

DURBAN UNIVERSITY OF TECHNOLOGY

USING OPTICAL METROLOGY IN INJECTION MOULDING

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Using Optical Metrology in Injection Moulding

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March 2025

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ABSTRACT

Quality control (QC) is integral to monitoring and controlling defective or poor-quality products from reaching the customer. Developments in optical metrology promise more accurate measurements and faster turnaround times to QC than current tactile measurements.

With the rising demand and complexity of injection moulded products, manufacturers are pressured to produce quality products faster, notwithstanding that the current metrological methods may not meet the output demand.

This study investigates the efficacy of optical metrological devices (3-D scanner) as a QC tool for injection moulding.

The study followed a quantitative and experimental methodology. This study adopted a probability, simple random type of sampling technique. A sample size of four was used. Measurements of four different products (closures and tubs) were undertaken, including eight attributes of the closures and five different attributes of the tubs. Tests were conducted on two samples of each product, utilising a 3-D scanner and contact measuring devices. The statistical conclusion validity method was used to determine the validity of the data obtained. Repeatability and reproducibility methods were used to determine the reliability of the data obtained from the tests conducted in the study.

The results indicated that optical metrology provided insufficient measurements for plastic injection-moulded products. The results also provided an understanding of optical measurements compared to tactile measurements.

Based on the study conducted, it can be concluded that even though there are established and emerging optical metrological technologies, such as 3-D scanners, which are versatile and fit for industries such as automotive and aeronautical manufacturing, they are currently not effective or adequate for routine quality control testing in injection-moulded plastic products. Although the 3-D scanner proved to be an inappropriate quality control measuring device for plastic injection moulded products in this study, it is recommended that further investigation is required. The importance of considering aspects such as product size, material composition, and colour of the products in future studies cannot be overstated, as these factors could significantly impact the effectiveness of the 3-D scanner.

Keywords: injection moulding, quality, measurement, optical metrology

List of abbreviations

CAD	Computer-Aided Design
CAGR	Compound Annual Growth
CMM	Coordinate Measuring Machine
Kg	Kilograms
LVDT	Linear Variable Differential Transformer
ml	Millilitre
mm	Millimetre
ms	Millisecond
QC	Quality Control
QMS	Quality Management System
TQM	Total Quality Management
SPC	Statistical Process Control

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Glossary

Cavity	The top section of the injection mould is primarily concave and is often the product's show surface.
CMM	A measuring device that measures the geometry of a physical object by measuring different points on the surface using a probe.
First article inspection	The inspection of the first production run of the product.
Gate	Cavity entrance.
In process check	The inspection occurs during the production run.
Manufactured	Items produced from raw material by machinery on a large scale.
Measurement	The process of measuring something, e.g., the dimensions or weight of an object.
Pre-production inspection	The inspection of the raw materials occurs before the commencement of manufacturing.
Pre-shipment inspection	This inspection is conducted on finished products that are packed for shipment. This is the final inspection and is random.
Probe	A small object that contacts an object that it is measuring.
Quality Control	The measurement and testing of products to ensure that they are consistent and meet the required specifications.

Quality Management System	A prescribed system that documents the procedures, processes, roles and responsibilities for accomplishing a company's objectives and policies.
Retro reflective	This occurs when a surface returns a large portion of the directed light beam to its source.
Shot	The amount of material utilised to fill a mould.
Van der Waal Forces	The intermolecular forces that bind molecules together.

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CHAPTER 1: OVERVIEW OF THE STUDY

1.1 Background of the study

According to Stojkic, Culjak, and Saravanja (2020), technological advancement in various industries has led to a revolution in manufacturing. The demand for practical and aesthetically pleasing quality products on the market has increased because of the sophistication of machines and customer expectations. Additionally, greater competitiveness in the marketplace and product performance optimisation have led to greater demands for the quality and precision of manufactured goods. Ivsac (2014) suggests that the perception of quality has evolved from when manufacturers prescribed quality standards to the present, where customers determine the essential requirements for the quality of their items.

Advancements in material science, particularly in the polymer industry, have been made to meet these customer needs. Injection moulding is one of the most common and preferred methods of converting polymers into various finished products. Nagrale (2021) reported that in 2021, the injection moulded plastics industry was estimated to be around \$268.3 billion. According to projections, the market for injection-moulded plastics will increase from \$283.8 billion in 2022 to over \$420 billion in 2030, with a compound annual growth rate of 5.78% throughout the forecast period (between 2022 and 2030). Nagrale (2021) postulated that the key factor driving the injection market of moulded plastics is their expanding application in the building, construction, automotive, and other industries.

The narrative is also seen in Morris (2021), who noted that the injection moulding process creates an array of products that are widely used in the food, beverage, chemical, medical, automotive, electronics and textile industries because these emerging products are hygienic, lightweight, and impervious and thus can be used to produce items such as tubs, bottles, jars, closures, drums, electronic casings, combs, automotive interiors, and machine parts.

To support this demand, *Injection Moulding Market Size, Shares & Trends (2021)* reported that there has been an increase in investments across various industries in the use of injection moulding technology. Figure 1 shows a study conducted by Grand View Research in 2021 (Grand View Research is a market research and consultancy company with operations in India and the United States), where the automotive and packaging industries utilise the largest injection moulding technology and products the most compared to other sectors

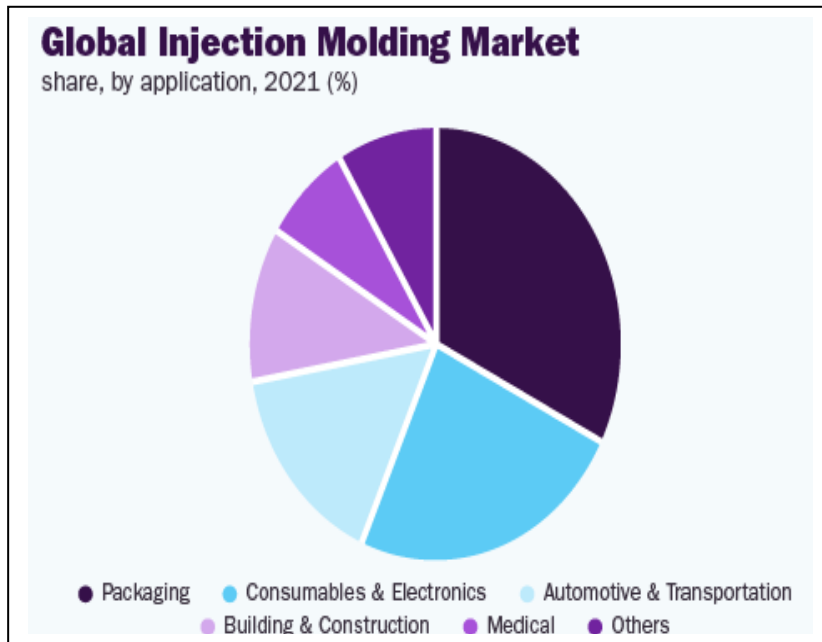


Figure 1: Global injection moulding market as per industry

(Sourced from [Grand View Research 2021](#))

Market Data Forecast (2023) (Market Data Forecast is a research company that offers customised published research data for its clientele worldwide) showed that in the automotive industry, where quality, consistency, and safety of products are of the highest importance, the use of plastic injection moulded parts has grown substantially using polymers like polypropylene, high-density polyethylene, and polystyrene. These polymers are being used for their rigidity, flexibility, and resistance to corrosion and external elements. For example, polypropylene is used to manufacture parts such as cable insulation, bumpers, automobile doors, carpet fibres, and bodywork.

Interestingly, [Injection Moulding Market Size, Share, and Trend Analysis \(2021\)](#) suggested that changes in market conditions and consumer needs, sustainability initiatives such as lighter weights of injection-moulded plastic products, and the lower cost of automotive injection-moulded plastic have resulted in automotive manufacturers replacing metal automotive parts with plastic injection-moulded parts. This practice has become more widespread in the industry.

Similarly, in the food industry, according to Nagrale (2021), plastics have become more commonly used as alternatives in frozen food packaging, vegetable packaging, bakery packaging, bottled water, packaged food, and ready-to-eat meal packaging due to their advantages, such as lower package weight, lower cost, and the ability to customise packaging design to preference. Technological breakthroughs in injection moulding have allowed manufacturers to explore and take advantage of these developments to give them more control, flexibility, and definiteness. Aminabadi, Tabatabai, Steiner, Gruber, Friesenbichler, Habersohn and Weber (2022) state that injection moulding is a complex process. The material, product design, mould design, and process parameters are essential for determining the final product quality. Chen and Turng (2005), are of the view that processing parameters must be set up once an injection mould has been produced and configured on a machine. The parameters are developed using data from the raw material suppliers, product designers, and mould designers. The next step is for the injection moulding machine to undergo a lengthy "trial" period. This entails producing goods and optimising the machine settings through "trial and error" so that the manufactured products satisfy the design requirements and functionality. Such an exercise must be done for every specific material and equipment, which is laborious, time-consuming, and costly.

Chen and Turng (2005) further elaborated that new quality control testing techniques must evolve accordingly to support these new products and technology. This ensures that customer needs have been met and that good-quality, defect-free products are manufactured.

In the 1980s, according to Stojkic *et al.*, (2020), contactless 3-D measurement techniques emerged as technology advanced. The most popular technique uses a 3-D scanner to measure optically, where structured light is projected onto the object's surface that needs to be measured. It provides rapid measurements with satisfactory precision, making it an ideal technique for manufacturing and quality control environments. Govindan (2015) asserts that newer optical scanners are steadily gathering more acceptance from manufacturers because they are touted to be more versatile, portable, operate faster, and have more accurate outputs, making them popular for use as quality measurement tools.

Furthermore, Chen *et al.*, (2005) stated that frequent product quality checks are still required in many industries as a quality control measure, even in cases where the machinery is known to be correctly set up and operational. Due to several unforeseen factors that emerge during processing, for example, variations in different batches of raw materials, the internal

environment, and machine settings, there is a probability that the product quality may deviate from the acceptable quality specifications. When this occurs, the machine's process settings are typically adjusted to restore the products to their required specifications. Over the past years, extensive research has been conducted on suitable quality control systems for both in-line and off-line quality control to overcome the above-mentioned challenges and manufacture and maintain a good quality product that meets all its design specifications.

According to Zhao, Lian, Wang and Xu (2022), quality control is an integral process to monitor and control defective or poor-quality products from leaving the organisation or from being sent to the customer. Therefore, each injection moulded product has a set of variables and attributes that form the dimensions of the products that need to be achieved and maintained. According to Gordan (2010), variables are quality characteristics that are measured and represented numerically, for example, diameter, height, length, and width. Gordan (2010) further elaborated that an attribute is a quality characteristic that cannot be represented on a number scale, for example, colour, surface smoothness, misprint, and functionality. Zhao *et al.*, (2022) stated that the structure of products must have accurate dimensions. It is essential, especially if the product has different components that fit together, to create an assembled product, for example, a container and a lid that fit together.

Zhang, Ong, and Lam (2008) assert that routine quality testing is conducted on the injection mould and the products manufactured from it along the injection moulding process to mitigate defective or poor-quality products. Furthermore, they described that various variable and attribute tests are conducted on injection moulded products, which depend on the product type manufactured, functionality, and the type of material utilised in the manufacturing process. These quality tests on the manufactured products may include but are not limited to the product's weight, dimensions (height, diameter, breadth, width) and thickness.

Notwithstanding these rapid developments, according to Bulgaru, Bocanet and Muntean (2019), the industrial sector must also adapt to changing trends in the rapidly evolving world of technology. For example, Industry 4.0, which is commonly referred to as the Fourth Industrial Revolution, is one of these trends that has significantly affected the manufacturing sector. Furthermore, Belgaru *et al.*, (2019) described quality as a crucial component of this revolution and that the trends of the Fourth Industrial Revolution have resulted in the industrial sectors moving over from contact (tactile and mechanical) metrology to optical metrology for quality testing, for example, the use of new scanning techniques and equipment by using computerised

tomography, the use of optic and laser sensors in metrology and the use of industrial robots for the construction of new control equipment.

The *Top-10 Mechanical Measuring Instruments (2019)* described contact metrology as the most used instrument for measuring injection-moulded finished products. These include both tactile and mechanical measuring tools. Tactile measuring instruments metrology is a science that consists of a probe that is in contact with the surface of the product being checked to take measurements of the product. An example of this is the *CMM* Park, Kwon, and Cho (2006) describe the process of the CMM, which measures the geometry of objects by measuring different points on the surface of the object being measured using a probe. The control of the probe can be done either automatically by the computer or manually by the operator of the CMM machine. The *Top-10 Mechanical Measuring Instruments (2019)* suggested that mechanical measuring instruments comprise instruments such as the vernier calliper and the micrometre. According to Kaur and Kaur (2015), the vernier calliper is a linear measurement instrument. It measures dimensions such as length, breadth, depth, diameter, thickness, and height. The scale of the vernier calliper is used for analysing measurements, as indicated in the diagram in Figure 2.

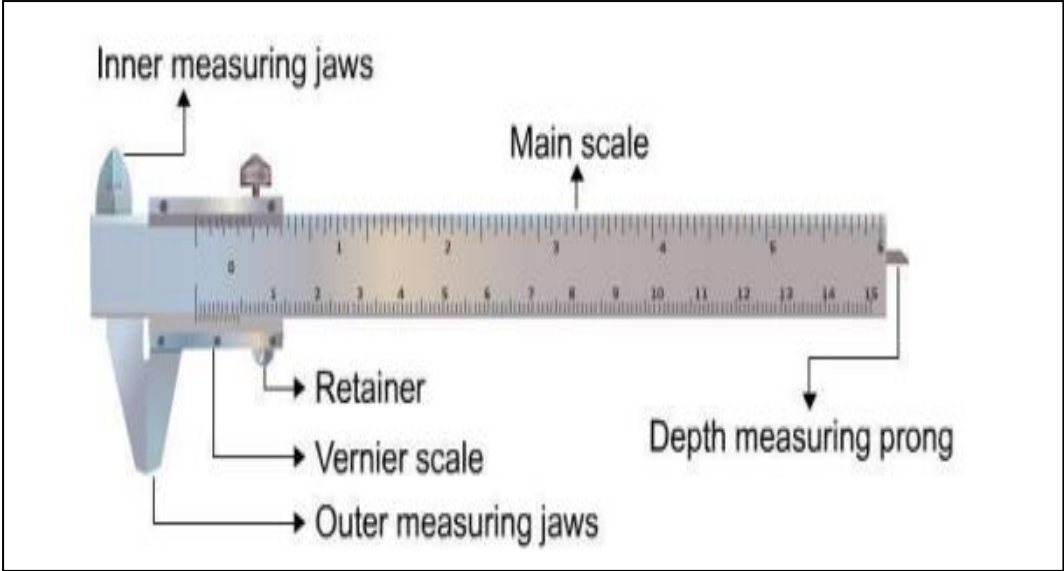


Figure 2: Parts of a vernier

(Sourced from Kaur and Kaur, 2015)

Diehr (2011) stated that the advent of technology and advancements in metrology led to the development of optical metrology. This has shifted from contact to optical instruments as quality tools in many industries. Optical metrology is the science and technology that utilises light for measurements (Morey, 2018). According to Govindan (2015), developments in optical metrology promise more accurate measurements and faster turnaround times for quality control than current tactile measurements. Furthermore, Govindan (2015) reported that manufacturers have increasingly used 3-D laser scanners, white light scanners, and laser trackers for optical dimensional metrology in the last few years. Ivsac (2014) cautions that faster technology is required to complete quality control testing during production cycles in these changing industrial revolutions. As a result, faster optical metrology technologies are overtaking standard measuring instruments.

According to Catalucci, Thompson, Samantha, Branson, and Leach (2022), modern manufacturing processes rely on precise metrology to ensure high-quality standards and enhance production efficiency. With Industry 4.0, optical metrology has witnessed a substantial increase in its application, with a growing number of manufacturing processes being redesigned to incorporate in-process measurement and control. Catalucci *et al.*, (2022) stated that optical metrology for digital manufacturing has become a major area of focus in manufacturing research. Moreover, they elaborated that although CMM solutions have been in use for many years, there is a noticeable shift towards maximising the benefits of optical measurement technologies. Intelligent, smart automated non-contact inspection devices facilitate quicker cycle times, reduced inspection times, and continuous monitoring of process quality measurement solutions, which have been adopted for many years. The current trend is to increasingly exploit the advantages of optical measurement technologies.

1.2 Statement Problem

Chen *et al.*, (2005), advised that developing and manufacturing injection moulded products can take weeks or months to prepare and perfect, thus straining resources and resulting in not fulfilling or meeting the demands and requirements of customers on time. According to Rogers (2015), with the rising demand for the number and complexity of injection moulded products, there is increased pressure on manufacturers to produce quality products at a faster rate, notwithstanding that the current metrological methods, particularly to determine quality control, may be time-consuming and may not be adequate to meet these requirements.

According to Zeiss (2017), getting manufactured products through the first inspection and into successful production is one of the most significant challenges in injection moulding. A pivotal aspect of the manufacturing process and the mould itself is testing the initial or first-off products that come out of the mould. Gordon (2010) identifies that a first-off inspection is required during the manufacturing process of injection moulded products. This inspection must be meticulous in measuring the various attributes of the product manufactured, such as accuracy and conformity in both shape and size. This is required to ensure that the finished products meet the needs and expectations of the customer. According to Zeiss (2017), the manufacture, assembly, delivery, and sale of final products are frequently delayed while waiting for the first manufactured products' quality control testing and approval. This is one of the main challenges with injection moulded products and justifies a change of thinking around the traditional quality control method to ensure speedy mould production, mould process verification and quality testing on finished products.

