The Evaluate section of the DSR and the verification and validation stages of the V-model were combined to continuously ensure that the artefact design remained relevant.

The Delphi technique was used to verify that the artefact complied with the system, phase and component requirements as determined in Phase Two. The Delphi technique was also used to determine the validity of the artefact in terms of addressing the problem identified in Phase One (Figure 26).

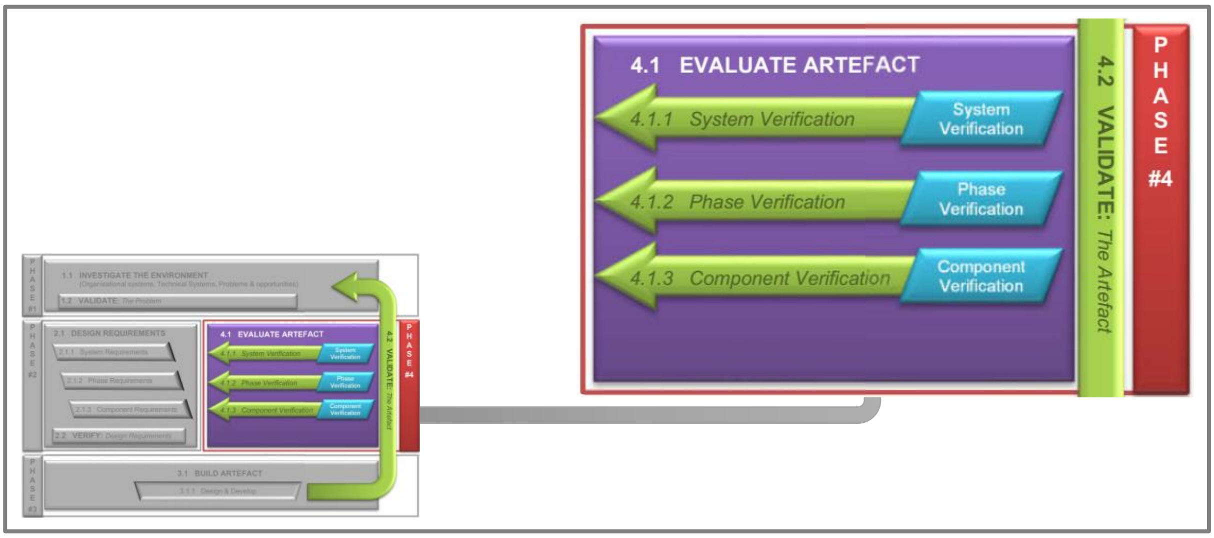

Figure 26: Phase 4 of DDV-method.

4.4.1 Results: Verification of the design requirements

DDV step 4.1 requires that the artefact be evaluated. The artefact was verified against the design requirements by means of specific questions in the Delphi questionnaire, indicated in Table 14. The participant’s responses are presented in Table 15.

Table 14: Verification of the artefact with Delphi questions.

VERIFICATION OF ARTEFACT	**QUESTIONNAIRE** *(Strongly Disagree, Disagree, Don't Know, Agree, Strongly Agree)*
2.1.1 System requirements	**2.2.1 This section relates to the system requirements of the artefact**
a) The model should address lean implementation fundamentals	a) The model includes the following lean principles: ▪ Respect for people ▪ Continuous improvement ▪ Reduction of waste ▪ 5 S
b) Simple in structure	b) The design of the model is simple in structure.
c) The sequence of the framework should be logical, systematic and easily understood.	c) The sequence of the model is logical, systematic and easy to understand.
d) The model should be able to provide feedback on whether the outcomes have been achieved.	d) The lean design process provides feedback on whether the outcome has been achieved.
e) The model should save overall project cost and design time.	e) The lean design process would save project cost and design time.
f) The model should improve overall delivery.	f) The lean design process would improve project delivery.
g) The model should be designed as a process of flow of information.	g) The lean design process presents a flow of information.
2.1.2 Phase requirements	**2.2.2 This section relates to the phase requirements of the artefact**
a) The model should have a phase where design input information is determined.	a) The lean design process has a phase to document design inputs.
b) The model should have a phase for ideation and invention (concept phase)	b) The lean design process has a concept phase.
c) The model should have a phase for evaluating the concept design.	c) The lean design process has an evaluation of the concept design phase.
d) The model should have a phase for detailed design of sub-assemblies and components.	d) The lean design process has a phase for detailed design of sub-assemblies and components.
e) The model should have a phase for evaluation of the design integration of the sub-assemblies.	e) The lean design process has a phase for evaluating the design integration of the sub-assemblies.
f) The model should have a phase for final design review of the complete machine.	f) The lean design process has a phase for final design of the machine.
g) The model should have a phase for creating and reviewing of manufacturing drawings.	g) The lean design process has a phase for creating manufacturing drawings
2.1.3 Component requirements	**2.2.3 This section relates to the component requirements of the artefact**
a) The model should have a component for technical review requirements.	a) The lean design process has a component for technical review requirements.
b) The model should have a component for concept review.	b) The lean design process has a component for concept review.
c) The model should have a component for detailed design review.	c) The lean design process has a component for detailed design review.
d) The model should have a component for the integration of the sub-assemblies.	d) The lean design process has a component for the integration of sub-assemblies.
g) The model should have a component for final design review.	g) The lean design process has a component for final design review.
h) The model should have a component for manufacturing drawing review.	h) The lean design process has a component for manufacturing drawing review.

Table 15: Participant’s responses to verify the component requirements as design requirements.

QUESTION NUMBER	PARTICIPANT LIKERTS SCORE												QUESTION AVG
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	
2.2.1 a)	5	5	4	4	4	4	4	5	3	5	5	4	**4.33**
	5	5	5	4	4	5	5	5	4	5	5	4	**4.67**
	5	5	5	4	5	4	5	4	4	5	4	4	**4.50**
	4	4	4	3	4	4	5	5	3	5	4	4	**4.08**
2.2.1 b)	4	5	4	5	1	4	4	4	3	4	3	4	**3.75**
2.2.1 c)	4	5	4	5	4	5	4	5	5	4	5	4	**4.50**
2.2.1 d)	4	5	4	5	2	5	4	4	5	4	4	4	**4.17**
2.2.1 e)	4	1	5	4	1	5	5	4	4	5	5	5	**4.00**
2.2.1 f)	3	5	4	5	5	5	3	4	5	4	4	5	**4.00**
2.2.1 g)	4	5	4	5	4	5	4	5	5	4	5	5	**4.58**
2.2.2 a)	4	5	4	5	4	5	5	4	4	4	5	4	**4.42**
2.2.2 b)	4	5	4	5	4	5	5	4	4	4	5	4	**4.42**
2.2.2 c)	5	5	4	5	4	5	4	4	4	4	5	4	**4.42**
2.2.2 d)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.2 e)	5	5	4	5	4	5	4	4	4	4	5	4	**4.42**
2.2.2 f)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.2 g)	3	5	4	3	4	5	4	4	4	3	5	5	**4.08**
2.2.3 a)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.3 b)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.3 c)	5	5	4	5	4	5	4	4	4	4	5	5	**4.50**
2.2.3 d)	5	5	4	4	4	4	4	4	4	4	5	4	**4.25**
2.2.3 e)	5	5	4	5	3	5	4	4	4	4	5	5	**4.42**
2.2.3 f)	3	5	4	3	3	4	4	4	4	3	5	4	**3.83**

The results of the questions and responses from the team of experts according to the Likert scale, for the Delphi technique, as provided in Table 14 and Table 15, therefore verified that the model adheres to all the design requirements, by achieving consensus. Each question has a score exceeding 3.7 on the five-point Likert scale.

The validation of the artefact will be discussed in the section to follow.

4.4.2 Results: Validation of the artefact

DDV step 4.2 was used to validate that the newly design process addresses the research problem.

The validation was determined by including specific questions in the Delphi questionnaire (Table 16) to prove that the artefact was valid in terms of the system, phase and component requirements.

Table 16: Validation of the research problem.

VALIDATION OF ENVIRONMENT	QUESTIONNAIRE *(Strongly Disagree, Disagree, Don’t Know, Agree, Strongly Agree)*
4.2 Validity of the artefact	**This section relates to the validity of the research problem**
a) The artefact should address the research problem	a) The artefact could be used as a standardised design process.
	b) The artefact could provide a more cost-effective design process.
	c) The artefact could shorten the overall project time frame from concept to prototyping.

Table 17: Participant’s responses to validate the research problem.

QUESTION	PARTICIPANTS’ LIKERTS SCORE												QUESTION AVG
NUMBER	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	
4.2 a)	4	4	4	5	3	5	5	4	5	5	5	5	**4.50**
4.2 b)	4	5	4	5	4	5	5	4	5	4	5	5	**4.58**
4.2 c)	3	4	4	5	3	4	3	5	5	5	4	5	**4.17**

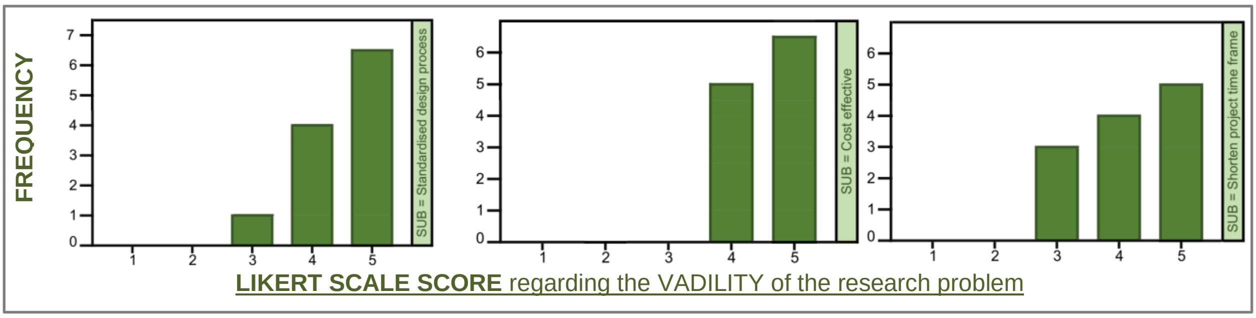

Figure 27: The spread and the centrality of the data for questions related to the validation of the research problem.

The histogram in Figure 27 shows the frequency recurrence and gives a clear indication of the results for the validation of the research problem. As a result, the majority of the Delphi experts awarded four and five on the Likert scale.

The results of Phase Four are discussed next.

4.4.3 Discussion: Results of Phase Four

The results of the questions and responses from the panel of experts to verify the artefact in terms of compliance with the design requirement; and to validate that the artefact addresses the research problem, are shown in Table 17. As defined in section 3.2, consensus is the agreement between the experts on rating a particular item of the questionnaire. If an average of more than 3.7 is therefore achieved, consensus is reached. The Delphi panel’s scores are on average above 4 for all three of the validation questions. Therefore, the results indicate that consensus is reached and that the research problem is a valid problem. The histogram (Figure 27) also clearly indicates that the research problem is a valid problem.

4.5 Conclusion

This chapter provided the results and findings of the DDV-method used to design the artefact. The quantitative feedback of the Delphi technique was used to verify the artefact against the design requirements to validate the research problem.

CHAPTER 5 – VERIFICATION

Verification can be defined as the process of checking and confirming. In qualitative research, verification refers to the technique used during the process of research to cyclically contribute to ensuring the rigour of a study. Verification plans help to determine when to continue, stop or modify the research process to attain reliability and validity and warrant rigor (Morse *et al*., 2002).

The purpose of this research was to develop a standardised design process for purpose-built machine tools, by utilising lean principles. Chapter 3 focused on the novel research design that is specific and structured in nature. Chapter 4 focused on the application of the research design that included the research findings and results.

The purpose of Chapter 5 is to verify that the artefact is relevant and adheres to the design requirements, with an overview of the findings of the verification process which are provided in reference to the following research question:

Research question 5: Does the artefact adhere to the specified design requirements?

5.1 Verification method

The design requirements for the artefact were determined in Chapter 4 and applied during the design of the artefact. These design requirements were reviewed to verify that they were part of the design inputs.

Verification of adherence to these design requirements was achieved by means of the following inputs:

The **Delphi technique** (Section 5.1.1)
A yes/no **checklist** (Section 5.1.2.)

These two verification methods are discussed in the following sections.

5.1.1 Delphi technique

Verification of the design requirements was achieved by means of the Delphi technique as shown in Table 18. Consensus was considered to have been attained if an average score of 3.75 or more was reached for each question relating to the design requirements in the Delphi questionnaire. As shown in Table 18, consensus was achieved with the average score for each question being more than 3.75.

Table 18: Design requirements from the Delphi questionnaire.

DESIGN REQUIREMENTS	RESULTS	CONSENSUS (Yes / No)
STRUCTURE		
The design of the model should be simple in structure	3.75	Yes
The sequence of the model should be logical and easy to understand.	4.50	Yes
The model should be able to provide feedback as to whether the outcome has been achieved	4.17	Yes
EFFECTIVENESS		
The lean design process would save project cost and design time	4.00	Yes
The lean design process would improve project delivery	4.00	Yes
The lean design process presents a flow of information	4.58	Yes
COMPLETENESS		
The model should include the following lean implementation principles:		
▪ Respect for people	4.33	Yes
▪ Continuous improvement	4.67	Yes
▪ Reduction of waste	4.50	Yes
▪ 5S	4.08	Yes
The model should have a phase in which design input information is determined	4.42	Yes
The model should have a phase for ideation and invention (concept phase)	4.42	Yes
The model should have a phase for evaluating the concept design	4.42	Yes
The model should have a phase for detailed design of sub-assemblies and components	4.50	Yes
The model should have a phase for evaluation of the design integration of the sub-assemblies	4.42	Yes
The model should have a phase for final design review of the complete machine	4.50	Yes
The model should have a phase for creating and reviewing of manufacturing drawings	4.08	Yes
The model should have a component for technical review requirements	4.50	Yes
The model should have a component for concept review	4.50	Yes
The model should have a component for detailed design review	4.50	Yes
The model should have a component for the integration of the sub-assemblies	4.25	Yes
The model should have a component for final design review	4.42	Yes
The model should have a component for manufacturing drawing review	3.83	Yes

5.1.2 Verification checklist

The following design requirement checklist (Table 19) was not included in the Delphi questionnaire, as it does not require the input of the panel of experts, since it was verified in the previous chapter. Reference is made to the various sections of Chapter 4 to verify the checklist. This is a result form the verification of the design requirements in Chapter 4 where the average results to the questions is more than 3.75.

Table 19: Design requirement verification checklist.

DESIGN REQUIREMENTS	CHECKLIST		
Completeness	**This section relates to the completeness of the artefact**	**(Yes / No)**	**Reference to section**
The model should have the following phase requirements	The lean design process has a phase to document design inputs	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 1
	The lean design process has a concept phase	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 2
	The lean design process has an evaluation of the concept phase	**Yes**	
	The lean design process has a phase for detailed design of sub-assemblies and components	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 3
	The lean design process has a phase for evaluating the design integration of the sub-assemblies	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 4
	The lean design process has a phase for final design of the machine	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 5
	The lean design process has a phase for creating manufacturing drawings	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 6
The model should have the following component requirements	The lean design process has a component for technical review requirements	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 1
	The lean design process has a component for concept review	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 2
	The lean design process has a component for detailed design review	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 3
	The lean design process has a component for integration of sub-assemblies	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 4
	The lean design process has a component for final design review	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 5
	The lean design process has a component for manufacturing drawing review	**Yes**	Chapter 4 Sec 4.3 Figure 25, Phase 6

5.2 Summary of verification

This chapter provided confirmation that the artefact adheres to the design requirements determined during Phase 2 of the DDV-method and thus answered the following research question:

Research question 5: Does the artefact adhere to the specified design requirements?

Consensus was achieved for all questions that formed part of the Delphi questionnaire and a “Yes” was awarded for each of the questions on the checklist, to verify the design requirements of the artefact.

CHAPTER 6 – VALIDATION

Anderson and Bates (2001) state that validation is to determine whether the model works for its independent purpose and to establish valid proof. Nordin *et al*. (2012) agrees that validation is a process to determine if a tool is “fit for purpose”.

In Chapter 1, the research problem was stated as follows:

> *The design process at a machine tool manufacturing company based in South Africa, requires much costly and time-consuming experimentation in the prototyping phase, which results in waste and constant rework with multiple iterations.*

The Delphi technique was also used to determine the validity of the artefact in terms of addressing the problem identified in Phase one of the DDV-model as discussed in Chapter 4. The previous chapter (Chapter 4) focused on the results and findings as a result of the application of the novel research design (Chapter 3). The verification of the artefact against design requirements and an overview of findings was discussed in Chapter 5.