Moreover, not only is there an increase in demand for injection-moulded products, but according to Govindan (2015), there is a demand for more complex and convoluted products. Thus, this adds further to the pressure to produce quality injection-moulded products at a faster rate.

It is thus understandable that the increase in the complexity of the design of injection moulded products has resulted in the need for alternative and more accurate measurement methods and instruments to produce verifications at a faster pace. Furthermore, Govindan (2015) cautions that one of the main disadvantages of traditional contact measuring metrology (such as verniers and CMMs) is that these measurement instruments are subjective and dependent on the persons conducting the testing and that it sometimes takes a longer time to measure all the variables required of the finished products. This supports the need for other forms of metrological instruments that could be used for quality testing and have a faster output.

1.3 Aim

This study will aim to determine the suitability of using an alternative metrological strategy, using optical technology, to measure selected injection-moulded plastic products.

1.4 Objectives of the Study

- To investigate and optimise the use of optical metrology, such as a 3-D scanner, as an alternative measurement tool in injection moulding **at Polyoak Packaging.**
- **To determine the efficacy of a 3-D scanner as a quality check tool on Polyoak Packaging's injection moulded plastic products.**
- To establish the benefits (if any) of using a 3-D scanner as a measurement tool over the traditional contact metrological measuring equipment.

1.5 Ethical consideration

Confidentiality of the product specifications and the mould drawings and design is important to prevent Polyoak Packaging (Pty) Ltd competitors from accessing information on the product design and specifications. Therefore, all raw data obtained during the study will be converted into a softcopy format and stored on Polyoak Packaging (Pty) Ltd.'s central drive. The hard copies will be destroyed with a paper shredder after conversion to the soft copy to restrict access to the information.

1.6 Rationale of the Study

The results of this study will enable an understanding of optical measurements compared to tactile measurements.

The study will contribute to the knowledge of the suitability of optical metrology and the feasibility of using a 3-D scanner as a measurement tool for injection moulds and its products.

1.7 Outline of Research Methodology

The study follows a quantitative and experimental methodology. Measurements of four different products (closures and tubs) will be undertaken, including eight attributes of the closures and five attributes of the tubs. Tests will be conducted on two product samples, utilising a 3-D scanner and contact measuring devices. The experiment's validity will be

established by calibrating all measuring equipment utilised in the study before its use. The repeatability and reproducibility method will be used to measure the reliability of the data results.

1.8 Delimitations

Due to the confidentiality of mould designs, the study's scope is confined to using Polyoak Packaging (Pty) Ltd injection moulding products.

Due to the costs and availability of a 3-D scanner, the samples will be tested using only 1 brand. Other brands of 3-D scanners are available in the industry and may have different features.

1.9 Scope

Injection moulded plastic products.

1.10 Hypothesis

H₁: Optical metrology can measure injection moulded products in the plastic manufacturing industry.

H₀: Optical metrology cannot be used to measure moulds in plastic manufacturing.

1.11 Assumptions

As a measurement tool, optical metrology will provide faster turnaround times during mould maintenance and quality checks.

1.12 Outline of chapters

This study comprises of five chapters. A brief description of each chapter is outlined in Figure 3.

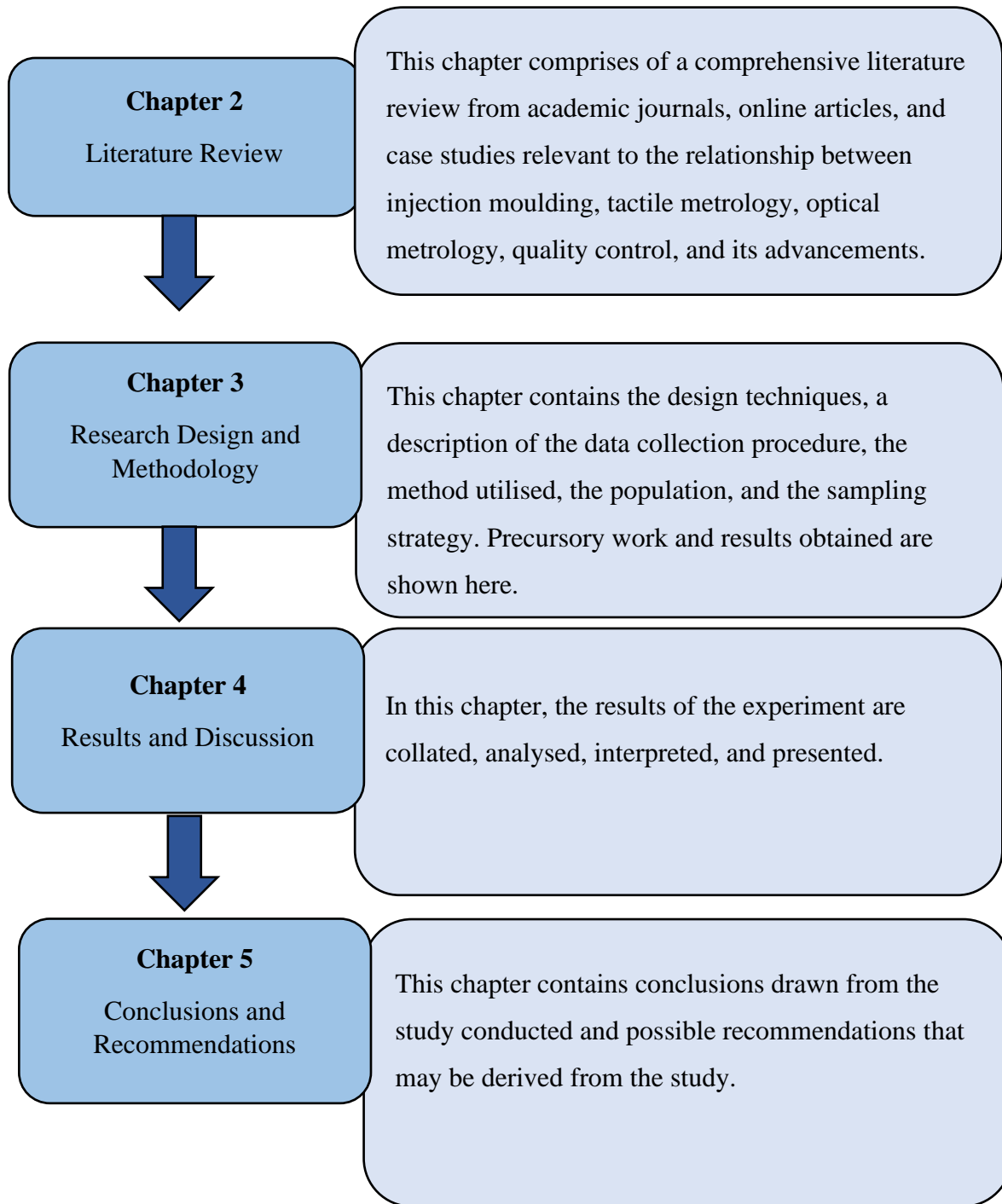


Figure 3: Illustration of the upcoming chapters in the study

1.13 Summary of the Chapter

The chapter presented an overview of the study. It is suggested that the injection moulding market is estimated to grow to \$420 billion by 2030. It cautioned that there has also been a demand for quicker and more efficient measuring devices during routine quality testing. With the advent of Industry 4.0, there has also been an increase in technological advancements, such as optical scanners. Therefore, this study aimed to determine if optical technology can be used during routine quality testing in selected injection moulded products. The hypothesis and null hypothesis were formulated, and Chapters two, three, four and five were outlined.

The next chapter will explore the review of the literature and present the gap of knowledge and critique around injection moulding and its concomitant quality control.

CHAPTER 2: LITERATURE REVIEW

Chapter Two provides an overview of the theory derived from historical research and literature on injection moulding, quality testing and measurement. This chapter includes relevant literature presented under the following headings: The History of Injection Moulding; The Injection Moulding Process; Injection Moulding Products; Materials in Injection Moulding; Quality Control; Quality Testing; Contact Measuring Instruments; Optical Measurement Instruments; and Scanning Metrology. This chapter will also bring focus to the study by first highlighting the development of the injection moulding process over the years, the importance and versatility of the injection moulding process, then bringing focus on the different quality control techniques and measuring devices used in routing quality control testing, and finally calling attention to the need for alternate measuring devices which are quicker and more advanced. A brief overview of each section in this chapter is outlined in Figure 4.

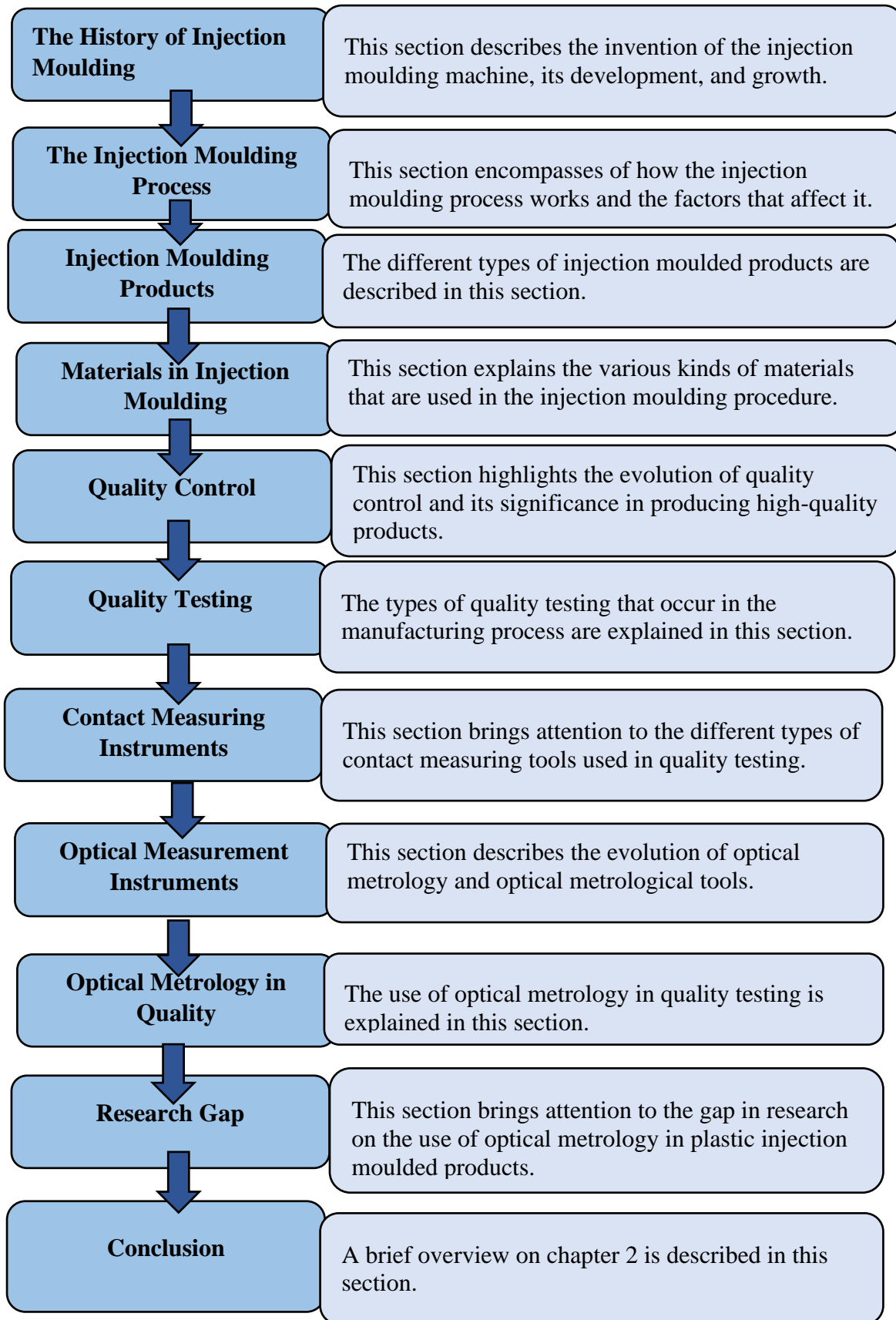


Figure 4: Illustration of Chapter 2

2.1 History of Injection Moulding

The history of injection moulding encompasses the invention of the injection moulding machine and its development and growth over the years.

According to Yang (2022), since the inception of the plastic injection moulding industry in the late 1800s, it has experienced continuous advancements and growth. Yang (2022) stated that, in today's world, the plastic injection moulding industry is at the forefront of producing goods for every sector of the economy, including medical, automotive, electronic, and home appliance industries. Products range from buttons to automotive components. He further elaborated that today's world cannot operate without plastic injection moulding because it has provided a diverse and invaluable method that has paved the path for current and future technological innovation and design.

Morris (2001) claims that brothers John Hyatt and Isaiah Hyatt built and patented the first injection moulding machine for plastic in 1872. The machine, depicted in Figure 5, was simple in design and served its purpose effectively. It consisted of a plunger-style component that pumped plastic into the mould (Morris, 2001).

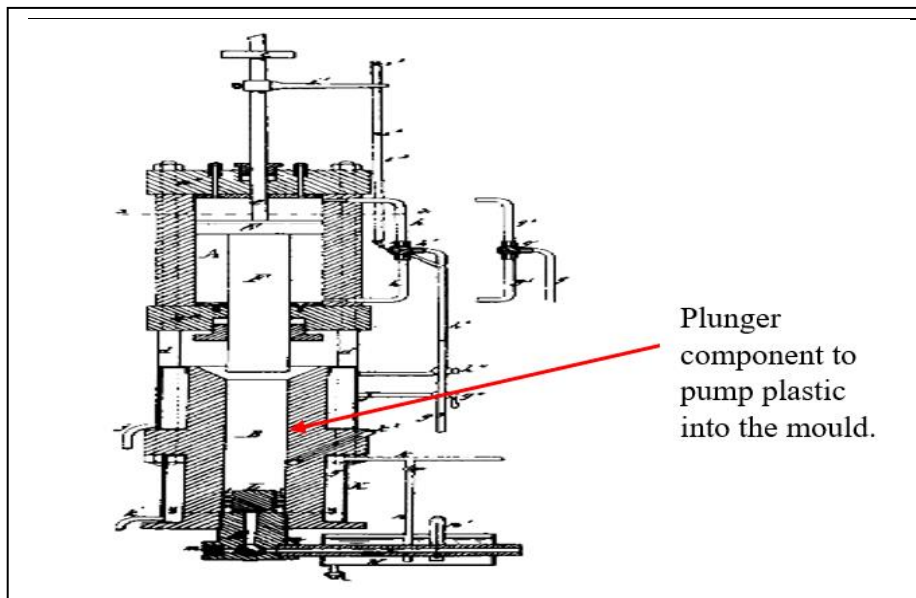


Figure 5: John Hyatt's 1st patent drawing of the injection moulding machine

(Source: AV Plastics, 2010)

Morris (2001) further narrated that James Hendry designed the first screw-type injection moulding machine in 1946. This replaced Hyatt's plunger model with an auger. Hendry's design transformed the plastics manufacturing industry. This screw-type injection moulding machine design involves an auger inserted into the cylinder to mix the material. This auger then moves forward and injects the mixed material into the mould. This injection moulding method is currently used in almost all injection moulding machines. Figure 6 illustrates the initial extrusion screw-type injection machine that was developed in 1946.

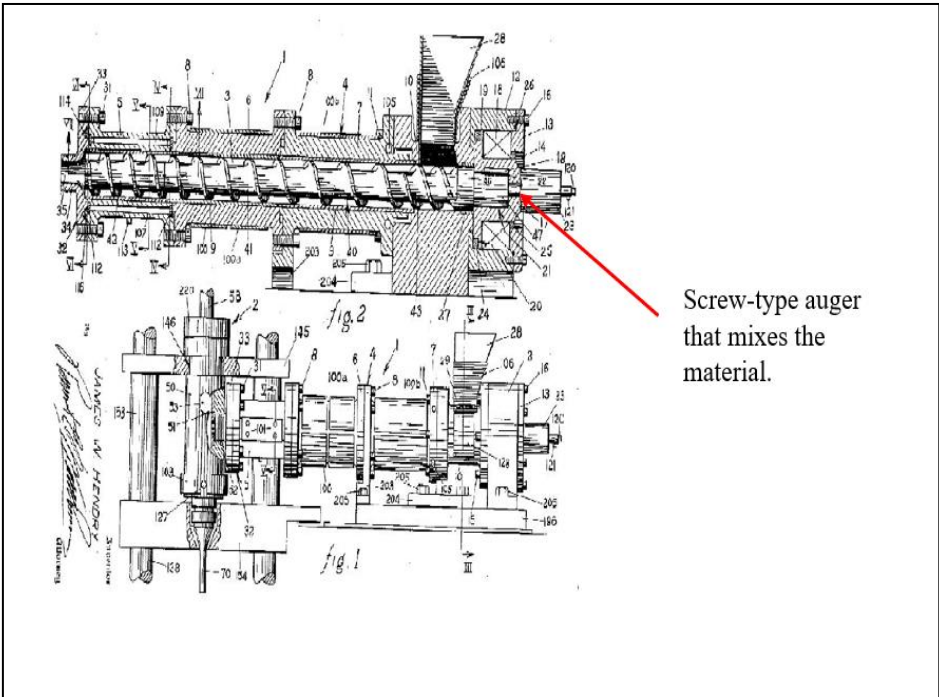


Figure 6: Patent drawing of James Watson Hendry's injection moulding machine.