The purpose of Chapter 6 is to summarise the finding of the validation process in reference to the following research questions:

Research question 6:	Has a valid research problem been identified?
Research question 7:	Has a valid research design been followed?
Research question 8:	Does the artefact address the research problem?

6.1 Validation methodology

By validating the research problem, research design and research output, this study could be considered valid. The validation was done as follows:

Research problem – the **Delphi technique** was used to determine the validity of the research problem (Section 6.1.1.).

Research design – the validity of the research design was determined by checking adherence to the **DSR guidelines** (Section 6.2.).

Research output – the validity of the research output was determined by the **Delphi technique** (Section 6.3.).

These three techniques are discussed in the following sections.

6.1.1 Validation of research problem

The validation of the research problem was confirmed by means of specific questions in the Delphi questionnaire. The results of these questions are shown in Table 20.

Table 20: Research question validation results from the Delphi questionnaire.

DELPHI QUESTIONS		RESULTS													
This section relates to the validity of the research problem		**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**AVG PER QUESTION**	**CONSENSUS (Y/N)**
ENVIRONMENT: RESEARCH PROBLEM	The current design process for purpose-built machine tools is inefficient.	5	4	3	2	3	1	5	4	5	4	4	5	**3.75**	Y
	The current design process is not cost effective	5	3	5	1	4	1	4	4	4	4	5	5	**3.75**	Y
	The current design process is time-consuming	5	4	4	2	5	2	5	4	4	4	4	5	**4.00**	Y

Reflecting on the responses received for the three questions as indicated in Table 20, the lowest ranked scores according to the Likert scale (1 and 2) were used to indicate the low scoring responders. The participants who awarded either 1 (Strongly disagree) or 2 (Disagree) were requested to elaborate on their responses with additional open-ended answers to enrich the data (section 4.1.2).

The overall conclusion drawn from the open-ended responses (previously discussed in Section 4.1.2) is that project management should play a larger role during the design process and that although the current process might be sufficient for smaller projects, an improved, more effective process will be required for more complex customer needs and the design of complete purpose-built machine tools. The average scores of the Delphi panel (3.75 for questions one and two, and 4 for the third question), confirmed that these problems are valid within the environment.

The following section will discuss the validation of the research design.

6.2 Validation of the research design

The validity of the research design was investigated by means of the DSR guidelines to ensure that the research questions are answered by the design outputs (Girardot and Jacquart, 2004).

The adherence to the DSR guidelines are shown in Table 21 and cross-referenced to the relevant chapters.

Table 21: Design science research guidelines (Adapted from Arnott and Pervan (2012).

NO	GUIDELINES	DESCRIPTION	CONFIRMATION	CHAPTER REFERENCE
1	**Design an artefact**	Design-science research must deliver a feasible artefact in the form of a model, a method or process.	The standardised lean design process for purpose-built machine tools was designed as the artefact.	Chapter 4.3 DDV Phase 3
2	**Problem relevance**	The objective of design-science research is to develop technological solutions to important and applicable organisational problems.	The Delphi technique validated that the standardised lean design process for purpose-built machine tools addresses the relevant business problems.	Chapter 4.1 DDV Phase 1
3	**Design evaluation**	The usability, quality, and efficiency of a design artefact must be rigorously demonstrated with evaluation methods.	The Delphi technique was used to evaluate the artefact and it was found that it was valid.	Chapter 4.4 DDV Phase 4
4	**Research contribution**	Effective design-science research must make an adequate, clear and verifiable contribution in the areas of the design artefact, design foundations, and/or design methodologies.	A contribution has been made by designing an artefact that could be used as an improved standardised lean design process.	Chapter 4 4.1.2 4.2.4 4.4.1
5	**Research Rigor**	Design-science research relies upon the implementation of rigorous methods in both the creation and evaluation of the design artefact.	The Delphi technique was used to evaluate the artefact.	Chapter 4 4.1.2 4.2.4 4.4.1 4.4.2
6	**Design as a search process**	The search for an effective artefact requires utilising available means to reach desired ends while satisfying laws in the problem environment	The integrated DDV-method was used as a research design for the standardised lean design process that will address problems in the problem environment.	Chapter 3
7	**Communication of research**	Design-science research must be presented effectively both to technology-oriented as well as to management-oriented audiences.	The research is communicated via the briefing prior to sending out the Delphi questionnaire and the dissertation.	Chapter 4 4.3.1

6.3 Validation of research output

Nordin *et al*. (2012) described validation as a process by which a judgement is made as to whether a tool is fit for purpose. It is critical to consider the environment in which the validation process was carried out. The validity of the artefact was determined by specific questions in the Delphi questionnaire. Table 22 shows the questions and results of the Delphi questionnaire.

Table 22: Research validation results from the Delphi questionnaire.

DELPHI QUESTION		RESULTS	CONSENSUS (Yes /No)
	This section relates to the validation of the research output.	**AVG**	

Validity	The artefact could be used as a standardised design process.	4.50	Yes
	The artefact could provide a more cost-effective design process.	4.58	Yes
	The artefact could shorten the overall project timeframe from concept to prototyping.	4.17	Yes

Consensus was reached by achieving an average score of 3.75 or more for each question and as a result, the artefact is validated as fit for purpose, as it addresses the research problem.

6.4 Validation conclusion

The aim of this chapter was to confirm the validity of the research problem, the research design and the research output (the artefact). This was achieved by using the DSR guidelines and utilising the Delphi technique. A summary of the results is shown in Table 23. The first column of the table states the validation requirement. Columns two and three indicate the methods used to prove the validity and the last column indicates the conclusion that was reached for each validation criterion.

Table 23: Summary of cross-validation results.

VALIDATION REQUIREMENT	DSR Guidelines	Delphi Technique	CONCLUSION
VALIDITY OF THE RESEARCH PROBLEM			
A valid research problem should be identified		**Confirmed by Question**	**Validated**
VALIDITY OF THE RESEARCH DESIGN			
A valid research design should be followed	**Confirmed**		**Validated**
VALIDITY OF THE RESEARCH OUTPUT			
The artefact should address the research problem		**Confirmed by Question**	**Validated**

Confirmation of the validity of the study is provided, thus answering the following research questions:

Research question 6: Has a valid research problem been identified?

Research question 7: Has a valid research design been followed?

Research question 8: Does the artefact address the research problem?

The validity of the study is therefore confirmed. Chapter 7 concludes this study.

CHAPTER 7 – CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

In this chapter, an overview of the research is discussed. Conclusions from the research objectives and findings will also be provided. Finally, limitations, recommendations and possible future research will also be provided.

7.2 Research overview

The purpose of this research was to develop a standardised lean design process for purpose-built machine tools.

In Chapter 2 a literature study was conducted on existing machine design processes, clarifying any abstruse concepts and terminology. The literature study addressed and described all the definitions of the various components required for this research. Research was successfully completed on the main components of this research, therefore addressing the research objectives.

An applicable research design was applied in this study, to achieve the research aim, defined (Chapter 3) as the DDV-method. A novel step-by-step method was designed for the research by combining the DSR paradigm with various design theories to develop a useful artefact. The V-model provided the progressive path for executing every phase in the development cycle. The Delphi technique provided the validation of the environment, verification of the design requirements and the validation of the artefact.

Chapter 4 provided the results and findings of the DDV-method applied in the research. A standardised lean design process was developed which incorporates existing design models to achieve an improved conceptual design time frame. This innovative design process provided a step-by-step method for addressing the challenging task of the design of purpose-built machine tools.

By solving the problem at hand, designers can use the artefact as a tool to optimise the design process, which will allow them to complete new purpose-built machines within a shorter lead time with minimal modifications and changes, and still be able to show a profit at the end of such projects.

The verification phase (Chapter 5) provides proof that the artefact conforms to the design requirements determined during phase 2 of the DDV-method, by reaching consensus from the outcomes of the Delphi questionnaire. The findings as presented in Chapter 4, show that although the average of the answers to the Delphi questionnaire was more than 3.7 on the Likert scale for 75% of the participants, some of the experts answered a 3 on some of the questions. This provides an opportunity for future research to investigate the design processes in the purpose-built machine tool industry in South Africa. The verification checklist (Chapter 5.12) addresses the completeness of the artefact with cross references to the relevant sections in Chapter 4.