(Source: AV Plastics, 2010)

Yang (2021) postulated that World War II and the growth of automobile technology bolstered the manufacturing sector for battle equipment in the United States of America. This sparked the initial phase of the post-war industrial revolution. Yang (2021) further described that post-war, there was an enormous demand for low-cost, mass-produced materials and, as a result, a demand for plastics. Due to the shortage of materials after World War II, plastics filled the gap by offering an inexpensive alternative. Plastic injection moulding and the use of plastics grew in popularity over the years.

2.2 The Injection Moulding Process

Morris (2001) described the injection moulding as a complex process. According to Tao (2001), the injection moulding process is dependent on several factors, such as mould design; the type of material that is used in the process, the purpose of the product or how the product will be used; components of the mould and how they will fit into each other; dimensions; weight; and surface texture of the product. Riley (2012) explained that careful consideration needs to be given to these factors to prevent defective or poor-quality products and high process waste during the trial phase of the mould. The current technology of the injection moulding process is illustrated in Figure 7. This provides a pictorial description of the injection moulding process. In this process, heat is applied to thermoplastic materials, which are then melted, shaped, and cooled. Injection moulding technology has progressed so much that most present-day injection moulding processes are extensively automated (Morris, 2001).



Figure 7: Injection moulding machine

(Source: [Mech4Study, 2018](#))

As Riley (2019) described, an injection moulding machine consists of a material hopper, an injection ram or screw-type plunger, and a heating element. Depending on the products

manufactured, the weight of an injection moulding machine may range from less than 5 tons to six thousand tons.

Because injection moulds are extremely expensive to build, Morris (2001) asserts that injection moulds are traditionally used in large production environments where thousands of products are produced. Hardened steel, pre-hardened steel, aluminium, and/or beryllium-copper alloy are used to manufacture moulds. Morris (2001) further explained that economic factors are thus taken into consideration when deciding on the material to be used to construct a mould. Steel moulds typically cost more to manufacture, but because of their longer lifespan, they can produce more products before they become worn out. This compensates for the higher initial cost. Since pre-hardened steel moulds are less wear-resistant, they are typically employed to manufacture larger products or bigger volumes.

Perkowski and Swigart (2017) posited that the injection moulding process consists of injecting materials (polymers and colourants) under high pressure and temperature into a mould, which then moulds the polymer into the required shape. Perkowski and Swigart (2017) further elaborated that moulds may contain one or several cavities. For moulds that contain several cavities, each cavity can either be identical and produce the same product or different and produce a variety of shapes or designs in one complete cycle.

Riley (2012) described that during the injection moulding process of thermoplastics, pelletised raw materials are fed into a thermal barrel with a corresponding screw. Upon reaching the barrel, the temperature rises, and the enhanced space between the molecules is at a higher thermal energy level, which causes Van der Waals forces. These Van der Waals forces then inhibit the relative flow of individual chains to weaken them. He further described that during this process, the viscosity of the thermoplastics is decreased, which allows the polymer to flow in tandem with the injection moulding unit's force. The screw moves the raw material, by blending and homogenising the temperature and viscosity distributions of the polymer. This in turn lessens the time required to heat it by the mechanical shearing of the material. The mechanical shearing of the material increases a substantial amount of frictional heating to the polymer. The material then streams forward through a check valve and gathers into a shot at the front of the screw. The amount of material utilised to fill the mould is referred to as a shot. The gate (cavity entrance) is applied with packing pressure until the gate solidifies. No additional material can enter the cavity after the gate has solidified. The screw then rotates and gathers material for the ensuing cycle, while the material inside the mould cools and is ejected

in the form of a product or part. By utilising cooling lines to circulate water or oil from an external temperature controller, the cooling time is reduced significantly. The mould then opens once the appropriate temperature has been attained, and an assortment of pins and sleeves are then pushed forward to de-mould the product. The mould closes afterwards, and the process begins again. For a two-shot mould, two different materials are combined to manufacture one product. This technique of injection moulding process is used to manufacture products with a variety of performance attributes and manufacture products with numerous colours.

2.3 The Injection Moulding Products

The section describes the wide range of injection moulded products manufactured through the injection moulding process.

As Morris (2001) described, the injection moulding process is one of the most common and preferred methods of converting polymers into products to create a wide array of products. According to Rogers (2015), plastic injection moulded products are used in many industries, such as the food, beverage, and chemical industries, because they can be hygienic, lightweight, and impervious. He further described that there are several types of injection moulded plastic products. Injection Moulded plastic products include tubs, hangers, bottles, jars, closures, drums, electronic casings, combs, automotive interiors, and machine parts. Examples of these injection moulded products are shown in Figure 8.



Figure 8: Types of injection moulding products

(Source: Polyoak Packaging Product Catalogue, 2023)

2.4 The Materials Used in Injection Moulding

This section describes the various materials that can be utilised to produce injection moulded products.

Melito (2021) stated that various materials can be used in the injection moulding process. Examples include metals, plastic, glass, polymers, and elastomers.

This section focuses on using polymers as a material source for the injection moulding process, as this study is based on the use of plastic injection moulded products. The polymers used in the injection moulded process include polypropylene (PP), high-density polyethylene (HDPE), polystyrene, and low-density polyethylene. Each material has its advantages and disadvantages. Table 1 provides a brief overview of the properties of polymers. This section focuses on Polypropylene, as the samples tested in this study were manufactured from this polymer. Polypropylene is the second most used polymer around the world. Todd (1994) postulated that due to the chemical structure of polypropylene. It has several advantages and is commonly used in manufacturing plastic packaging.

Nicholas and Cheremisinoff (2011) proclaimed that polypropylene is a thermoplastic polymer primarily composed of propylene (or propene) monomer units. Its production involves chain-growth polymerisation, through which propylene monomers undergo polymerisation to yield the polypropylene polymer structure. They further explained that polypropylene is renowned for its toughness, rigidity, and crystalline nature. Polypropylene can be manufactured as a homopolymer, exclusively composed of propylene units, or as a copolymer with other monomers, allowing for its properties and performance variations.

Table 1: Mechanical and physical properties of polymers

(Source: Gupta, Srivastava, and Himanshu, 2015)

Polymers	Density (g/cm ³)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Impact Strength
Epoxies	-	55-130	2.7-4.1	110-150	3-4	-
Phenolic	-	50-60	4-7	80-135	2-4	-
Polyesters	-	34-105	2.1-3.5	70-110	2-4	-
Vinylesters	-	73-81	3-3.5	130-140	3	-
Poly lactide	1.24	56.3	3.6	-	-	-
Polyester	1.2	61	4	-	-	-
Polyvinyl chloride (PVC)	1.35	48	3.300	-	-	0.32 J/cm
Polystyrene	-	46	2.9	-	-	0.17 J/cm
Polypropylene (PP)	0.899 - 0.920	26 - 41.4	0.95 -1.776	55.2	0.83-1.73	21.4 -267 J/m
Low density polyethylene(LDPE)	0.910 - 0.925	4-78.6	0.055 -0.38	-	-	>854 J/m
High density polyethylene (HDPE)	0.941-1	14.5- 38	0.413- 1.490	-	0.41-1.07	26.7 J/m

Maddah (2016) listed these advantages as the following:

- PP has a high melting point.
- PP is chemically inert.
- PP is light in weight and can be transported more easily, making it ideal for the packaging industry where lightweight products are required.

- PP has good mechanical strength; it is malleable and can tolerate flexing, bending, and vibration without serious distortion.
- It is economical and relatively low in cost during manufacturing.
- PP has low moisture absorption characteristics and is resistant to water and moisture.
- PP is a food contact-approved material, making it suitable for food packaging such as tubs, containers, and closures.
- PP is used for frozen food products, such as ice cream, due to its resistance to freezing.
- PP is highly resistant to chemical leaks and corrosion, making it suitable for use in the chemical and agricultural industries.

Todd (1994) stated that materials chosen for the manufacturing process are based on the requirements of the finished products. The type of material chosen plays a critical role in the quality of the product that is manufactured. Each material type has different processing parameters that must be considered when selecting the material to use in manufacturing. This is based on the final product's intended use and functionality. **These properties also encompass light absorption and refraction (Mitchell, 2003).**

According to Kaur and Gurnani (2023), the velocity of light as it moves through a medium other than a vacuum is determined by an essential optical property known as the index of refraction. This index is critical for understanding how light is reflected and refracted through different materials at varying angles. When light moves through a less dense medium at a lower temperature, it travels more quickly, resulting in a lower refractive index. Mitchell (2003) stated that polypropylene has a refractive index of 1.47. It is important to note the refractive index of polypropylene; as Javid, Haleem, Singh, and Suman (2021) pointed out, because laser triangulation is pivotal in multiple scanning techniques, including structured light. For instance, a laser sheet generates a profile, while a single-point laser gathers range information about an object, and a patterned laser creates point cloud data. Furthermore, a laser sheet scanner projects a plane of laser light, which is observed at an angle using a camera to accurately measure the shape of an object within the scanning area. This comprehensive understanding of laser triangulation's applications and the refractive properties of the sample to be tested is important because the refractive index of the sample may affect the 3-D scanned image integrity.

Catalucci, Thompson, Samantha, Branson, and Leach (2022), stated that one of the complex challenges in 3-D scanning is the hindrance caused by light refraction when acquiring accurate shapes and detailed data from transparent materials. To overcome this issue, scanning spray powder on transparent and varying material objects is recommended, thus highlighting the sensitive nature of 3-D scanning. For this study, the refractive index is an important factor to consider due to the refractive index of polypropylene, which may cause light from the 3-D scanner to travel faster through the sample. This could potentially impact the accuracy of the 3-D scanner's results. Thus, to mitigate the effects of light refraction, a scanning spray will be applied to the tested samples in this study.

2.5 Quality Control

This section explores the evolution of quality control, its various forms, and the importance of producing high-quality products during injection moulding.

Hamid, Chew and Altun (2019) narrated that during the 1920s, statistical sampling techniques were introduced into quality control. Gordan (2010) described quality control as measuring and testing products to ensure that they are consistent and meet the required specifications. This led to the initial development of Quality Management Systems (QMS). According to Dalgaard, Reyes, Chen, and Park (2019), a Quality Management System is a prescribed system that documents the procedures, processes, roles, and responsibilities for accomplishing an organisation's objectives and policies. Dalgaard *et al.*, (2019) narrated that a QMS assists in managing an organisation's activities to satisfy a customer's needs and expectations.

Hamid *et al.*, (2019) stated that Walter A. Shewhart had led the development of statistical quality control. Walter Shewhart first used statistical process control (SPC) in the Bell Telephone Company's Hawthorne Plant in 1924, where the philosophy and practice of Total Quality Management (TQM) first emerged. SPC is the application of statistical methods to monitor an activity or manufacturing process. TQM is a system that provides manufacturers with a framework for adopting effective quality and production procedures throughout their whole business. According to Juran and Godfrey (1999), there was an increase in demand to improve output and productivity in the 1920s. Juran and Godfrey (1999) further asserted that as the pressure in product demand increased, there was a breakdown in quality control. It had

become evident that a more solid, organised, and logical approach to quality was required. Therefore, quality procedures are created to prevent non-conforming products from being produced by establishing checks and controls early in the production process.

This standard was imperative then and has been carried out to current times. According to Hamid *et al.*, (2019), experts like Joseph M. Juran and W. Edwards Deming played a crucial role in creating the quality management systems that industries still use today. When the quality of products manufactured in Japan began exceeding those manufactured in the USA and Europe in the 1970s, it encouraged the rise of the quality revolution. According to Hill (2023), the 1980s saw a strong focus on quality improvement. During the 1980s, the American economy struggled to compete with Japan. This prompted business executives to support the TQM movement. This served as the foundation for operational excellence in the United States. Motorola created a quality control approach known as Six Sigma in 1986. Using qualitative and quantitative tools like control charts and process mapping, Six Sigma helps businesses improve processes and reduce manufacturing defects. Many organisations now use Six Sigma to improve profitability. Hill (2023) further narrated that the ISO 9000 series of quality management standards was published in 1987 by the International Organisation for Standardisation (ISO). These standards were developed to assist businesses in documenting and managing the various elements of a quality management system, thus improving customer satisfaction, fulfilling regulatory obligations, and accomplishing continuous improvement. In the past few decades, there has been a substantial change in approaches to quality management systems. In the year 2000, the ISO 9000 series of quality management standards were amended to emphasise customer satisfaction. In 2015, the ISO 9001 standard was updated to emphasise risk management more. A brief overview of the evolution of the quality moment is described in Figure 9.

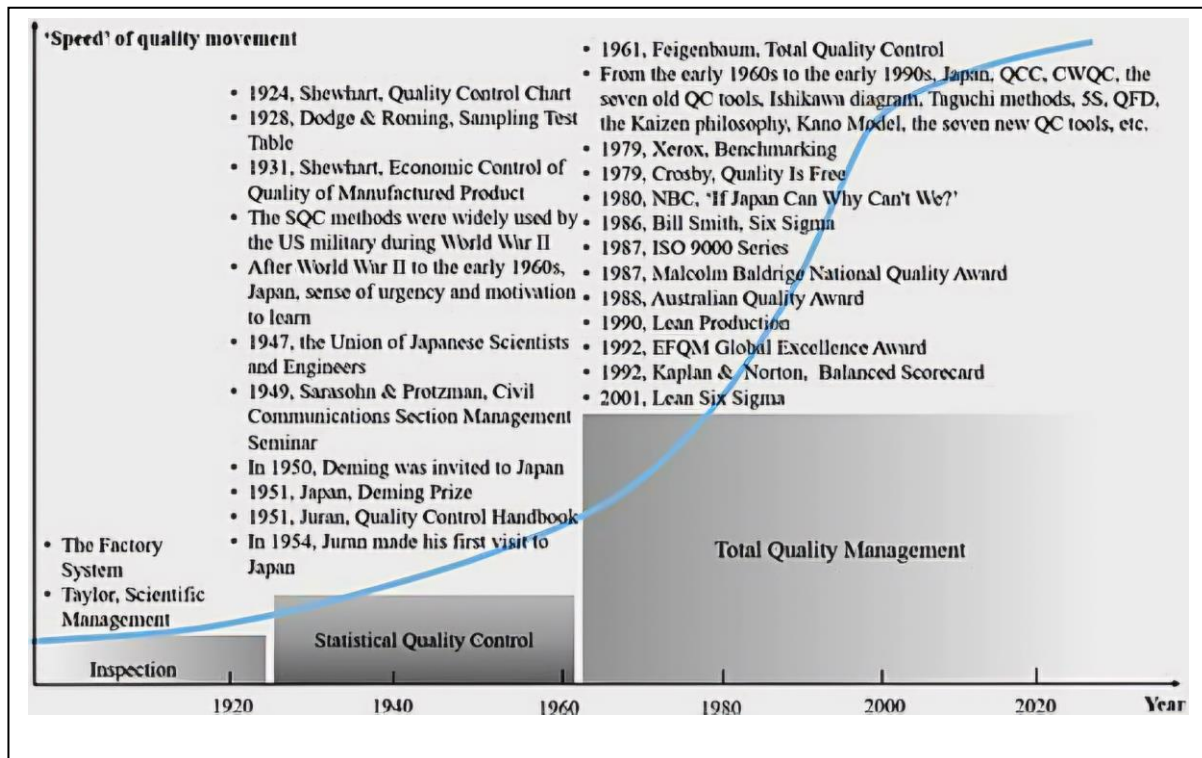


Figure 9: History of the quality movement.

(Source: Wen, Sun, and Yan, 2020)

Kumar (2015) stated that quality control is integral to all businesses of different sectors. He elaborated that quality control is important to all businesses for customer satisfaction, cost reduction, business growth and compliance. Customer satisfaction is attained by meeting customer needs and expectations, which results in positive feedback, loyalty, and a good reputation for businesses that provide quality products and services. Good-quality products lower the possibility of defects or product failures, eventually saving costs. Conversely, low-quality products or defects can lead to an increase in production costs or product recalls. Kumar (2015) further stated that brand worthiness is created by high-quality products and services, which also help to draw in new customers and increase market share. Quality control is critical in certain industries due to regulatory, legal, or ethical requirements or certifications. Adhering to these quality standards and compliance requirements is important to avoid legal or financial penalties. Since quality promotes customer happiness, cost-effectiveness, corporate growth, and compliance with essential regulatory and legislative requirements, it is fundamental to all

businesses' success. Routine quality testing conducted on end-line products is critical to quality control.

Mahajan and Ulhe (2020) described quality control as primarily focusing on simple finished product inspection. The complexity of the injection moulding process can allow for errors or deviations from the required product standard or specification during the manufacturing process. This can result in quality defects on the finished product. These quality defects can range from minor to major defects. The quality defects can be visual (for example, short shots, sink marks and warping) or a variable defect (for example, underweight products, opening torques, and width), which could be caused by the moulding process, process parameters, material, or tooling (Mahajan and Ulhe, 2020). These defects can be detected during routine quality control testing. Visual testing depends on the person inspecting the product to detect the defect, which could result in the defects being undetected by the person conducting the inspection.

As shown in Table 2, several visual defects affect injection moulded products.

Table 2: Visual moulding defects (Melito, 2021)

Visual defects that affect the quality of injection moulding products	
Moulding Defects	Defect Description
Flow Lines	Flow marks, streaks or waves that are discoloured.
Sink Marks	These are localised, small indentations on the surface of the product.
Vacuum Voids	Trapped air bubbles cause this empty space on the product.
Surface Delamination	When thin layers of the surface of the product begin to peel away.

Weld Lines	The discoloured line is where two flow lines on the product's surface meet.
Short Shots	The molten plastic does not fill the cavity completely
Warping	When different parts of the surface cool down unevenly. The product is distorted or wavy.
Discolouration	These are dark-coloured marks on the surfaces. They are caused by problems with tooling, incorrect process parameters, poor-quality materials, or degraded materials.
Jetting	A deformation of the product results in weakness.
Flash	A small flap or thin extra material on the products.

Mohamed, Yusoff, Rohani, Harun, Hamid, and Ramly (2004) stated that variable characteristics, such as height and mass, can be measured. These characteristics contribute to the quality of the manufactured product, which is measured with various measuring devices, such as verniers, callipers, and scales. As shown in Table 3, several variable attributes affect injection-moulded products.

Table 3: Variables attributes on injection moulded products (Mitchell, 2004)

Variable attributes that affect the quality of injection moulding products	
Variable	Defect Description
Height	Height is the measure of a product from base to top. It is either above or below the required height specification.
Wall Thickness	Wall thickness is the extent from the surface to the opposite surface of a product. The thickness of the product's wall is thinner or thicker than the required specification.
Diameter	Diameter is the length of a straight line through the centre of an object. The diameter of the product is wider or smaller than the required specification.
Mass	Mass is the amount a product weighs. The mass of the product can be larger or smaller than the required specification.
Brimful Capacity	Brimful capacity is the volume a product can fill before it overflows. The volume of the brimful capacity of the product is more or less than the required specification.

These variable attributes play a critical role in the manufacture of quality products. They are tested during routine quality testing to ensure conformance to the required specifications of the products.

2.6 Quality Testing

Zhang, Ong, and Lam (2008) stated that quality testing is the process that companies use to ensure that their products and services comply with customer requirements. This includes testing products to ensure that they meet the product specifications. To mitigate defective or poor-quality products, testing is conducted on the injection moulding mould and the products manufactured along the injection moulding process. Zhang *et al.*, (2008) asserted that various variable tests are conducted on injection moulded products, which depend on the product's manufactured product type, the product's functionality and the type of material utilised in the manufacturing process. These quality tests on the manufactured products may include but are not limited to, the product's weight, dimensions (height, diameter, breadth, width) and thickness. Testing compliance with variable specifications is an integral part of manufacturing to ensure a high-quality product is produced.

This is further supported by Zhao (2022), who elaborated that testing dimensions is a critical quality test, especially for components that fit into each other. If a component of the manufactured product must fit into another component, it must be within the required specification of both components. If a component is too small or big or has the incorrect shape, it will not fit with the other component. These types of quality testing are done at various points in the manufacturing process. Quality tests can be conducted on moulds and products during the design and pre-production phases, at first product inspections, as an in-process check, and during pre-shipment inspections (post-production) before shipping the products. Current technology includes contact (tactile and mechanical measuring tools) and non-contact (optical measurements) methods.

2.7 Contact Measuring Instruments

Glassburn (2019) described contact measuring instruments as requiring direct contact with the measured object or item. He further asserted that tactile and mechanical measuring tools are the most common methods used in routine quality control testing. Mechanical measuring instruments used in injection moulding include the vernier calliper, the micrometre, and the Coordinate Measuring Machine (CMM).

The vernier calliper and CMM will represent contact measuring instruments for data collection in this study.

2.7.1 The Vernier

According to Ohmid and Mishra (2019), the calliper was invented in 9 AD. There are different callipers, including the inside calliper, the outside calliper, the divider calliper, the oddleg calliper, the vernier calliper, the digital calliper, the dial calliper, and the micrometre calliper.

Ohmid and Mishra (2019) stated that the vernier was invented in 1631 by the French Mathematician Pierre Vernier. The vernier calliper is a linear instrument that measures dimensions such as length, breadth, thickness, depth, circumference, and height. Figure 10 illustrates the different components of the vernier.

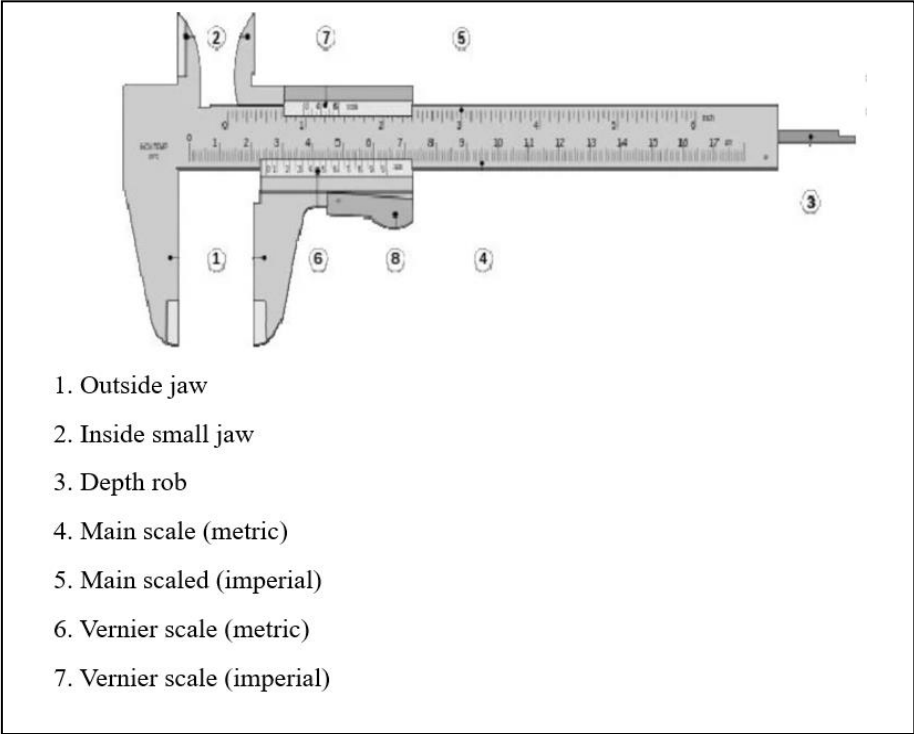


Figure 10: Illustration of the vernier calliper

(Source: Ohmid and Mishra, 2019)

Karim (2023) stated that using a vernier as a measurement instrument has several advantages and disadvantages, which are tabulated in Table 4.

Table 4: Advantages and disadvantages of a vernier (Karim, 2023)

Advantages	Disadvantages
Good precision and accuracy.	The user requires good eyesight.
Has an integrated scale.	Results are subjective to the user of the measuring instrument.
It is a versatile measuring instrument.	Limited to linear readings.
It is a durable measuring instrument.	More accurate tools are available.
It is low cost.	Requires manual reading and interpretation.

Although the vernier calliper has several advantages, its use is limited to the shape of the sample being tested. Moreover, it is very subjective to the user, resulting in the need for a more efficacious measuring instrument.

In a study conducted by Muteti and El-Badawi (2018), it was found that measurements of the thoracic pedicle taken with the vernier varied. The variations in measurements increased on narrow pedicles. They posited that the results were less reliable when the diameter of the thoracic pedicle decreased, and therefore, caution should be taken when measuring with a vernier.

Al-Essa and Alkarashi (2021) conducted a study on the precision of callipers. Callipers are often used in ophthalmic surgical procedures. The study evaluated forty-one callipers to determine their accuracy and if it could potentially be a reason for clinical and surgical errors. They had inferred that callipers used extensively may become worn out and damaged, resulting in incorrect measurements, which could lead to major surgical errors and implications. All callipers should be calibrated against a standard ruler before being used to guarantee accuracy. To identify potential errors and eliminate preventable challenges, it is advised that all callipers used in surgical operations undergo routine screening and calibration. There are many advantages to verniers. However, they are potentially prone to errors during measurements.

2.7.2 The Coordinate Measurement Machine

Park, Kwon, and Cho (2006) stated that the CMM is a tactile contact measuring device. They elaborated that tactile metrology is a science consisting of a probe in contact with the measured object's surface. This probe then traces a line on a flat surface or a circular arc on a cylindrical object. These measurements are then used in data analysis. The CMM calculates the geometry of objects by measuring different points on the surface of the object being measured with the probe. The control of the probe can be done either automatically by the computer or manually by the operator of the CMM machine. As shown in Figure 11, there are four different types of CMM machines, namely: the bridge type CMM, the gantry type CMM, the cantilever type CMM, and the horizontal arm CMM. The function and operation of the four types of CMM are the same; they are just classified according to their structure (Syam, 2022).

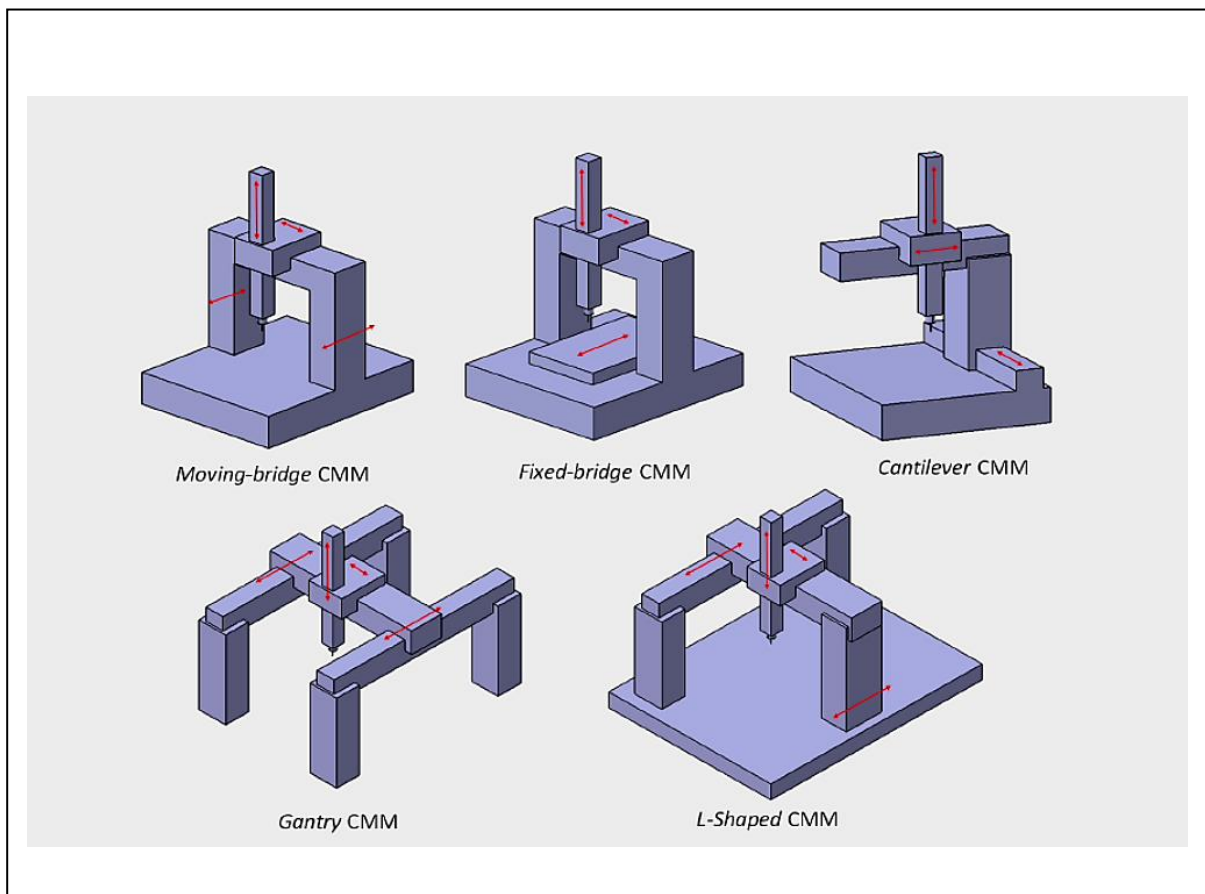


Figure 11: Different types of CMM machines

(Source: Syam, 2022)

Park *et al.*, (2006) described that the probes of the CMM translate physical measurements into electrical signals. They elaborated that different types of probes can be used in a CMM. This

includes touch trigger probes, displacement measuring probes, and proximity or non-contact probes. The most frequently used probe is the touch trigger probe. The touch trigger probe touches the object's surface being measured and then sends a signal with the coordinates of the surface point it has been in contact with. The touch trigger probe repeats this process at various points along the measured object. The displacement measuring probe passes over the target surface of the measured object. The probe then scans the surface and conveys the constant data stream to the measurement system. The displacement measuring probes use the linear variable differential transformer (LVDT) sensing. LVDT is an electromechanical transducer that can transform a mechanically linked object's straight-line movement into an analogous electrical signal. The proximity or non-contact probe operates similarly to the displacement measuring probe. The proximity probe uses a laser rather than LVDT technology (Top-10 Mechanical Measuring Instruments, 2019).

As shown in Table 5, there are several advantages and disadvantages to the use of CMM.

Table 5: Advantages and disadvantages of a CMM (Govindan, 2015)

Advantages	Disadvantages
High precision and accuracy.	CMM is expensive.
Requires less labour.	CMM is not portable.
Accurate dimensions can be obtained.	It is difficult to restart the entire CMM system.
Robustness against external force and error accumulation.	Some parts of the object being measured are not obtainable by the probe.
The software can be updated without changing the actual CMM.	CMM could possibly take hours, depending on the size of the object being measured.

Govindan (2015) stated that CMMs are still used in demanding industries like aerospace and the automotive sector because of their ability to measure parts with sub-micron accuracy. However, CMMs have some limitations. Kupriyanal (2018) supported this by elaborating that to inspect a part, CMMs use touch trigger probes that must meet every surface of the object

being measured. Kupriyanal (2018) elaborated that the accuracy may be questionable when scanning objects with hard-to-reach places or challenging surfaces. Hidden features may need to be added subsequently using software. The necessity of touching components increases the possibility of harming them, and scrapes and scratches have occurred when using CMMs. Other factors, such as cost and available space, must be considered before purchasing a CMM. These factors affect the type of measurement instrument chosen for routine quality control testing.

According to Kupriyanal (2018), CMM sensor tips have a limited capacity, which limits the amount of data they can gather in a single sweep. Large, complicated items may become difficult for machine operators to measure, compromising their chances of achieving project deadlines.

Kupriyanal (2018) described a team at the British Museum that had to quickly collect more than four hundred plaster castings of historic Mayan monuments. Digitising each cast using CMM machines would have taken more than an hour, but they discovered they could use a 3-D scanner and produce the desired results in less than ten minutes each.

Over the years, the design of parts in the plastic manufacturing industry has grown in complexity, thus creating a need to develop new metrology procedures to optimise the entire manufacturing process (Diehr, 2011). Bharti (2010) stated that due to the increase in competition in injection moulding on a global scale, the trial-and-error method to determine process parameters is no longer accepted as a viable method for optimisation. According to Bharti, (2010), part design, mould design, machine performance and processing conditions play a critical role in product quality. Deviations in these parameters will lead to longer startup times, higher costs, and poor-quality defects.

Govindan (2015) stated that the CMM has been the preferred measurement machine for repeatable and accurate results over the years. However, in the last few years, this perception has slowly changed with the advancement in optical scanners, which are smaller, portable, and promise faster measurement output times.

An alternative method, such as optical metrology, could minimise the time taken for quality checks on moulds during mould design and maintenance and produce more accurate products during the first production run. Over the years, optical scanners have been developed for dimensional metrology inspection owing to an increasing need for more rapid technology.

2.8 Optical Measurement Instruments

The advancement of technology and advancements in metrology has led to the development of optical metrology (Diehr, 2011). Optical metrology is the science and technology that utilises light for measurements (Morey, 2018). Optical measurement devices are used to measure curved surfaces of aircraft wings, perform part inspections, and perform reverse engineering in the aerospace industry. In the automotive industry, optical measurement devices are used for alignment profiling, dimensional measurement, and quality control in the aerospace and automotive sectors. Optical measurement devices are used in the automotive industry for alignment profiling, dimensional measurement, and quality control (Govindan, 2015).

Osten (2018) stated that optical metrology uses light to measure dimensions, distances, surface topographies, and temperature. According to Osten (2018), optical profilometers (optical surface profilers) are used to measure surface profiles precisely. Paschotta (2006) supported this by inferring that lasers or interferometers may be used for precise and sensitive measurements of distances and displacement. According to Paschotta (2006), the field of non-contact metrology has been growing. Optical measurements or non-contact metrology allow for overly complex and sensitive items to be measured without touching them and without risk or damage to these items. Figure 12 is an example of an optical measurement device (3D scanner) which uses light properties.



Figure 12: A 3-D scanner

(Source: WD Hearn Product Catalogue)

According to Stavroulakos (2016), metrology is critical in additive manufacturing as multiple machines are used, and each machine needs process feedback to meet its specifications. Several studies have been conducted in the field of additive manufacturing regarding metrology. In a study conducted by Stavroulakos (2016), non-contact metrology (active optical form measurement systems) was utilised to measure the surface texture of machine parts in additive manufacturing. The study showed that the measurements could be conducted instantaneously and that there were significant improvements in the accuracy and precision of the results. It also allowed for measurements with tolerances of a range within a hundred micrometres and for measuring rough surfaces. This was integral in quicker start-up times and more precise end products for the additive manufacturers that utilised non-contact metrological instruments.

According to Clark (1998), single-point optical triangulation instruments have successfully measured distance and surface texture on objects such as tyre threads, circuit boards, road surfaces, pipes, ships, and tunnels, resulting in more accurate measurements and products.

Hanaphy (2023) elaborated that a 3-D scanner describes an object's shape in an exact, digital, three-dimensional form by taking measurements of the object's surface. High-precision 3-D scans are used for more than dimensions analysis and inspection, unlike measurement data obtained from a CMM. The measurement data produced from 3-D scanners allow for digital assessment and inspection in a visible and comprehensive reporting approach, which is completed more quickly and easily. In addition, 3-D scanners are useful for reverse engineering, ensuring components' shape, fit, and functionality at a distance, validating CAD models of 3-D printed parts, and opening new digital tactics for routine quality control testing.