The validation phase of the research (Chapter 6) focused on the confirmation of the research problem, the research design and the research output. This was achieved by using the DSR guidelines and the Delphi technique. During the validation of the research problem, two participants awarded low scores on two of the statements. These participants were then asked to elaborate why they did not agree. Both mentioned that they do not think the problem is not valid, but merely that the current design process would be sufficient for simple small design projects. Their disagreement might also mean that from their experiences, they have encountered other problems that might also need to be addressed if further research is conducted.

7.3 Contribution

This research contributes to the field of science, engineering and technology:

By designing the new DDV-method and applying it in the research design, other researchers can now also use this method to solve various research problems in various areas, such as process improvement and new process development. Each step in the DDV-method addresses different aspects of the research problem. The design requirements are variable and can be applied to various disciplines within the engineering environment and other fields of study. Once the design requirements are determined, an artefact can easily be designed and developed. During the evaluation phase of the DDV-method, the artefact is validated against the research problem and the artefact is verified against the requirements determined in the second phase. This cross-validation and verification provides proof that the artefact is, indeed, valid.

The artefact developed in this research study provides a standardised lean design process. The artefact consists of an easy-to-follow process flow that also provides a step-by-step method to eliminate waste e.g. regarding design errors and unnecessary parts that are manufactured. By implementing the lean design process in the purpose-built machine tool industry, mistakes can be identified early in the design process. Therefore, time and money will be saved by correcting the mistakes before resources are allocated to manufacturing a faulty part and as a result, avoiding the additional cost implications when rectifying the mistake. Designers can reach their deadlines faster with more job satisfaction, fewer frustrations and less waste, which will result in more profitable projects.

This study can contribute to the industry by implementing the lean design process in the purpose-built machine tool industry, for organisations to save time and resources when designing and developing new purpose-built machine tools.

This study will contribute to the literature by:

- assisting fellow researchers to create lean design models for similar industries;
- assisting researchers with similar research design challenges by using the newly designed DDV model and;
- providing design requirements for a lean design process.

7.4 Limitations and recommendations

This research provides a standardised lean design process for purpose-built machine tools as the artefact. However, more detail is required on how to document each of the process steps within the lean design process.

Future research should focus on the implementation of the lean design process in the machine tool industry. The lean design process can also be applied to various other industries with specific modifications to the processes of a specific industry.

Although the lean design process focused on the various phases of lean design, future research could focus on the standard procedures and approvals within each of the design phases.

During this research the following lean principles were used to design and develop the artefact:

- Respect for people;
- Continuous improvement (Kaizen);
- Reduction of waste (Muda);
- 5S.

Further lean principles, not limited to the following, can also be included during implementation for future researchers:

- Heijunka (to divide each of the process steps within the lean design process into sub-steps);
- KPIs (set goals for each of the process steps);

- Gemba (add a process block for interactive practical research that will encourage designers to spend time on the shop floor).

7.5 Conclusion

A lean design process can only achieve the set goal if every step of the process is followed meticulously. Each of the steps can be seen as building blocks - and by following the steps (compiling the blocks), the end result can be successfully achieved (the house can be built). However, if some of the steps are overlooked (blocks left out) the end result will not be successful (the house will not be complete). In other words, shortcuts cost more money in the end and waste time.

In order to save time and money for the organisation, the lean aspect of the design process, to reduce waste, should always be the goal for designers.

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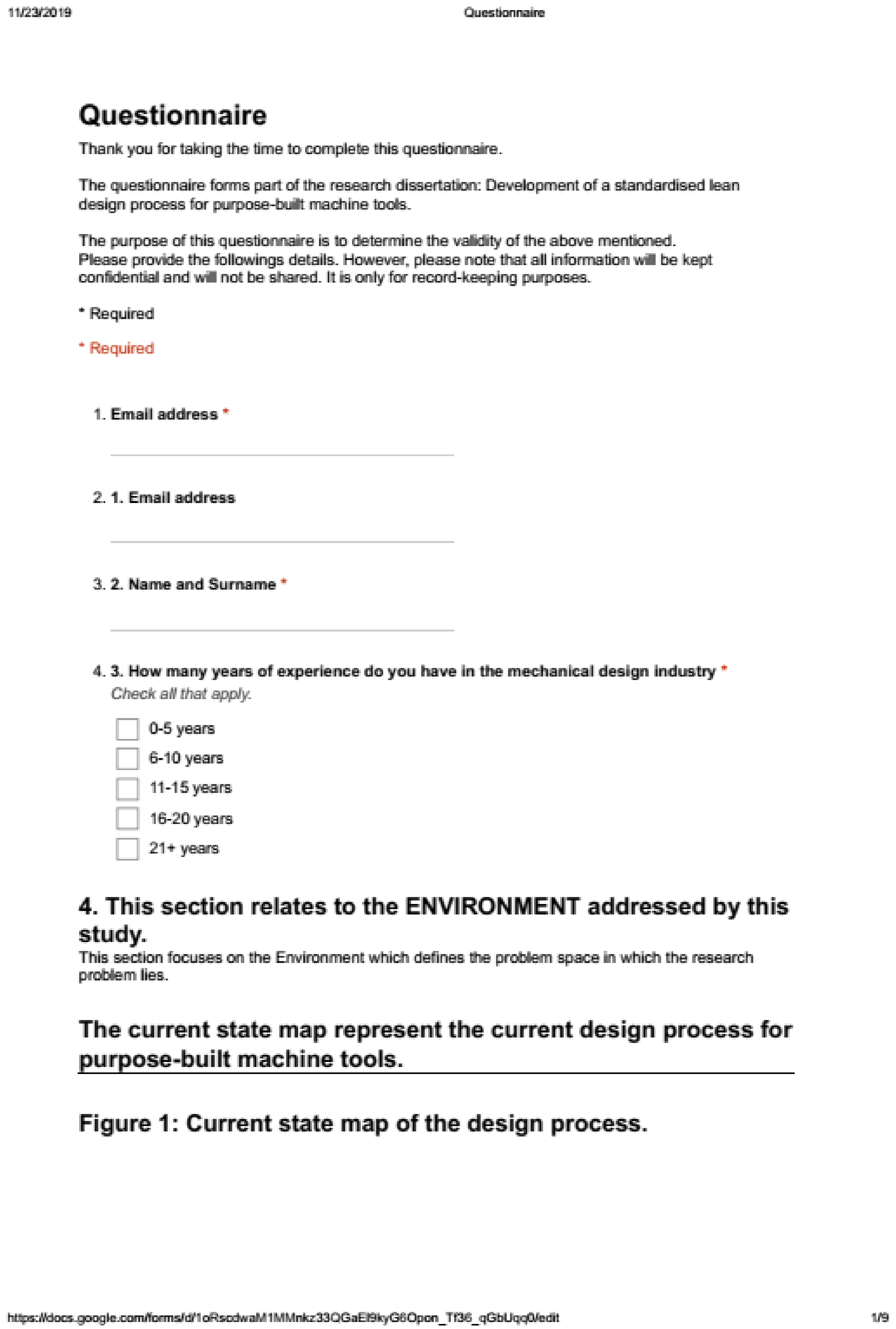
ANNEXURE A – DELPHI QUESTIONNAIRE



11/23/2019 Questionnaire

Questionnaire

Thank you for taking the time to complete this questionnaire.

The questionnaire forms part of the research dissertation: Development of a standardised lean design process for purpose-built machine tools.

The purpose of this questionnaire is to determine the validity of the above mentioned.
Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

* Required

* Required

1. **Email address ***

2. **1. Email address**

3. **2. Name and Surname ***

4. **3. How many years of experience do you have in the mechanical design industry ***
   Check all that apply.
   ☐ 0-5 years
   ☐ 6-10 years
   ☐ 11-15 years
   ☐ 16-20 years
   ☐ 21+ years

4. This section relates to the ENVIRONMENT addressed by this study.

This section focuses on the Environment which defines the problem space in which the research problem lies.

The current state map represent the current design process for purpose-built machine tools.

Figure 1: Current state map of the design process.

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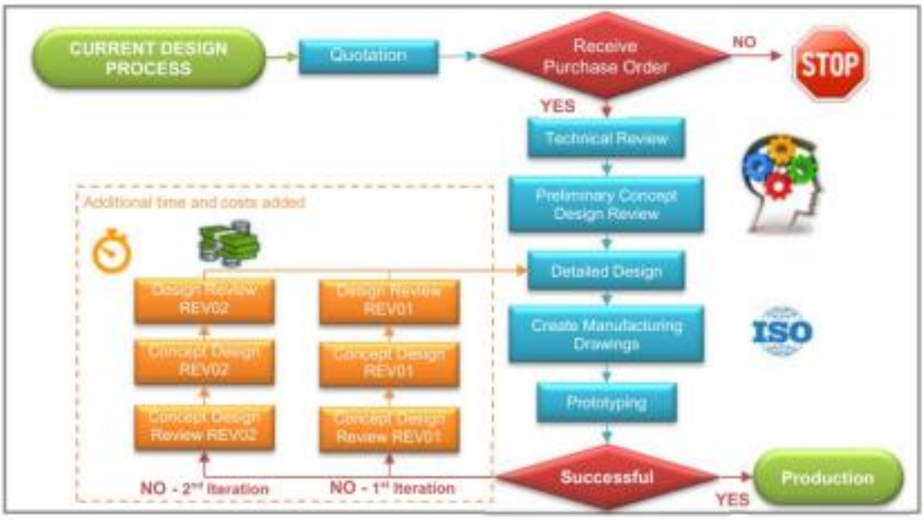


5. 4.1 The current design process for purpose-built machine tools is inefficient. *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

6. 4.2 The current design process is not cost effective. *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

7. 4.3 The current design process is time consuming. *

Mark only one oval.

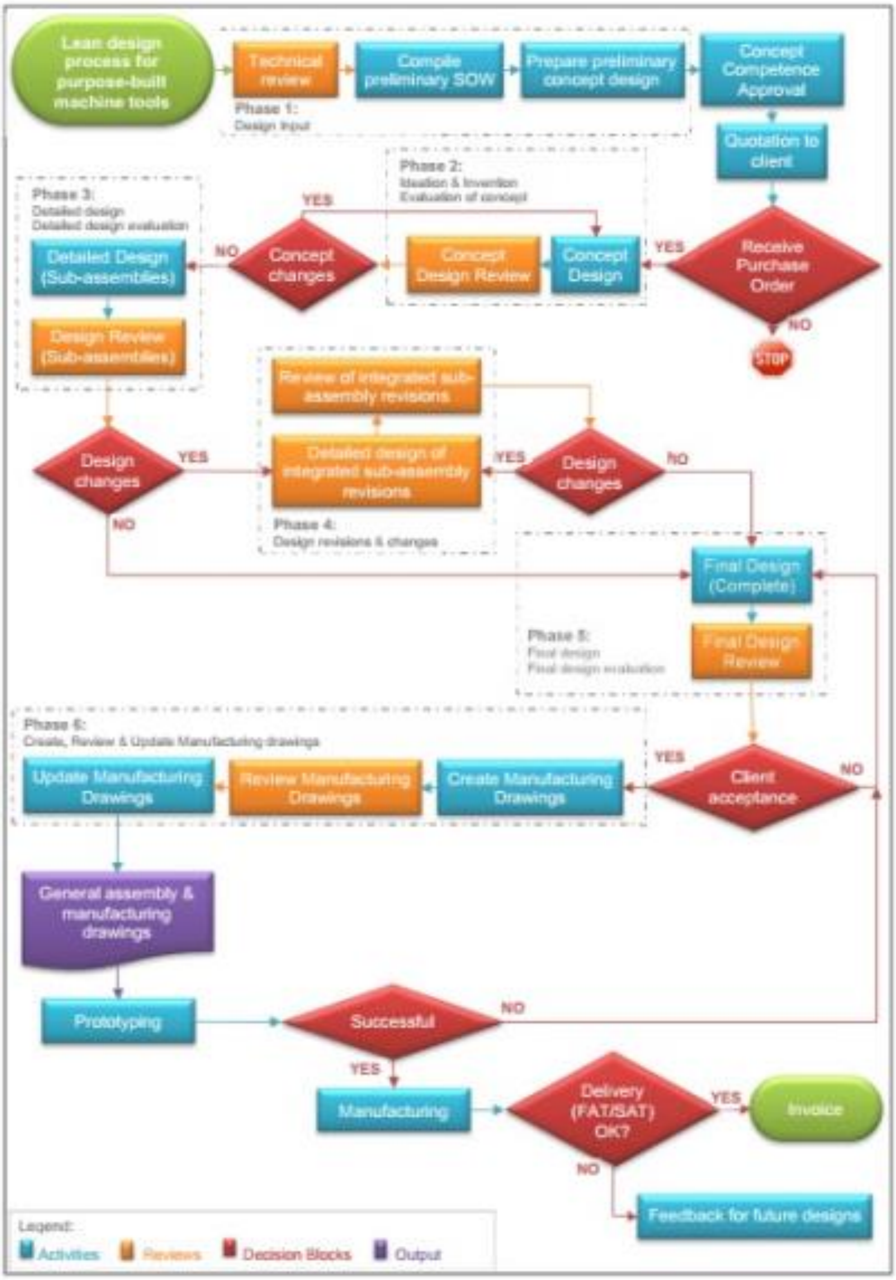
- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

5. This section relates to the STRUCTURE of the artefact.

Please answer the following questions

The artefact is represented in the form of a future state map for the lean design process for purpose-built machine tools.

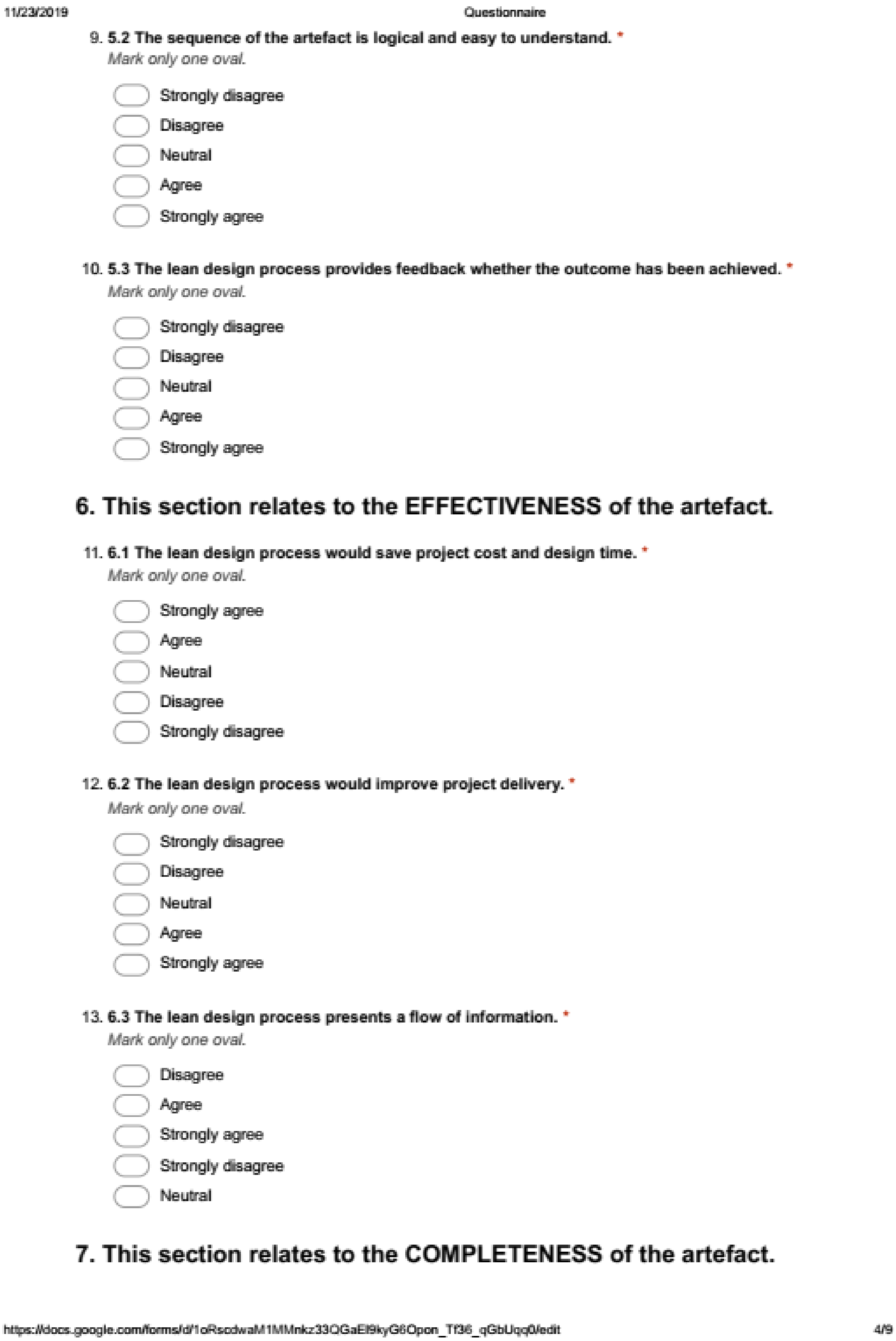
Figure 2: Future state map for lean design process.