Hanaphy (2023) stated that there are numerous types of 3-D scanners, i.e., desk-top scanners, hand-held scanners, and fixed scanners that can be mounted onto robotic arms. The type of scanners utilised will depend on the size of the tested object and the user's needs.

Arayici and Hamilton (2006) described several advantages and disadvantages of 3-D Scanners, summarised in Table 6.

Table 6: Advantages and Disadvantages of a 3-D Scanner (Arayici and Hamilton, 2006)

Advantages	Disadvantages
3-D Scanners are portable and light.	Have high initial costs.
3-D Scanners are quick to use.	The data processing and storage require a large computational power and storage.
Have a high degree of accuracy.	Requires a specialist to operate.
3-D Scanners reduce human input and errors.	Possible inference from ambient light.
Can scan intricate objects, 2-D surfaces, and 3-D surfaces.	
Adjustable to preferred accuracy and capture speed.	

Arayici and Hamilton (2006) stated that 3-D scanners, with their high precision, can capture the finest details of an object. Their ability to streamline procedures significantly reduces the time needed to extract data from intricate shapes and geometries, thereby lightening the workload and improving productivity. The importance of ensuring that objects meet strict criteria is paramount in quality control. When manufactured items undergo quick measurement and tolerance checks by 3-D scanners, any variations from the original design can be promptly identified. The adaptability of 3-D scanners makes them an essential tool for conducting regular quality checks on injection-moulded plastic goods.

Osten (2018) supported these advantages of using 3-D scanners by stating that handheld 3-D scanners are frequently excellent in speed, accuracy, and size and are also the most popular choice in many industries. Govindan (2015) stated that the optical scanner market is expected to continue expanding due to the growth of scanners and their developing technology each year.

2.9 Optical Metrology in Quality

According to Zeiss (2017), part inspection of products or objects in manufacturing industries is one of the most common uses of a 3-D scanner. The manufacturing sector utilises optical metrological technology in manufacturing industries to confirm that finished products can function as intended. This method is essential for preventing costly and laborious production

errors and guaranteeing product quality and customer satisfaction. Hanaphy (2023) supported this by stating that although most manufacturing operations depend on product consistency, there are some industries where there is particularly little tolerance for inaccuracies, and finished products must frequently fulfill strict requirements for heat resistance, weight, and chemical resistance in highly regulated sectors like aerospace. These inaccuracies can lead to product failures. These failures can be avoided by 3-D scanning to ensure products are manufactured according to standards.

Hanaphy (2023) described a study where a group at Luxembourg Air Rescue has already used a 3-D scanner to model helicopters in a real-world aviation application. This allowed the engineers to check the outside of the aircraft for damage from accidents during strong landings or flying in severe weather, among other things. By promptly identifying and addressing flaws, the team could reduce helicopter downtime due to the data collected.

A study conducted by Arayici and Hamilton (2006) to model 3-D scan-built environments showed that 3-D scanners successfully collected data on buildings, sites, and physical objects for reconstruction and restoration.

Hughes, Rahman, Lin, Marpoulos, Mohamad, Salleh, and Rahman (2023) conducted a study based on implementing a 3-D scanning system for quality inspection in manufacturing. Their study used a 3-D scanner as a quality inspection instrument on three objects with different geometries, surfaces, and shapes. Hughes *et al.*, (2023) presented that their results had an average accuracy of 98.69 percent of the objects measured with the 3-D scanner. They stated that the 3-D scanner had reduced human error during routine quality inspection, and the results were accurate and reliable.

Lee and Park (2023) studied using 3-D scanning technology on shipbuilding and composite small crafts. They stated that deviations in the ship's body frame, the ship's finished mould, and the shaped hull of the small craft could cause deformation of the final product. This could lead to poor quality of the composite small crafts. In the study, 3-D scanning technology was used on the ship body frame, finished mould of the ship, and shaped hull of the small craft during quality inspection to identify deviations. The study's results demonstrated that the shape of the design data and the final product differed. According to Lee and Park (2023), this study's findings depicted that manufacturing errors must be considered when calculating a ship's performance using design data. These manufacturing errors were detected with the use of the

3-D scanner. They elaborated that shipbuilders could utilise these findings to enhance the quality of their products, precisely calculate the quantity of composite materials needed, or perform reverse engineering to enhance their current models.

2.10 Research Gap

It was noted from the literature review that optical metrology in form of 3-D scanners are extensively used in the aeronautical and automotive industries. Studies show that due to advancements in the optical metrology field, metrological testing equipment such as the 3-D scanner is the preferred measuring equipment in the aeronautical and automotive industries. This study uses optical metrology as 3-D scanners to measure injection moulded plastic products.

2.11 Summary of the Chapter

The chapter showed that there are both advantages and disadvantages to the use of tactile metrological instruments. It was noted that with the increase in demand for high-quality injection moulded products, more efficient routine quality testing was required. This section showed that previous studies using 3-D scanners as quality measurement instruments yielded positive results in various industries, such as the automotive and aeronautical sectors.

The next chapter covers the research design and methodology used in this study.

CHAPTER 3: RESEARCH METHODOLOGY

With the assistance of a flow diagram, this chapter describes how this research was designed. The research methods and techniques that are available for use in the research are also discussed, along with those methods and techniques that were chosen for the research. The methods used to verify the experiment conducted and the results will be discussed. The study (consisting of using a 3-D scanner, a CMM, and a vernier as measuring instruments) will be introduced, and the preliminary work and findings will be reviewed. A brief overview of each section in this chapter is outlined in Figure 13.

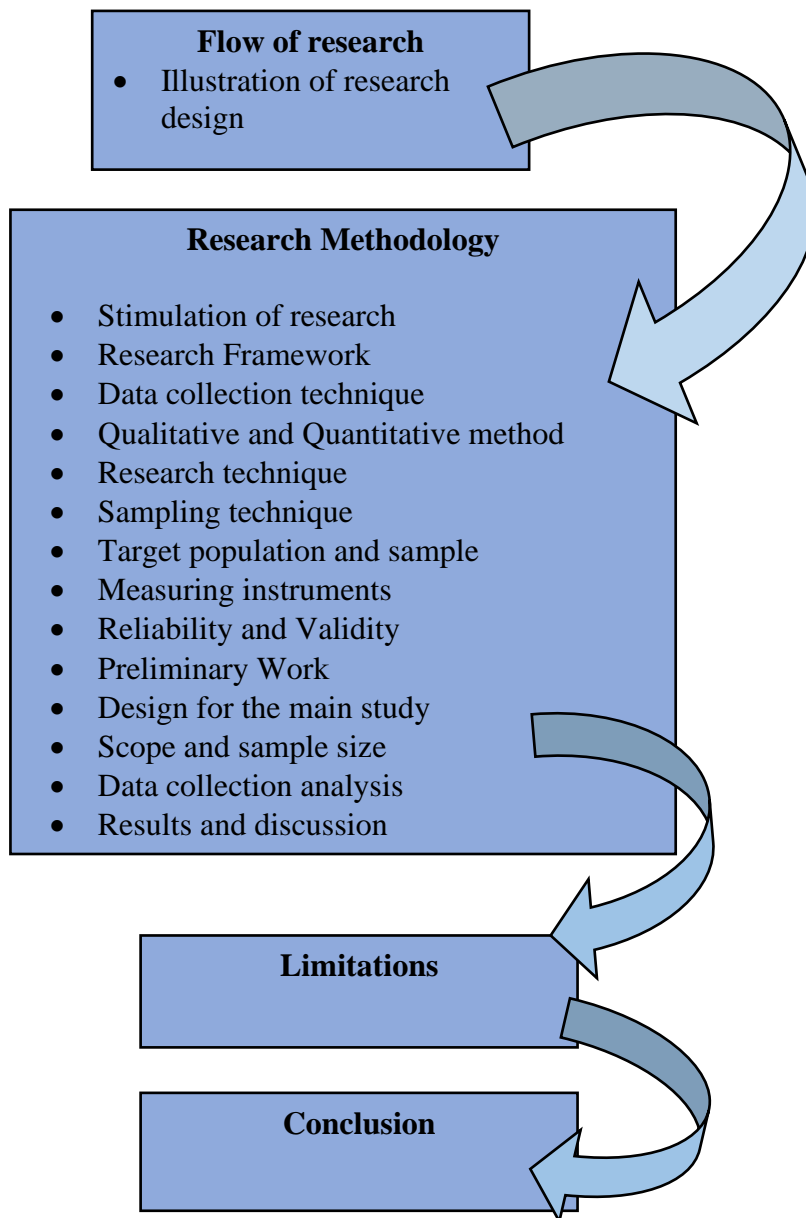


Figure 13: Illustration of Chapter 3

3.1 Flow of Research

The research design of the study is illustrated in Figure 14.

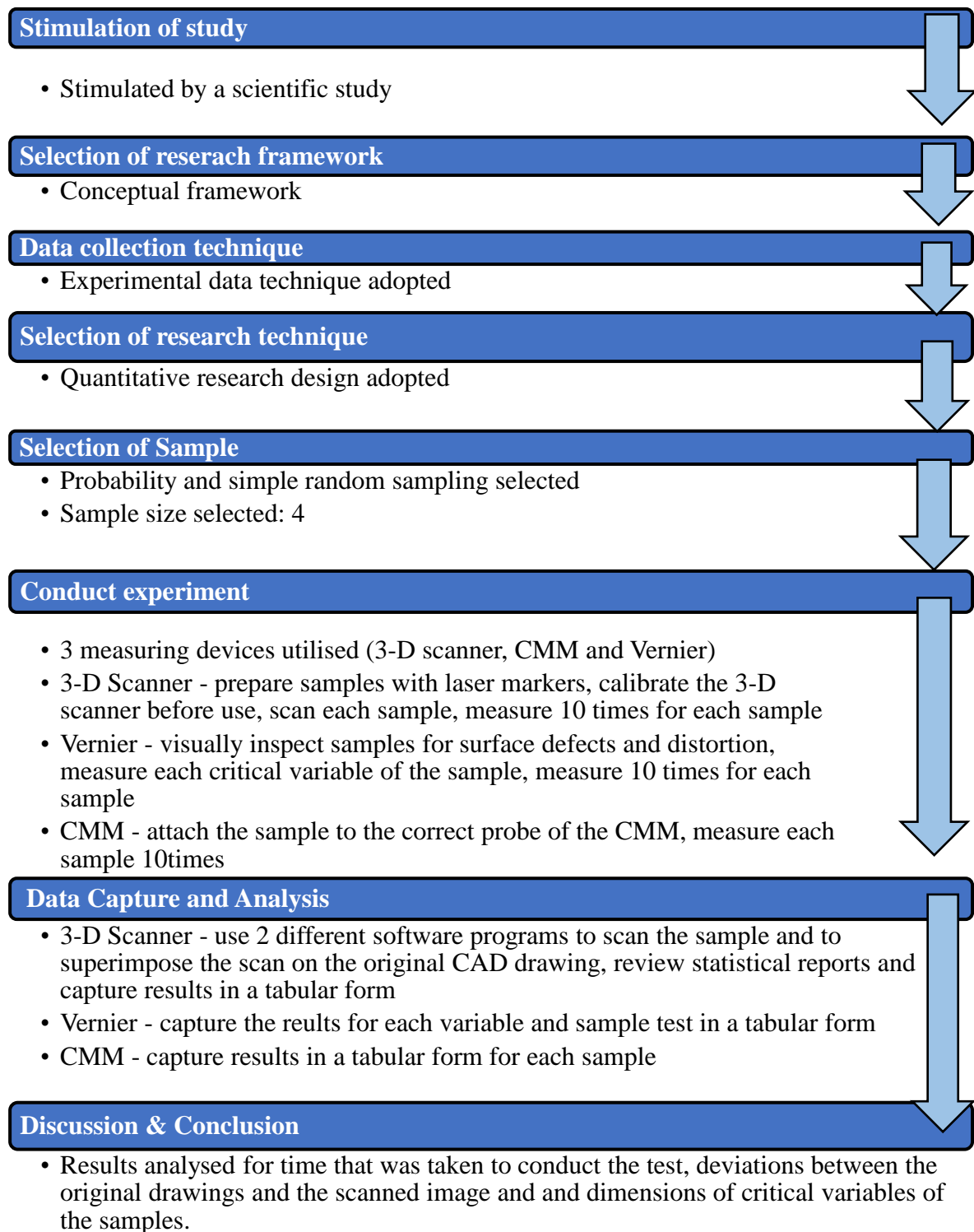


Figure 14: Illustration of the research design of the study

3.2 Research Methodology

According to Ellerton (2021), most professional careers engage in some form of research. Research is a way of perceiving, analysing, comprehending, and creating parameters that guide a specific process or test novel concepts. It is a methodical approach to investigating and analysing observations to explain or solve ideas. Ellerton (2021) elaborates that several methods stimulate or promote research. These methods include inductive reasoning, deductive logic, critical thinking, scientific method, and collaborative effort. Ellerton (2021) expounds that inductive reasoning, or inductive logic, is generating a general conclusion from a set of data. Inductive reasoning consists of observations, seeking patterns, and developing a theory or general conclusion. Part-to-whole arguments, extrapolation, and forecasts all benefit from inductive reasoning.

Gabbay, Thagard, Woods, Bandyopadhyay, and Forster (2011) explained that deductive reasoning involves the utilisation of formal logic and observations to validate theories and hypotheses. It commences with an assumption, which is then either confirmed or disproven through observations or logical reasoning. Deductive reasoning usually yields logically clear conclusions. Critical thinking, as defined by Ellerton (2021), involves the ability to assess information and make sound decisions. It requires individuals to be aware of their biases and assumptions when processing information and to apply consistent criteria when evaluating sources. Forming arguments and evaluating information sources both require critical thinking. It highlights a rational, unbiased, and self-aware approach that can help form conclusions and aid researchers in choosing trustworthy sources. The scientific method is the process of conducting tests and experiments to establish facts based on objective evidence. It involves the following steps: observation, forming a hypothesis, making predictions, conducting experiments, and analysing the results. These principles are applicable to a wide range of fields including technology, business, and scientific research. Firchow and Gellman (2021) described coordination between researchers, institutions, organisations, and/or communities as a collaborative research component. This collaboration can give a project a unique set of skills. This research was stimulated by the scientific method, specifically current measurement devices used for routine quality testing and new and emerging technology for routine quality testing that could be advantageous in injection moulding industries.

3.2.1 Research Frameworks

In Crawford's (2020) view, there are two main types of research frameworks: theoretical and conceptual. He explained that while the conceptual framework provides a systematic approach to examining a research problem or topic, the theoretical framework can be utilised to form new hypotheses or test existing ones. The conceptual framework helps in identifying key variables and interpreting the relationships between them, while theoretical frameworks draw from existing theories and research to guide study design, data collection, and analysis, ensuring that the research is thorough, suitable, and well organised. This research adopts a conceptual framework.

3.2.2 Data Collection Techniques

Kumar (2011) described data collection as a method of collecting and analysing precise data from various resources to evaluate potential outcomes, trends, and probabilities. There are various data collection techniques: observation, ex post facto, experimental data, correlation data, case study, content analysis, ethnography, developmental research, grounded theory, historical research design, and action research. The data collection technique chosen for a particular study depends on the type of data a researcher wants to collect, and the type of research conducted. According to George (2022), observation is the process of gathering data without making inquiries.

This technique is subjective because the researcher or the observer must add their judgment to the data. Marilyn (2020) defines an ex-post-facto design as a method of establishing a cause-and-effect relationship between a dependent and independent variable. In ex-post-facto investigations, researchers analyse how a specific attribute, historical event, or characteristic influences the dependent variable while holding the independent variable constant. Experimental data is collected when the researcher takes deliberate action to bring about and measure change or make an impact by modifying a variable. It is possible to project to a larger population and establish a causal relationship between variables using experimental data. According to Mousami and Bairagi (2019), correlation research, including predictive research, is used to investigate the association between the studied variables. Shanks and Bekmamedova (2018) posited that the case study data collection technique uses various methods and sources to gather information for its data.

Techniques for gathering data include participant and direct observations, questionnaires, and related documents. Luo (2019) explains that content analysis is a method used to identify the presence of words, themes, or concepts in a specific set of qualitative data. Through content analysis, researchers can assess and explore the occurrence, significance, and connections of specific words, topics, or concepts. Ethnography is a type of qualitative research that involves living and working closely with members of a particular community or organisation to observe their relationships and behaviour. The written report produced by the ethnographer is also known as "ethnography" (Caufield, 2020). Bhandari (2021) states that in a correlational study design, associations between multiple variables are examined without the researcher altering or modifying any of the variables.

It is an aspect of quantitative research that is not experimental. The structured examination of creating, refining, and assessing instructional programs, procedures, and items that are required to fulfill the standards of coherence and efficiency is known as developmental research. Tie, Birks, and Francis (2019) state that grounded theory is a commonly utilised methodology in numerous research endeavours. Grounded theory studies can employ both qualitative and quantitative data collection methods. The objective of grounded theory is to formulate or construct theories based on systematically gathered and analysed data through comparative evaluation.

Clary (2022) stated that the intended purpose of historical research design is to establish facts that support or contradict a hypothesis by gathering, examining, and synthesising information from the past. George (2023) described action research as the type of research that is used to solve issues in social systems like schools and other groups. He emphasised the importance of generating knowledge and taking action within the specific social context to address the presented problem. The goal of action research is to both examine and resolve a problem at the same time. Action research combines the study with the action taken simultaneously. This study will follow an experimental data collection technique, using three types of measuring devices as the variables are changed.