8. **5.1 The design of the artefact is simple in structure.** *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree



9. **5.2 The sequence of the artefact is logical and easy to understand.** *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

10. **5.3 The lean design process provides feedback whether the outcome has been achieved.** *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

6. This section relates to the EFFECTIVENESS of the artefact.

11. **6.1 The lean design process would save project cost and design time.** *

Mark only one oval.

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree

12. **6.2 The lean design process would improve project delivery.** *

Mark only one oval.

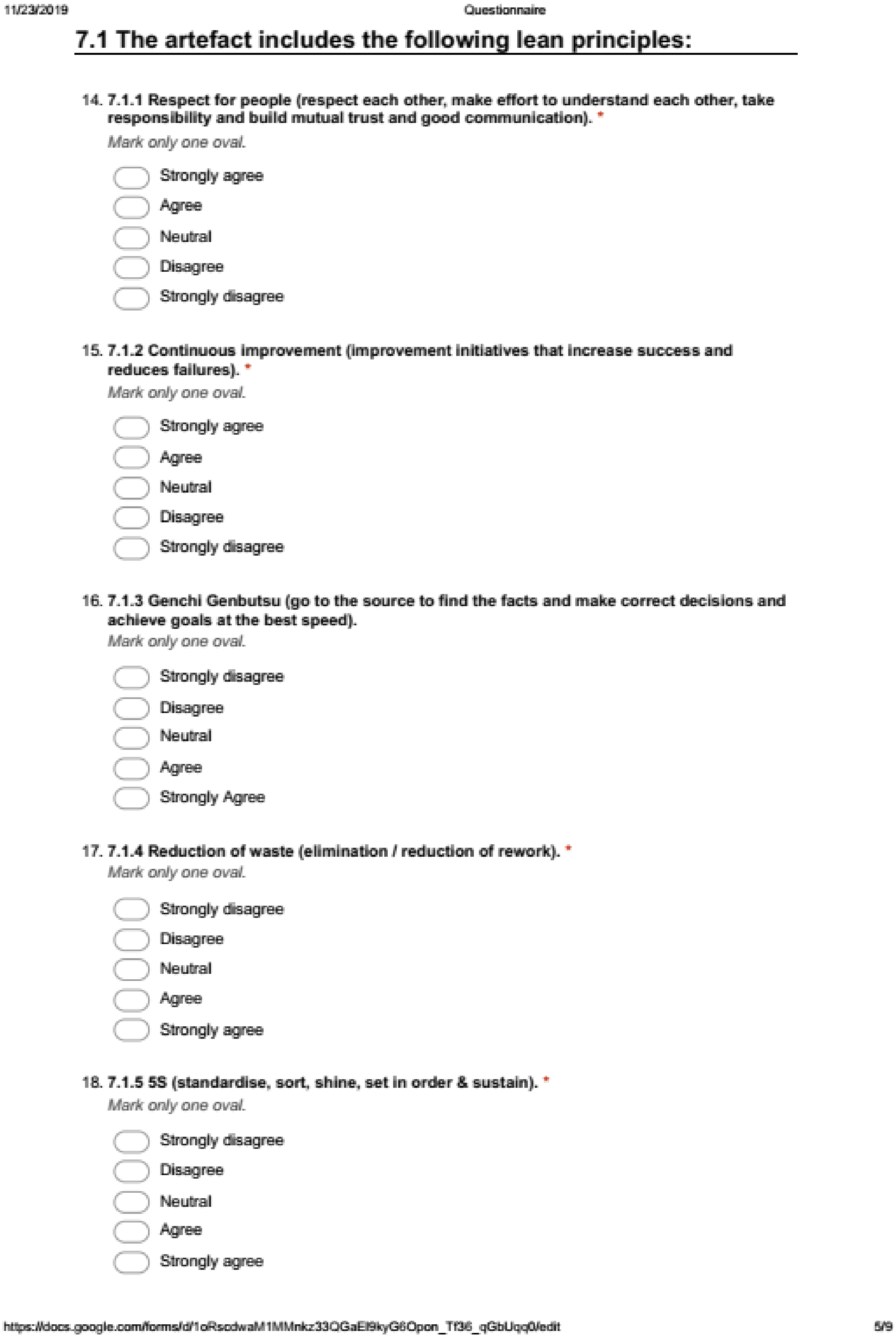
○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

13. **6.3 The lean design process presents a flow of information.** *

Mark only one oval.

○ Disagree
○ Agree
○ Strongly agree
○ Strongly disagree
○ Neutral

7. This section relates to the COMPLETENESS of the artefact.



7.1 The artefact includes the following lean principles:

14. 7.1.1 Respect for people (respect each other, make effort to understand each other, take responsibility and build mutual trust and good communication). *

Mark only one oval.

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree

15. 7.1.2 Continuous improvement (improvement initiatives that increase success and reduces failures). *

Mark only one oval.

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree

16. 7.1.3 Genchi Genbutsu (go to the source to find the facts and make correct decisions and achieve goals at the best speed).

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly Agree

17. 7.1.4 Reduction of waste (elimination / reduction of rework). *

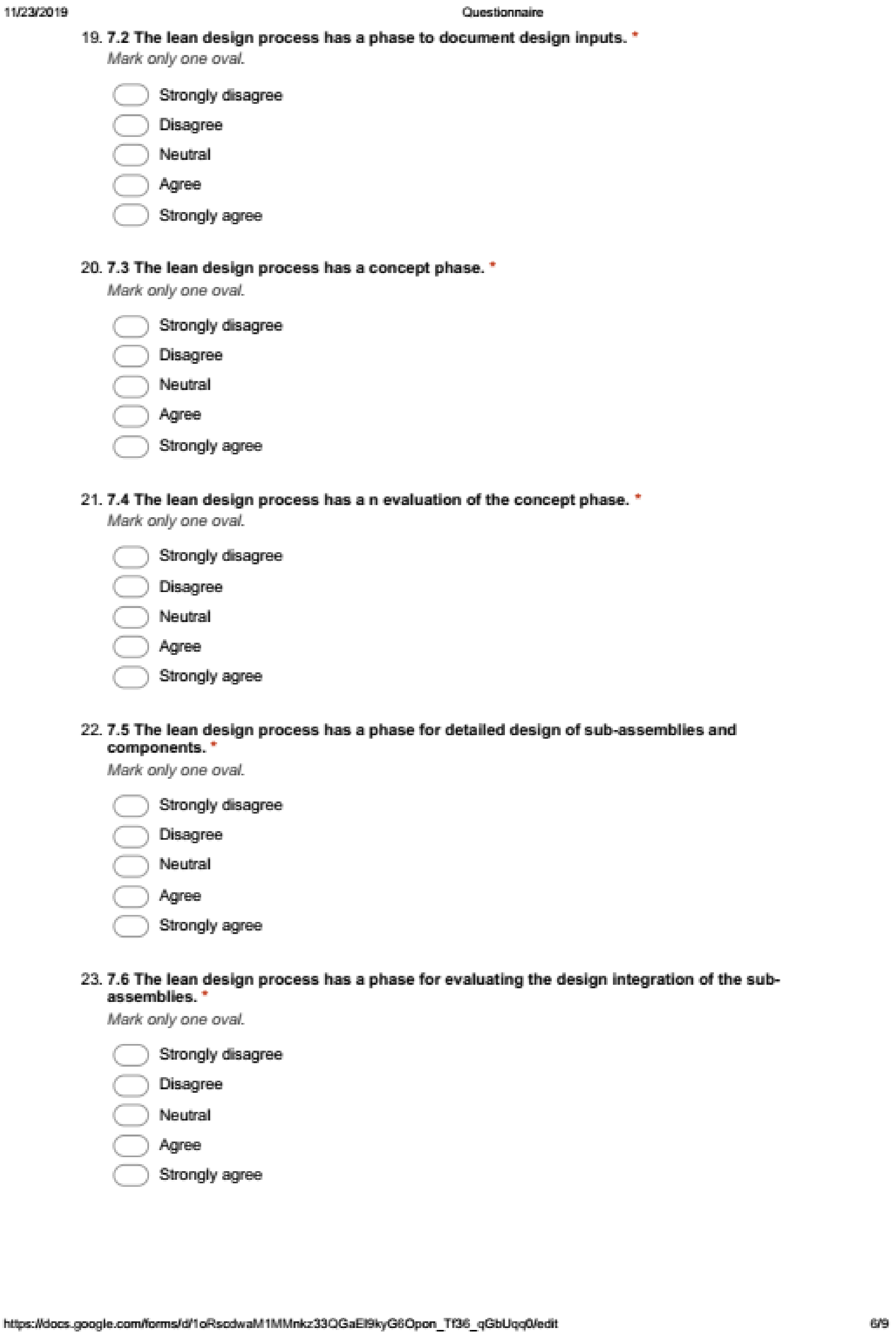
Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