3.2.3 Qualitative and Quantitative Research Techniques

Mishra and Alok (2011) stated that research can be done using two distinct techniques: qualitative and quantitative. In Streefkerk's (2019) view, words play a crucial role in conveying qualitative research, allowing for the analysis of ideas, emotions, and experiences. This form

of research provides valuable insights into unfamiliar topics. Common qualitative techniques include open-ended interviews, verbal descriptions of observations, and literature reviews exploring theories and concepts. On the other hand, as per Mousami and Bairagi (2019), quantitative research involves the collection and interpretation of numerical data. This type of research is often used to identify patterns, formulate hypotheses, investigate causation, and generalise findings to larger populations. It relies on structured data collection and the application of statistical, mathematical, or computational methods. Notably, quantitative research results are typically represented in numerical form, highlighting one of its defining characteristics. Foretelling the future of a product or service and adjusting after carefully examining these numbers is practicable.

This study utilised a quantitative and experimental research design methodology. In an experimental research design, there are two groups, namely a control group that will not experience any changes and an experimental group that will be subjected to changes. The experimental group is the different measuring devices during routine quality testing of the samples. The control group are the samples that are tested. The experimental framework of this study was based on the use of 3-D optical metrological equipment and contact measuring equipment (vernier and CMM) as measurement devices on injection moulded plastic products.

3.2.4 Sampling Techniques

Gupta and Gupta (2011) identified two main sampling methods: non-probability and probability.

Non-probability sampling involves choosing a sample of the population in a non-random manner. This considers non-random factors such as availability, proximity, and convenience. Nikolopoulou (2022) stated that there are five different types of non-probability sampling: convenience sampling, consecutive sampling, quota sampling, judgemental or purposive sampling, and snowball sampling. Convenience sampling is a method in which samples are chosen from the population solely based on what is available and the researcher's convenience. Consecutive sampling involves a researcher selecting one subject or group of subjects, conducting research over time, evaluating the data, and then, if needed, moving on to the next subject or group. Quota sampling entails dividing the population into groups or strata. Using the purposive or judgmental sampling method, researchers choose samples entirely based on their expertise and reliability. When the sample size is small and not readily available,

researchers employ the snowball sampling technique, where study participants are requested to identify potential participants for the study (Nikolopoulou, 2022). Gupta and Gupta (2011) described probability sampling as a technique where every person in the population is randomly chosen to participate in the study and has an equal chance of being chosen.

According to Nikolopoulou (2022), there are four types of probability sampling, namely stratified sampling, simple random sampling, systematic sampling, and cluster sampling. Stratified sampling involves taking a random sample from specific population subgroups or strata. Each subgroup, distinguished by a shared attribute such as gender, colour, or religion, is represented to ensure fair representation of the entire community. On the other hand, simple random sampling involves randomly selecting samples from the entire population with an equal chance for each sample to be chosen. Simple random sampling is the most widely used method for determining a random sample. Systematic sampling selects samples from an arbitrary point at regular intervals to provide a random sample from the target population. This approach works efficiently when there are already records of the target group. Cluster sampling is the technique of separating the target population into groups, also referred to as clusters. The sample is then a subset of these groups chosen at random. Cluster sampling is an efficient method when studying large, widely distributed populations. Usually, it involves current groups that share certain similarities.

Mishra and Alok (2011) described several differences between non-probability sampling and probability sampling. These differences are depicted in Table 7.

Table 7: The main differences between non-probability and probability sampling (Gupta, M and Gupta, D, 2011).

Differences between non-probability and probability sampling	
Non-probability	Probability
Samples are chosen based on the researchers' subjective evaluation.	Samples are selected randomly.
Not each member has an equal chance to be chosen.	Every member of the population has an equal probability of being chosen.
Sampling bias is not a major consideration for the researcher.	Adopted to decrease sampling bias.
It is useful in an environment where the sampling group members have similar characteristics.	Efficient for gathering information from a diverse population.
It does not aid in correctly portraying the population.	An effective method to get a true portrayal of the population.
Finding the right audience is uncomplicated.	Finding the right audience is challenging.

According to Mousami and Bairagi (2019), adopting a probability sampling technique has several benefits. These benefits include a lack of systematic mistakes and bias in sampling, a higher degree of dependability of research findings, a rise in the reliability of sampling error conclusions, the capacity to conclude the general population, economical cost, and simple and uncomplicated application.

This study adopted a probability and simple random sampling technique.

3.2.5 Target Population, Sampling Techniques and Samples

A population is the whole group a researcher wants to study and draw conclusions about. A sample is a specific group or set of participants from which a researcher gathers data. The sample size is typically smaller than the population's total size. The samples used in this study consisted of injection moulded products manufactured by a plastic manufacturer in South Africa. The population size of the injection moulded products for this study is four hundred and ninety-six. A data list of all injection moulded products was created. The products used in this study were then randomly selected from the list by picking a number. The sample size chosen for this study is four. A sample size of four was chosen as there are several different variables to test on each sample. Two samples were selected for each product.

A 38mm C3 closure was selected as sample A, which is depicted in Figure 15.



Figure 15: Sample A 1 and A 2: 38mm C3 Closure

A 250ml tub was selected as sample B, which is depicted in Figure 16.



Figure 16: Sample B1 and B2: 250ml Tub

A 125ml tub was selected as sample C, as shown in Figure 17.



Figure 17: Sample C1 and C2: 125ml Tub

A 1 kg tub was selected as sample D, as depicted in Figure 18.

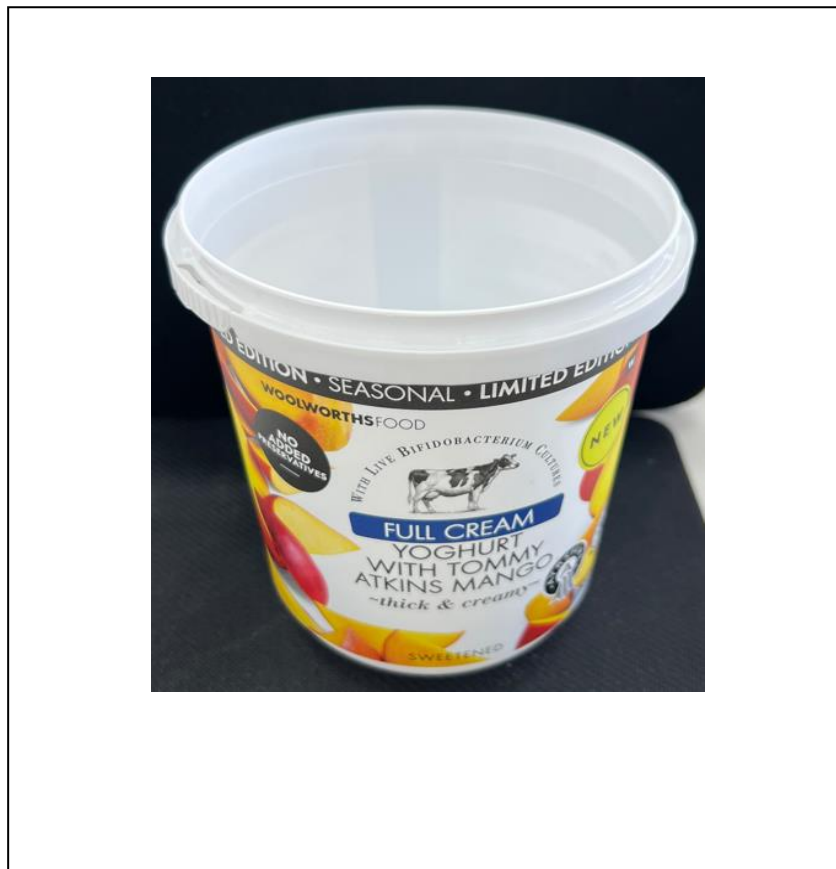


Figure 18: Sample D1 and D2: 1kg Tub

3.2.6 Measuring Instruments

Data sets were taken from measurements of the samples selected using three different measuring instruments: a vernier (contact measuring instrument), a CMM (contact measuring instrument), and a blue light 3-D scanner (non-contact measuring instrument). Two of these instruments were contact measuring instruments, and one was a non-contact measuring instrument.

The 3-D scanner utilised both infrared and blue laser technology. The technology utilised a parallel infrared laser for scanning large surface areas. The parallel blue laser crosses were used for fast or quick scanning, and the single blue laser was used for scanning objects with depth or deep holes. As per the manufacturing specifications of the 3-D scanner, the scanner is touted as

having a scanning accuracy of 0.02mm and 0.03mm/m of volume accuracy (WD Hearn Metrology, 2021). As shown in Figure 19, before the commencement of the scanning with the 3-D scanner, the samples are prepared by placing laser markers on the individual samples.

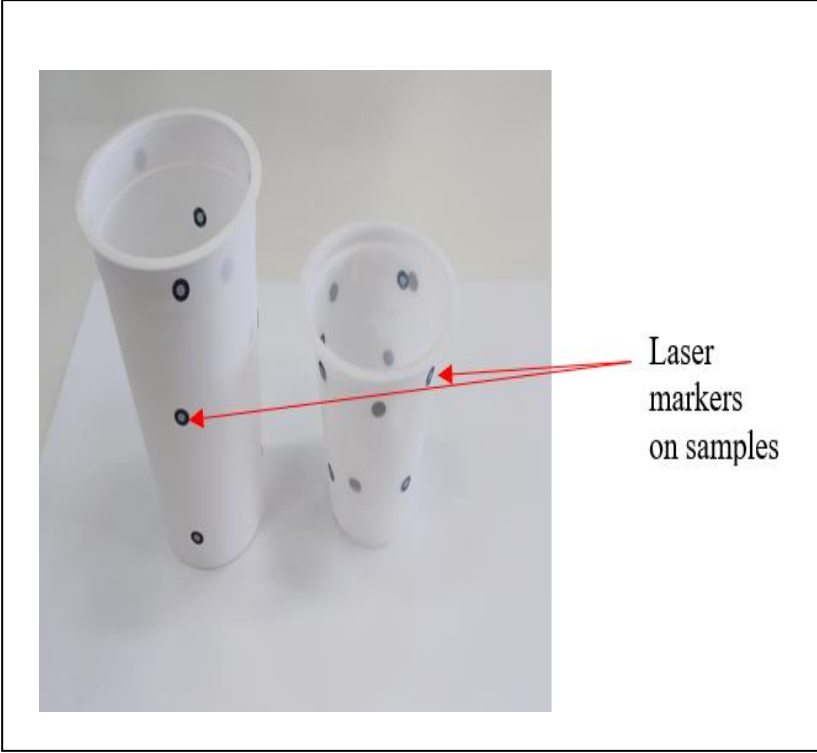


Figure 19: Samples prepared with laser markers

According to the supplier’s manual of the 3-D scanner (WD Hearn Metrology, 2021), laser markers are required for the handheld 3-D scanner as they provide dedicated laser points or reference points on the samples scanned, which facilitate accurate measurements of the samples. The laser markers are dots that contain a special coating that renders them retro-reflective. Once the samples are prepared with the laser markers, the 3-D scanner requires calibration. Calibration is required each time the scanner is switched on.

As per the supplier’s manual (WD Hearn Metrology, 2021), the 3-D scanner is calibrated using a calibration board and the appropriate scanning software. As shown in Figure 20, the calibration process comprises aligning the 3-D scanner with the circle and trapeze shape on the scanning software.

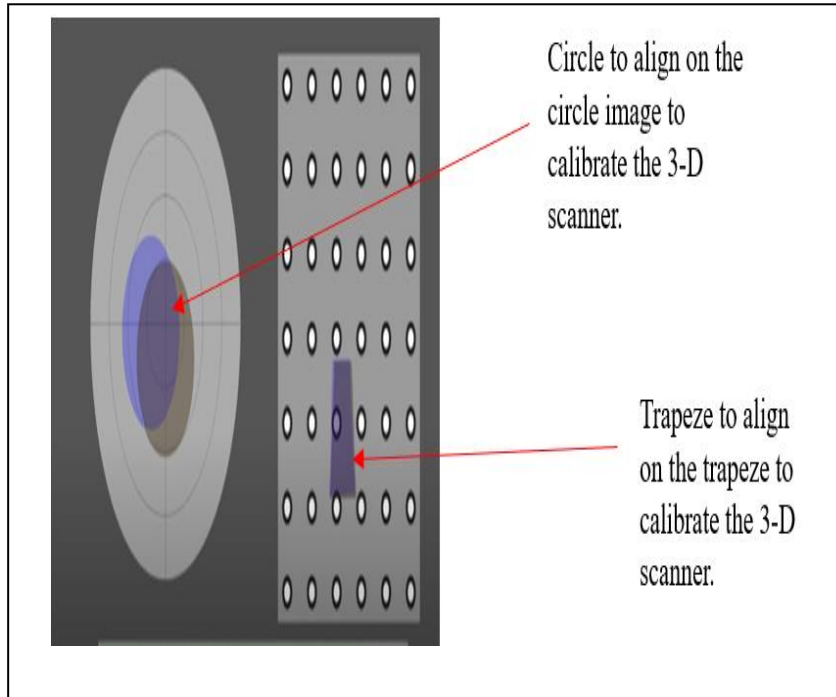
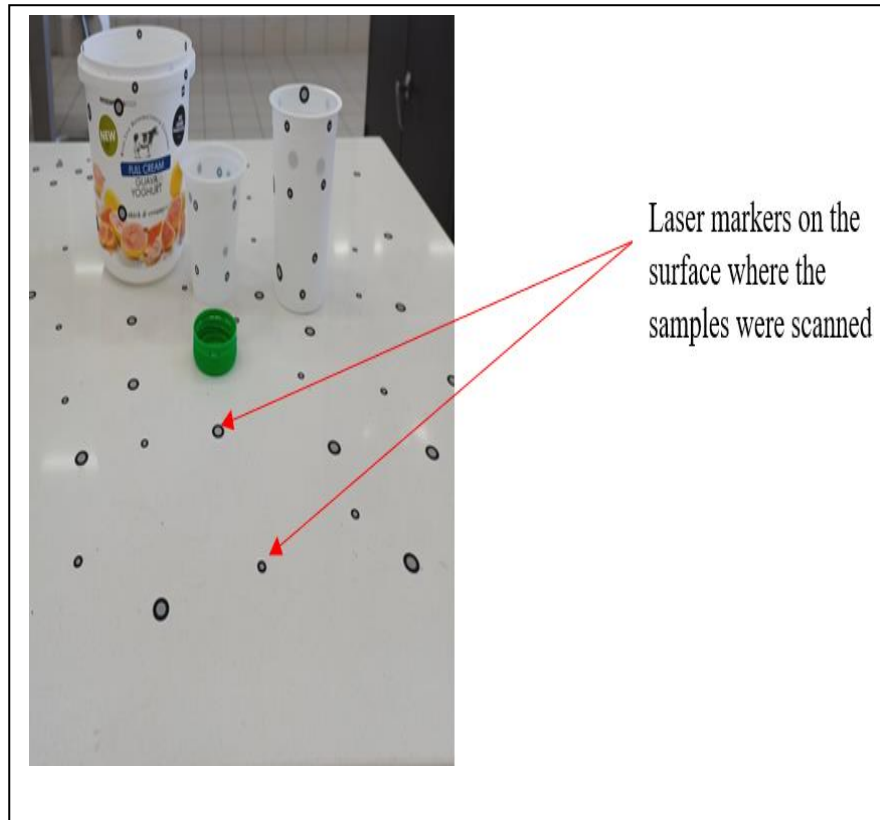


Figure 20: Calibration of the 3-D Scanner

The calibration accuracy of the 3-D scanner is calculated once the 3-D scanner's circle and trapeze shape is aligned with the circle and trapeze image. Once the 3-D scanner is calibrated, the surface where the sample is scanned is also set up with laser markers (Figure 21). As per the supplier of the 3-D scanner (WD Hearn Metrology, 2021), the surface is also set up with laser markers, which are then scanned to set up the outer parameters within which the samples are scanned. The parameter settings contain different advanced settings options. The parameter settings selected depend on the sample type scanned (WD Hearn Metrology, 2021).



Laser markers on the surface where the samples were scanned

Figure 21: Surface that was set up with laser markers

Once the applicable parameters are set up, the samples are scanned using the 3-D scanner in conjunction with the 3-D scanner software. The scanned image from 3-D scanner software is then imported into a second software program. The product's original Computer-Aided Design (CAD) drawing is also imported into the second software program. The 3-D scanned image is then aligned to the original CAD drawing on the second software program. Several surface points are plotted onto the aligned drawings, where points on the scanned image and the CAD drawing are calculated to determine if there are any deviations along those points between the scanned image of the product and the CAD drawing. All measurements that are conducted are repeated ten times to ensure the accuracy of the results obtained.

The second metrological equipment utilised in this study is a vernier. As per the sample manufacturer's internal procedure (Mitchell, 2022), before commencing with the measurement, the sample products are visually inspected to ensure that there were no damages to the sample products (that is, no high or low spots on the sample products), all measuring surfaces were

100% flat, and the measuring surfaces of the sample products were sturdy. All measurements conducted are repeated to verify accuracy.

The third metrological equipment utilised in this study is a coordinate-measuring machine CMM. Park, Kwon, and Cho (2006) stated that the CMM takes readings in six degrees of freedom and presents these readings in a mathematical form. The CMM measures the physical geometrical characteristics of the samples. This machine is computer-controlled, and it uses software. A probe attached to the third-moving axis of the CMM is utilised for the measurements. According to the internal procedure of the sample manufacturer (Mitchell, 2022), the samples are placed on the measurement table into a fixture that secures the sample to ensure it does not move during the measurement cycle. The type of fixture used during the tests depends on the measured sample type. A generic fixture was used for samples B, C, and D, and a vacuum fixture was used for sample A. The products were then measured using the touch probe.