18. 7.1.5 5S (standardise, sort, shine, set in order & sustain). *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree



11/23/2019 Questionnaire

19. **7.2 The lean design process has a phase to document design inputs.** *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

20. **7.3 The lean design process has a concept phase.** *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

21. **7.4 The lean design process has a n evaluation of the concept phase.** *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

22. **7.5 The lean design process has a phase for detailed design of sub-assemblies and components.** *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

23. **7.6 The lean design process has a phase for evaluating the design integration of the sub-assemblies.** *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

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24. **7.7 The lean design process has a phase for final design of the machine.** *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

25. **7.8 The lean design process has a phase for creating manufacturing drawings.**

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

26. **7.9 The lean design process has a component for technical review requirements.** *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly Agree

27. **7.9 The lean design process has a component for concept review requirements.** *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

28. **7.10 The lean design process has a component for detailed design review.** *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

29. **7.11 The lean design process has a component for the reviewing of integrated sub-assemblies.** *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

30. **7.12 The lean design process has a component for final design review.** *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

31. **7.13 The lean design process has a component for manufacturing drawing review.**

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

This section relates to the VALIDITY of the artefact.

32. **The artefact could be used as a standardised design process.** *

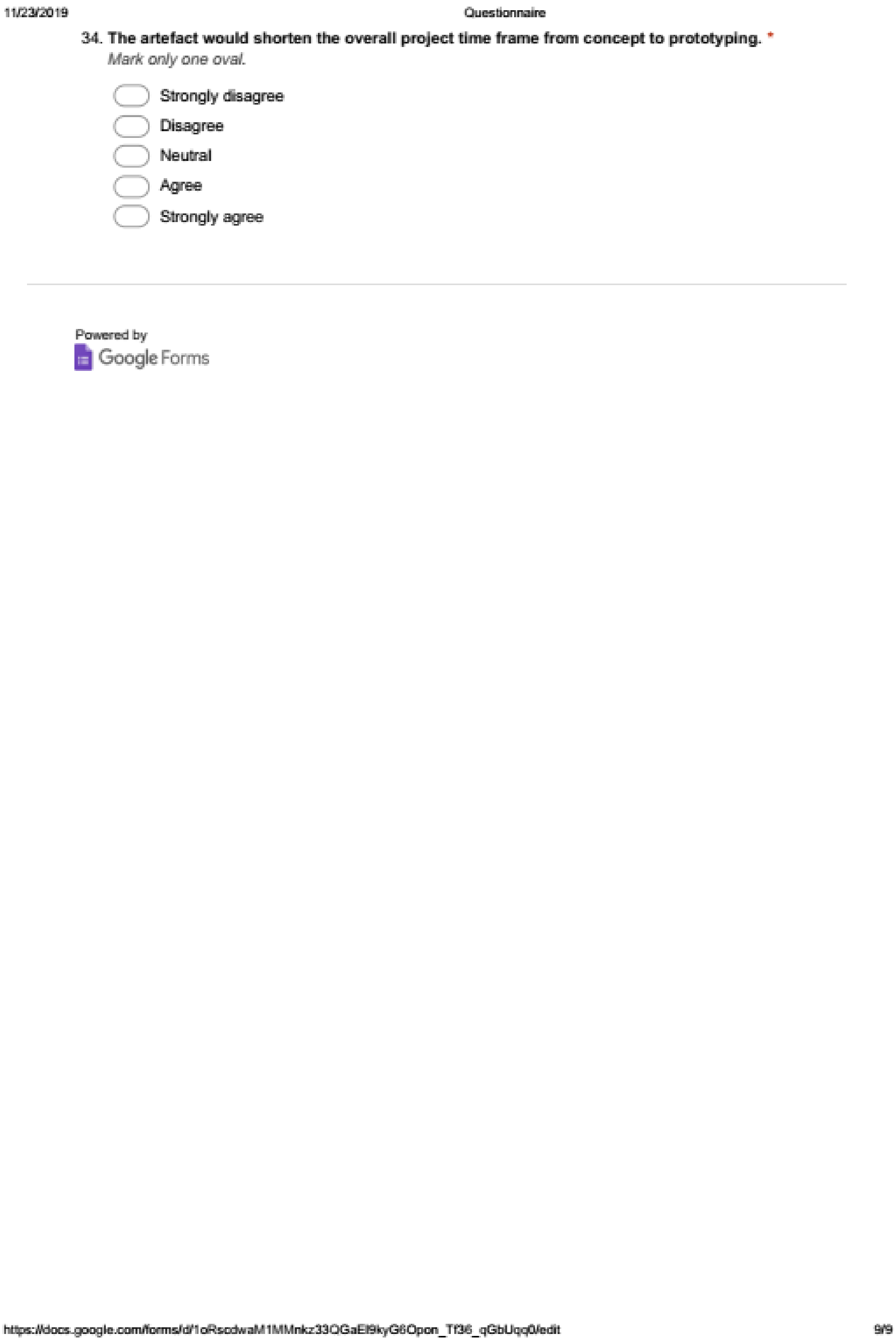
Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree

33. **The artefact would provide a more cost effective design process.** *

Mark only one oval.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree



34. The artefact would shorten the overall project time frame from concept to prototyping. *

Mark only one oval.

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

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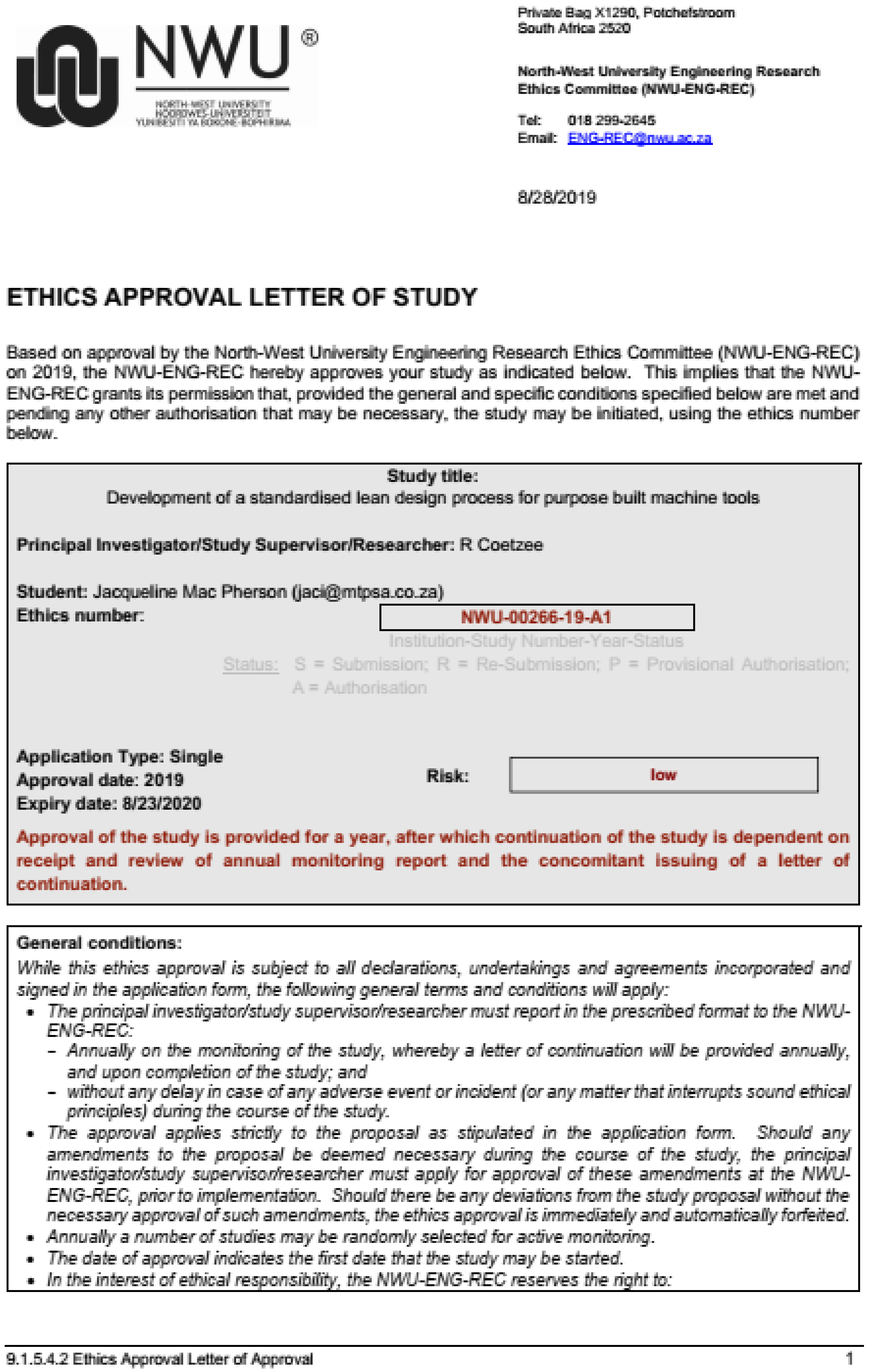
ANNEXURE B – DELPHI QUESTIONNAIRE FEEDBACK

		Questions	Participants responses												Avegrage per question	Average per section
			1(0-5)	2(0-5)	3(0-5)	4(6-10)	5(11-15)	6(11-15)	7(11-15)	8(16-20)	9(21+)	10(21+)	11(21+)	12(21+)		
Environment		The current design process for purpose build machine tools is inefficient.	5	4	3	2	3	1	5	4	5	4	4	5	3.75	3.83
		The current design process is not cost effective	5	3	5	1	4	1	4	4	4	4	5	5	3.75	
		The current design process is time consuming	5	4	4	2	5	2	5	4	4	4	4	5	4.00	
Structure		The design of the artefact is simple in structure.	4	5	4	5	1	4	4	4	3	4	3	4	3.75	4.14
		The sequence of the artefact is logical and easy to understand.	4	5	4	5	4	5	4	5	5	4	5	4	4.50	
		The lean design process provides feedback whether the outcome has been achieved	4	5	4	5	2	5	4	4	5	4	4	4	4.17	
Effectiveness		The lean design process would save project cost and design time.	4	1	5	4	1	5	5	4	4	5	5	5	4.00	4.19
		The lean design process would improve project delivery.	3	5	4	5	5	5	3	4	5	4	4	5	4.00	
		The lean design process presents a flow of information.	4	5	4	5	4	5	4	5	5	4	5	5	4.58	
Completeness	The artefact includes the following lean principles	Respect for people *(respect each other, make effort to understand each other, take responsibility and build mutual trust and good communication)*	5	4	4	5	4	5	3	4	4	4	5	5	4.33	4.35
		Continuous improvement *(improvement initiatives that increase success and reduces failures)*	5	5	4	5	4	5	4	4	5	5	5	5	4.67	
		Genchi Genbutsu *(go to the source to find the facts and make correct decisions and achieve goals at the best speed)*	3	5	4	4	5	5	5	4	1	3	4	4	3.92	
		Reduction of waste *(elimination / reduction of rework)*	5	5	4	5	4	4	4	5	4	5	5	4	4.50	
		5S *(standardise, sort, shine, set in order & sustain)*	4	5	4	4	3	5	3	4	4	4	5	4	4.08	
	The artefact includes the following phase requirements	The lean design process has a phase to document design inputs.	4	5	4	5	4	5	5	4	4	4	5	4	4.42	
		The lean design process has a concept phase.	4	5	4	5	4	5	5	4	4	4	5	4	4.42	
		The lean design process has a n evaluation of the concept phase.	5	5	4	5	4	5	4	4	4	4	5	4	4.42	
		The lean design process has a phase for detailed design of sub-assemblies and components.	5	5	4	5	4	5	4	4	4	4	5	5	4.50	
		The lean design process has a phase for evaluating the design integration of the sub-assemblies.	5	5	4	5	4	5	4	4	4	4	5	4	4.42	
		The lean design process has a phase for final design of the machine.	5	5	4	5	4	5	4	4	4	4	5	5	4.50	
		The lean design process has a phase for creating manufacturing drawings.	3	5	4	3	4	5	4	4	4	3	5	5	4.08	
	The artefact has the following component requirements	The lean design process has a component for technical review requirements.	5	5	4	5	4	5	4	4	4	4	5	5	4.50	
		The lean design process has a component for concept review requirements.	5	5	4	5	4	5	4	4	4	4	5	5	4.50	
		The lean design process has a component for detailed design review.	5	5	4	5	4	5	4	4	4	4	5	5	4.50	
		The lean design process has a component for the reviewing of integrated sub-assemblies.	5	5	4	4	4	4	4	4	4	4	5	4	4.25	
		The lean design process has a component for final design review.	5	5	4	5	3	5	4	4	4	4	5	5	4.42	
		The lean design process has a component for manufacturing drawing review.	3	5	4	3	3	4	4	4	4	3	5	4	3.83	
Vadility		The artefact could be used as a standardised design process.	4	4	4	5	3	5	5	4	5	5	5	5	4.50	4.42
		The artefact would provide a more cost effective design process.	4	5	4	5	4	5	5	4	5	4	5	5	4.58	
		The artefact would shorten the overall project time frame from concept to prototyping.	3	4	4	5	3	4	3	5	5	5	4	5	4.17	

ANNEXURE C – ETHICAL APPROVAL



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North-West University Engineering Research
Ethics Committee (NWU-ENG-REC)

Tel: 018 299-2645
Email: ENG-REC@nwu.ac.za

8/28/2019

ETHICS APPROVAL LETTER OF STUDY

Based on approval by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 2019, the NWU-ENG-REC hereby approves your study as indicated below. This implies that the NWU-ENG-REC grants its permission that, provided the general and specific conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title:
Development of a standardised lean design process for purpose built machine tools

Principal Investigator/Study Supervisor/Researcher: R Coetzee

Student: Jacqueline Mac Pherson (jaci@mtpsa.co.za)
Ethics number: NWU-00266-19-A1
Institution-Study Number-Year-Status
Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application Type: Single
Approval date: 2019
Expiry date: 8/23/2020
Risk: low

Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of annual monitoring report and the concomitant issuing of a letter of continuation.

General conditions:
While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:

- *The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-ENG-REC:*
  - *Annually on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and*
  - *without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.*
- *The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-ENG-REC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.*
- *Annually a number of studies may be randomly selected for active monitoring.*
- *The date of approval indicates the first date that the study may be started.*
- *In the interest of ethical responsibility, the NWU-ENG-REC reserves the right to:*

  - *request access to any information or data at any time during the course or after completion of the study;*
  - *to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;*
  - *withdraw or postpone approval if:*
    - *any unethical principles or practices of the study are revealed or suspected;*
    - *it becomes apparent that any relevant information was withheld from the NWU-ENG-REC or that information has been false or misrepresented;*
    - *submission of the annual monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or*
    - *new institutional rules, national legislation or international conventions deem it necessary.*
- *NWU-ENG-REC can be contacted for further information via ENG-REC@nwu.ac.za or 018 299 2645*

Special conditions of the research approval (if applicable): NA

Special in process conditions of the research for approval (if applicable): NA

The NWU-ENG-REC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-ENG-REC for any further enquiries or requests for assistance.

Yours sincerely,

RCoetzee

Dr Rojanette Coetzee
Chairperson NWU-ENG-REC

Current details:(25767984) \NWUNextCloud\ENG-REC\Letters sent\[Date]\9.1.5.4.3_NWU-ENG-REC_REC_EAL_[student surname_name]

File Reference: 9.1.5.4.2