All measuring instruments used in the study were calibrated before use. This ensures their accuracy and that they measure what they were designed to measure.

3.2.7 Reliability and Validity

According to Middleton (2019), validity and reliability are used to assess research integrity. Validity pertains to the accuracy of a measurement, while reliability refers to its consistency. These factors are crucial in ensuring the accuracy and consistency of test results. Middleton (2019) stated that there are different types of reliability methods. These include test-retest reliability, interrater reliability, and internal consistency. The test-retest method examines consistency across time. It determines whether repeating the measurement yields the same outcomes; for example, a test is administered to fifty individuals on January 1st, and then, a month later, an identical kind of test with an equivalent degree of difficulty is administered to the same group of fifty participants (Bobbitt, 2021). Interrater reliability assesses the consistency of a sample when assessed by different raters or observers. It ensures that consistent results are achieved when the same measurement is conducted by different individuals. Internal consistency, on the other hand, evaluates the consistency of measurements. It aims to ascertain if the researcher obtains consistent results from different test sections that are intended to measure the same thing. Cornell (2024) stated that internal consistency can be measured by two

methods, namely, Cronbach's alpha and split-half reliability testing. The Cronbach alpha is a formula used to calculate the extent to how closely related items are in a study. For example, calculating the Cronbach alpha score for a 10-item scale that measures empathy as a one-dimensional category. Cornell (2024) described split-half reliability testing as randomly testing internal consistency by connecting to split halves. For example, a charismatic leadership questionnaire with ten questions regarding motivating and inspiring others can be created. Then, the overall results of the odd- and even-numbered items can be compared.

Middleton (2019) asserted that there are various types of validity, namely, construct validity, content validity and criterion validity, face validity, predictive validity, concurrent validity, external validity, internal validity, and statistical validity. Conformance of a measure to current theory and understanding of the concept being measured is known as construct validity. Content validity is the degree to which the assessment captures every facet of the idea being assessed. Criterion validity is the degree to which the result of a measure corresponds to other valid measures of the same subject. Bhandari (2023) described face validity as a measure that assesses whether a test effectively evaluates what it is supposed to. This type of validity evaluates whether a measure seems relevant and suitable for its intended assessment. Middleton (2019) stated that predictive validity is whether test results have any connection to performance on a certain criterion is known as predictive validity. Nikolopoulou (2023) stated that concurrent validity is when a new test is compared to an existing or established standard as part of the concurrent validity assessment process. The term "external validity" describes how well study findings translate to real-world situations. Internal validity is the term that describes whether an experiment's findings are the result of influencing the independent variables or treatment variables. Statistical conclusion validity is whether the findings reached by the researcher can be substantiated by the statistical methods (Middleton, 2019).

Repeatability and reproducibility methods were used to determine the reliability of the data obtained from the tests conducted in the study. Repeatability was conducted with the same experiment, same person, and same setup of the experiments on the same day to determine if it yielded similar results.

This study used the test-retest reliability method to ensure results accuracy. Each sample was measured ten times for all three measuring devices. The statistical conclusion validity method was used to determine the validity of the data obtained.

3.2.8 Design for Main Study

The study is a scientific study based on a conceptual framework. It used an experimental data technique. The experiment used three measuring devices: two contact measuring devices (the vernier calliper and CMM) and one non-contact device (the 3-D scanner). Each sample was measured ten times for each measuring device. The results were then captured and analysed.

3.2.9 Scope and Sample Size

The injection moulded products of a South African plastic manufacturer were selected for this study. The sample size consisted of four different types of injection moulded products.

3.2.10 Data Collection and Analysis

The data from all three measuring instruments were collected and analysed, and a comparative study was conducted to determine if there were any benefits to using optical metrology as a measurement device during routine quality checks on injection moulded plastic products. The data collected for the 3-D scanner utilised 2 different software programs to facilitate reading the scanned images. The first software program scanned and saved the sample image, and the second software program superimposed the sample scanned image on the original CAD drawing of the sample tested. The second software allowed overlay discrepancies between the scanned image and the original CAD drawing to be measured.

3.2.11 Results and Discussion

The data from each test was collated and analysed using a cross-tabular data analysis method. The results were analysed for the time it took to conduct the test for each measuring instrument, the superimposed images between the scanned image and the original CAD drawing, and the dimensions of the samples' critical variables.

3.3 Limitations

There were some limitations to the study. These limitations included a lack of previous research on using optical metrological measuring equipment as a measuring tool in injection moulding in the plastic manufacturing industry. A second limitation is that the sample size may be too small or insufficient to conclude a valid result. However, it was not practical to increase the sample size due to time constraints and the availability of the measuring devices

3.4 Summary of the Chapter

The chapter presented the research as a quantitative study. An experimental data technique was used in this study. Three types of measuring instruments were used as the variables in this study. A simple random sampling technique was used to select the samples used in the study. The repeatability and reproducibility methods were used to determine the reliability and consistency of the study's results, where each test was repeated ten times on each instrument and each sample. Calibration was done on each measuring instrument. Results from the vernier and the CMM were captured in a tabulated form. The 3-D scanner used two types of software programs. The first software captured the image of the samples that were scanned, and the second software superimposed the scanned image onto the original CAD drawing.

The next chapter covers the results obtained and the analysis and interpretation of the results obtained.

CHAPTER FOUR: RESULTS AND DISCUSSION

Chapter Four summarises the data and results obtained from the three measuring devices (vernier, CMM, and 3-D scanner) used in the study. Each device was used to measure the critical quality control parameters of the following injection moulded products, in duplicate: Sample A=38mm closure, Sample B = 250ml tub, Sample C= 125 ml tub and Sample D= 1kg tub. The results were evaluated to determine the time taken for measuring samples for each measuring device and the efficacy of the results obtained.

4.1 Evaluation of 3-D Scanned Images and Statistical Reports

The scanning process was conducted thoroughly, with ten images taken for each sample scanned by the 3-D scanner. Samples A1 and A2 were scanned twenty times each, including ten scans for the inside and outside of the sample. This meticulous approach was necessary as the critical quality variables for samples A1 and A2 were located inside and outside the samples (the closures). A total of one hundred scanned images were captured, ensuring a comprehensive and accurate representation of the samples.

According to Hanaphy (2023), 3-D scanned images comprise of surface points, which result in point clouds. These surface points are a collection of over a million points from the surface of the samples scanned. He further elaborated that a point cloud is a structure produced when the object's shape is captured using a 3-D scanner. Each 3-D image of the samples scanned during the experiment contained a point cloud, as the point cloud makes up the image of the scanned sample, which is required to obtain measurement results for the samples during quality testing. Each point cloud comprised a collection of spatial data points, each representing an individual location on the surface of the scanned sample. The surface points scanned consisted of circle points, which represented the coordinates width (X), height (Y), and depth (Z). Various point clouds from the scanned image and the original CAD drawing of the sample were aligned and combined into a single point cloud. Utilising the software program Polyworks® Metrology Suite 2021, the point clouds were segmented into useful groups or regions according to shape, colour, or features (edges, corners, planes, and forms), which represented a comparison of the scanned 3-D image to the original CAD drawing.

As shown in Figures 22-26, the comparison of the 3-D scanned image and the original CAD drawing was depicted as false-colour images and subsequently analysed. Patra, Shekher, Manish, Solanki, Shivendra, Ramachandran, Rajaraman and Krishnan (2006) described false-colour images as a collection of techniques for capturing colour images that were captured in either the visible or non-visible regions of the electromagnetic spectrum. Patra *et al.*, (2006) further elaborated that a false-colour image is an image that shows an object in colours other than that of a true-colour image, often also referred to as pseudo-colour. False-colour images are used to enhance contrast, distinguish details of the scan, and assist with measurements of the sample scanned. In this study, the 3-D scanner adopted different colours in their images; the green showed the points of the scanned 3-D image that were in specification to the CAD drawing, and the yellow showed the points of the samples that were on the warning side of the specifications of the CAD drawing and the red showed the points of the samples that were out of specification as compared to the CAD drawing of the samples measured. Grey colours were also present in the superimposed images of the samples measured. The grey areas were points of the samples that the 3-D scanner had failed to measure. Sample A (Figures 22-23), sample B (Figure 24), sample C (Figure 25), and sample D (Figure 26) contained grey areas on the images scanned.

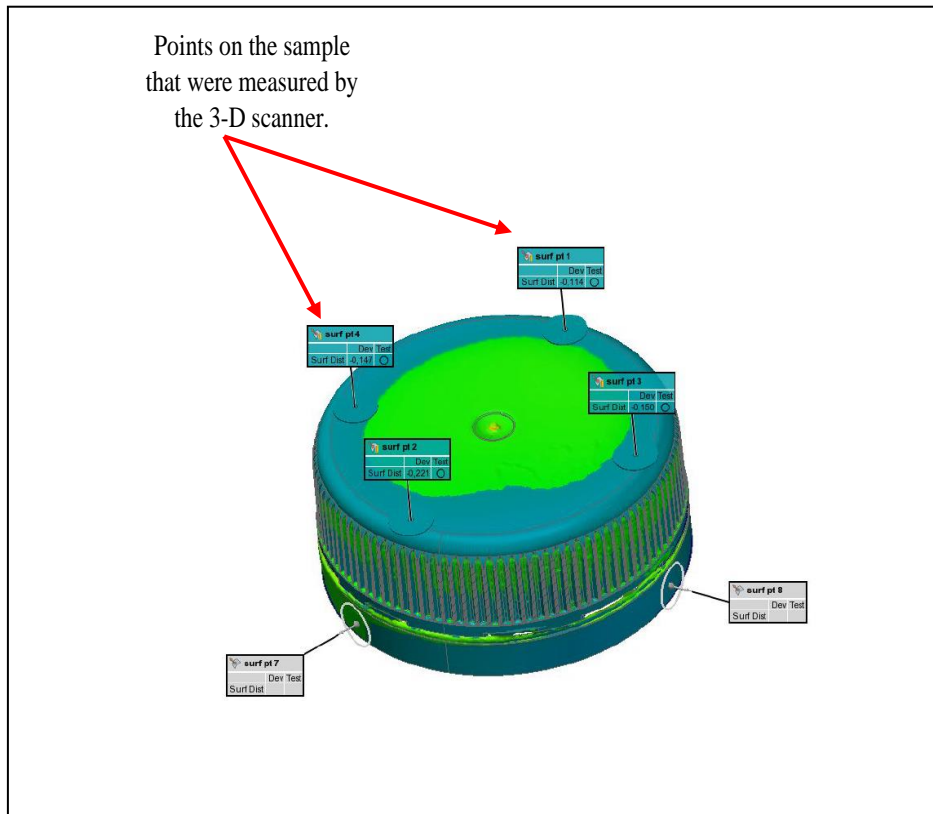


Figure 22: A 3-D scanned image of the outside of Sample A (38mm closure)

According to Figure 22, points 7 and 8 are in the colour grey. This grey indicates that points 7 and 8 were not scanned by the 3-D scanner, resulting in an incomplete scan and results. The failure of the 3-D scanner to detect all points on the scanned sample resulted in an incomplete scan and, therefore, inconclusive results.

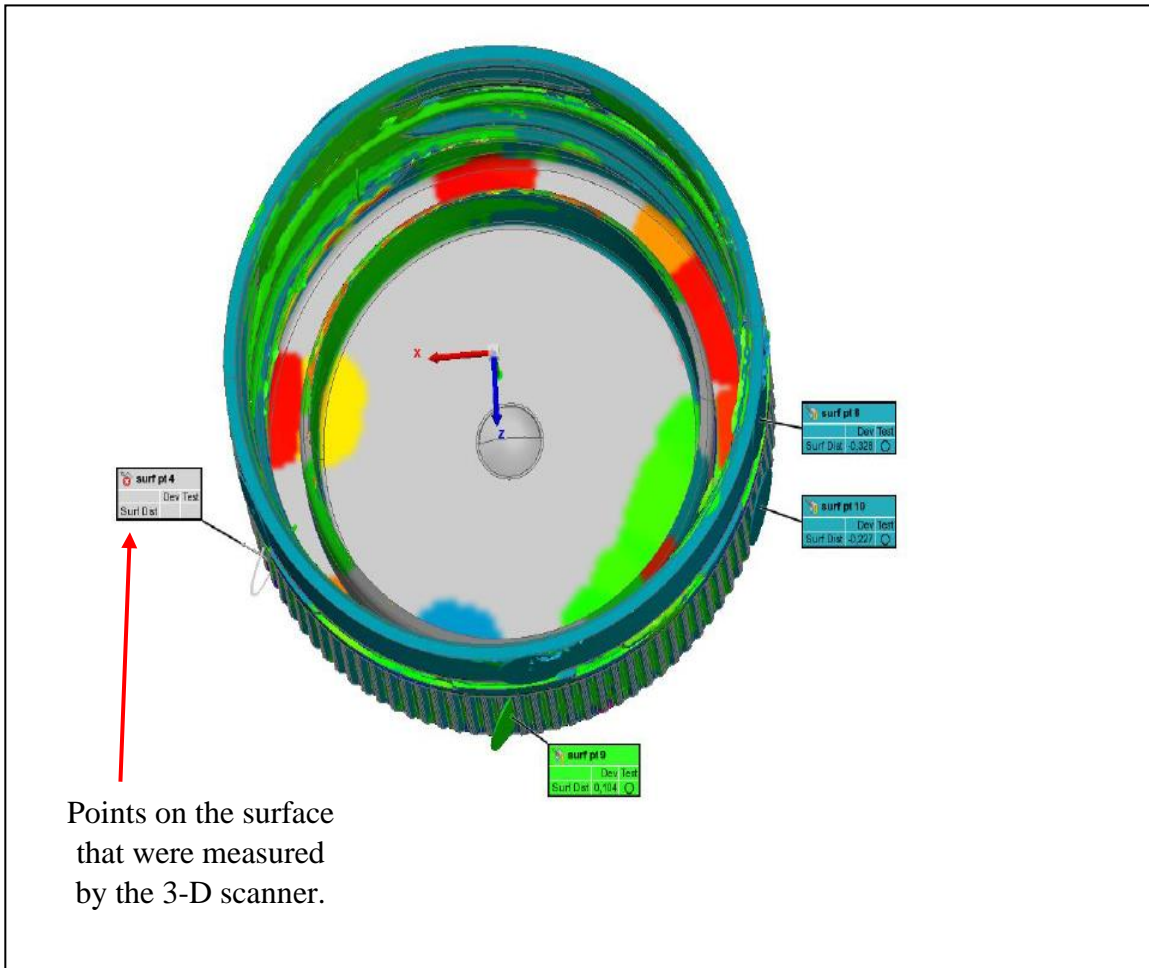


Figure 23: A 3-D scanned image of the inside of Sample A (38mm closure)

In Figure 23, point 4 is grey. This grey indicates that the 3-D scanner did not scan point 4, resulting in an incomplete scan and inconclusive results. The failure of the 3-D scanner to detect all points on the sample that was scanned resulted in an incomplete scan and, therefore, inconclusive results.

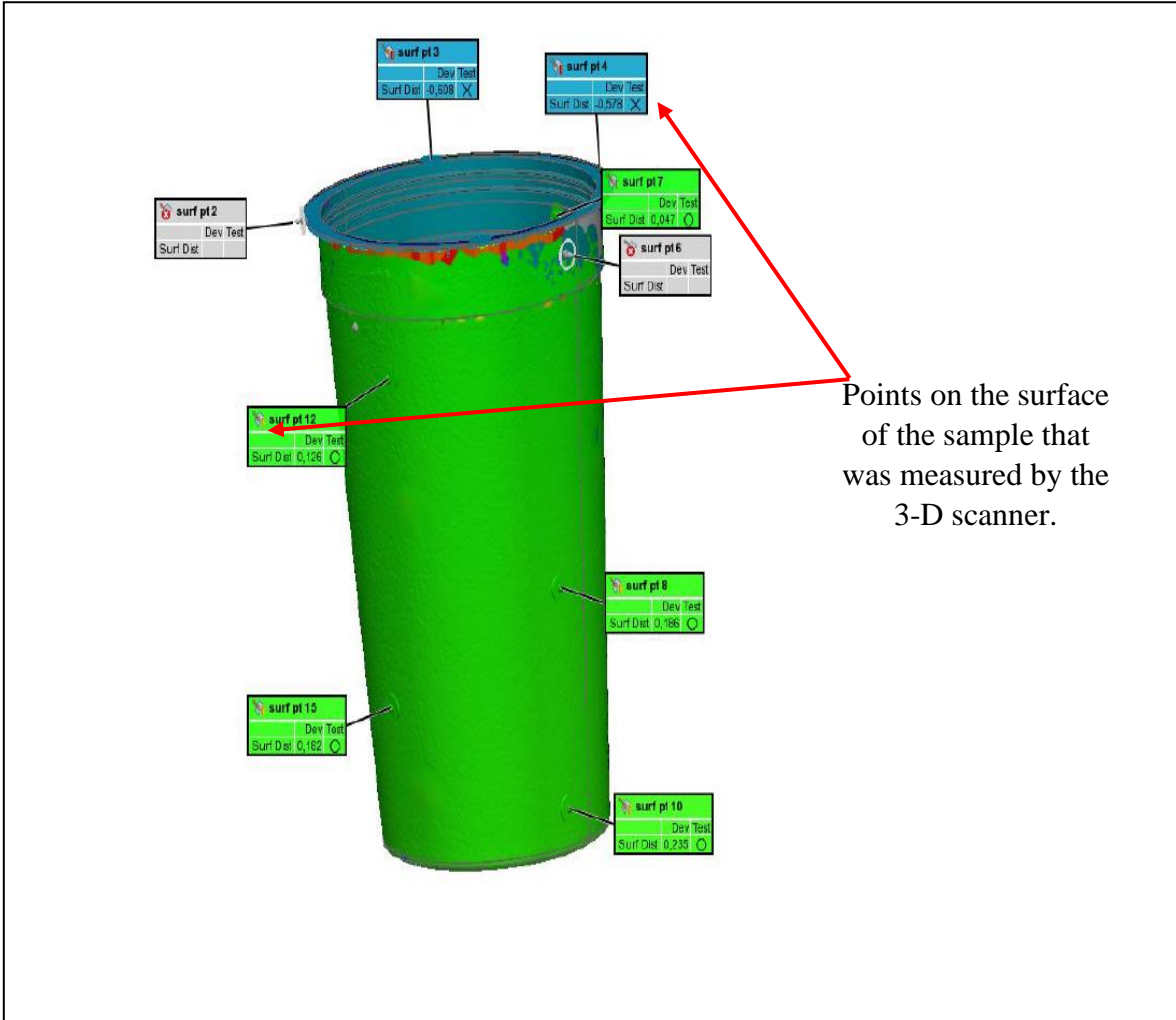


Figure 24: A 3-D Scanned image of Sample B (250ml tub)

According to Figure 24, points 2 and 6 are grey. This grey indicates that points 4 and 4 were not scanned by the 3-D scanner, resulting in an incomplete scan and results. The failure of the 3-D scanner to detect all points on the scanned sample resulted in an incomplete scan and, therefore, inconclusive results.

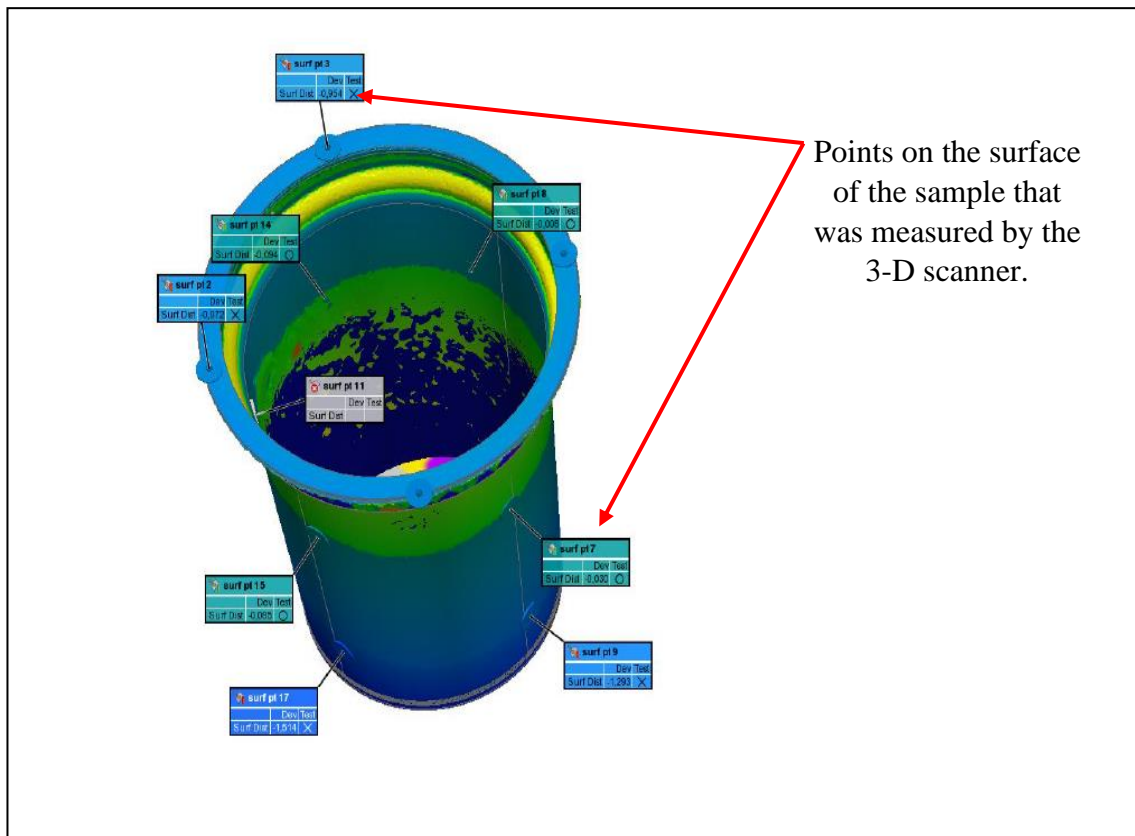


Figure 25: A 3-D scanned image of Sample C (125ml tub)

In Figure 25, point 11 is grey. This grey indicates that the 3-D scanner did not scan point 11. The failure of the 3-D scanner to detect all points on the scanned sample resulted in an incomplete scan and, therefore, inconclusive results.

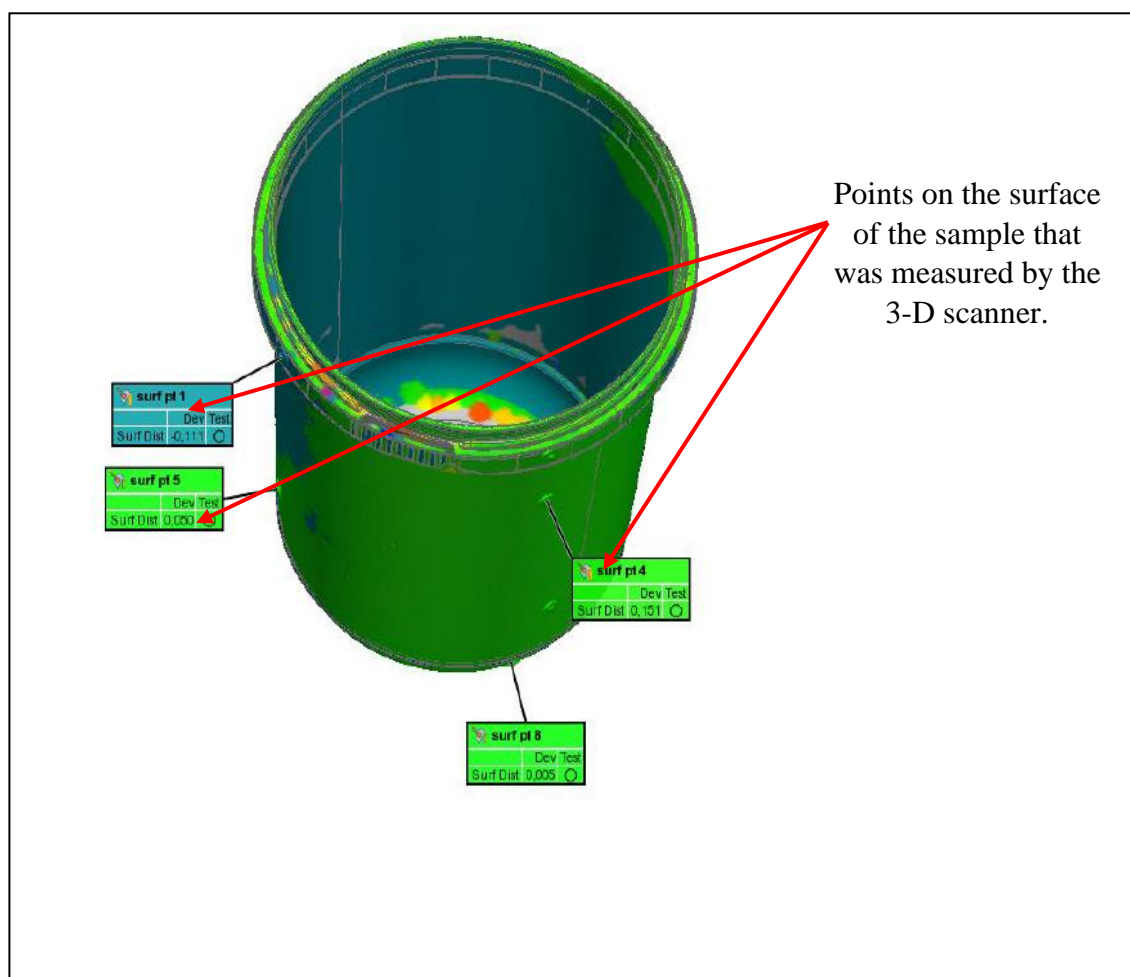


Figure 26: A 3-D Scanned image of Sample D (1kg tub)

According to Figure 26, the green and blue colour of all points indicates that all sample points were scanned. This provided a complete scan and results of the sample that was scanned.

Even though the 3-D scanner contained the feature of a single blue laser for the scanning of objects that have depth or deep holes in them, it failed to capture sufficient surface points of the depth of the samples that were scanned. An anti-glare spray was then used on the samples to assist the single blue laser in capturing the depth of the samples. However, the 3-D scanner still failed to capture sufficient surface points of the depth of the samples. From a visual analysis of the scans, it was noted that the smaller the sample was, the fewer surface points were captured for depth, as the 3-D scanner could not detect the surface points for depth in the smaller samples. Therefore, these samples were incompletely scanned and measured.

When a sample was scanned and aligned with the original CAD drawing, a statistical report of the scanned image was generated. The statistical report contained measurements of the sample's surface points.

4.1.1. Sample A1 and A2: 38mm Closure

Table 8 below is the statistical report of the 3-D scanned image that was generated for Sample A. Table 8 depicts the ten surface points that were captured by the 3-D scanner from Sample A. However, only eight of these surface points were measured. The image that accompanies the statistical report in Table 8 is Figure 27. Typically, when a report is generated, a measured value must be illustrated on a scanned image. In this case, not all the points were illustrated on the scanned image even though they were measured. The generated statistical report (Table 8) showed that eight surface points were measured, however, Figure 27 only illustrated four surface points (points 4, 8, 9, and 10). All the measurements in the statistical report were not graphically represented on the accompanying scanned image in Figure 27. The lack of representation of all measurements on the scanned image made it difficult to correlate the data from the statistical report to the scanned image. Furthermore, even though surface point 4 was depicted in Figure 27, it showed a grey colour, meaning no result was measured for that point.

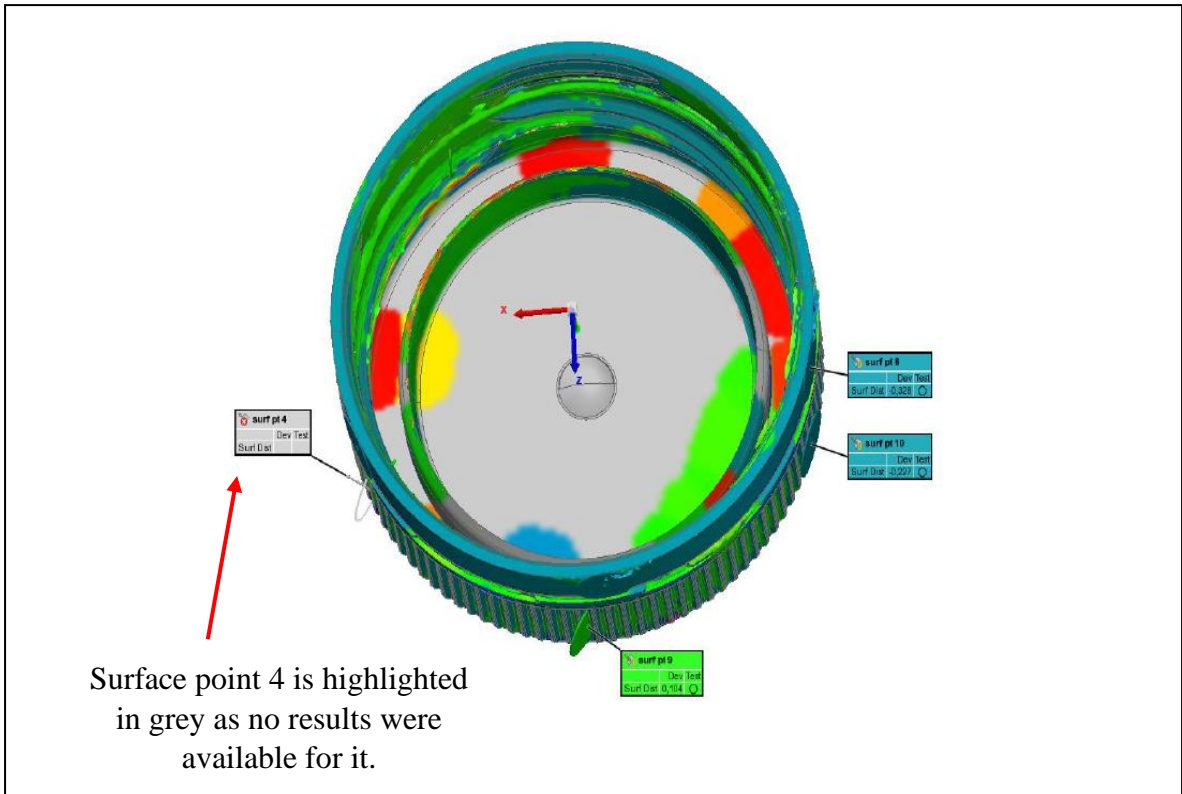
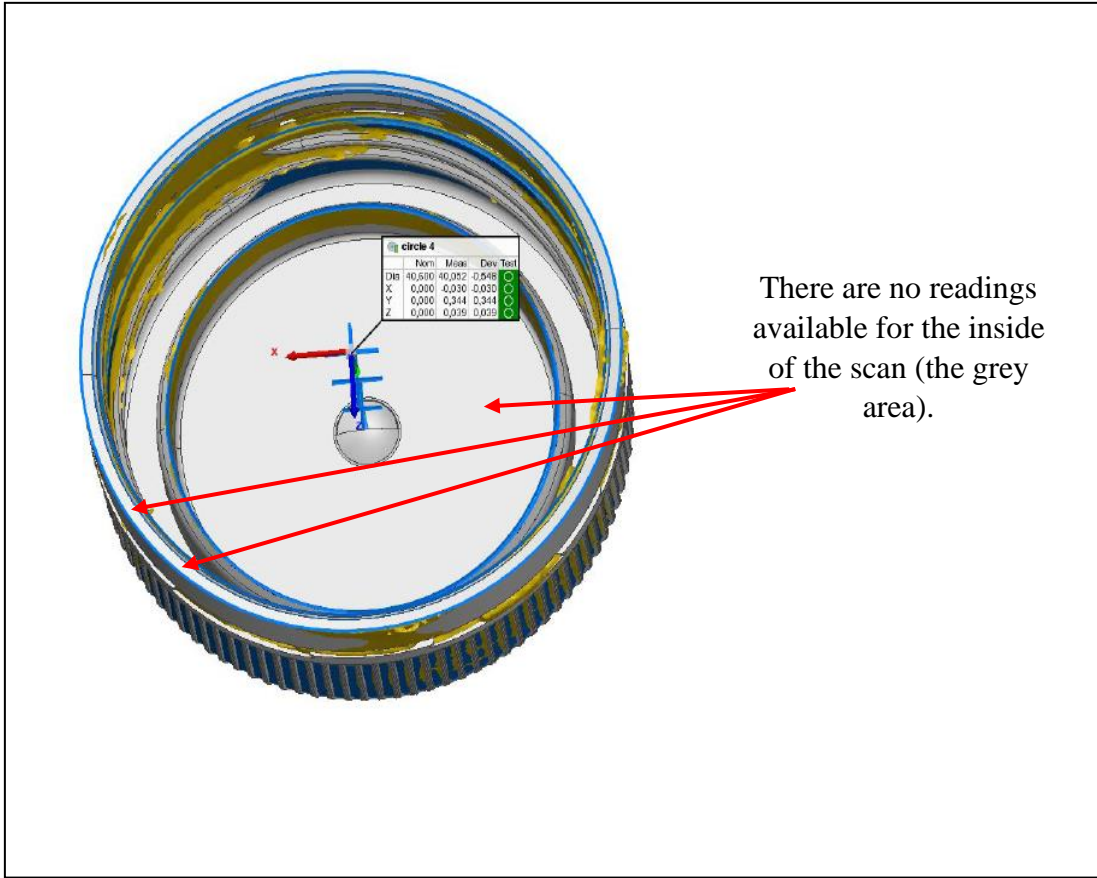


Figure 27: A 3-D scanned image of the inside of Sample A (38mm closure) of the surface points measured

Table 8: Statistical report of Sample A (38mm closure) surface points measured

Control View								
Control View Name	Surface Points							
Units	Millimeters							
Coordinate Systems	world							
Data Alignments	best-fit to ref 1							
All Statistics	Total: 10, Measured: 8 (80,000%), Pass: 8 (80,000%), Fail: 0 (0,000%), Warning: 7 (70,000%)							
Char No.	Object Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
	surf pt 1	Surface Distance		-0,192	±0,500	-0,192	Pass	
	surf pt 2	Surface Distance		-0,455	±0,500	-0,455	Pass	
	surf pt 3	Surface Distance		-0,372	±0,500	-0,372	Pass	
	surf pt 4	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	surf pt 5	Surface Distance		0,150	±0,500	0,150	Pass	
	surf pt 6	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	surf pt 7	Surface Distance		-0,034	±0,500	-0,034	Pass	
	surf pt 8	Surface Distance		-0,328	±0,500	-0,328	Pass	
	surf pt 9	Surface Distance		0,104	±0,500	0,104	Pass	
	surf pt 10	Surface Distance		-0,227	±0,500	-0,227	Pass	



















Table 9 below is the generated statistical report of the 3-D scanned image of Sample A on the X, Y, and Z planes. The accompanying image of the statistical report in Table 9 is Figure 28, which shows the measured circle points and where they are located on the scanned image. Table 9 showed that a total of eighteen points were taken, and 18 points were measured. There was a 100 percent pass of all eighteen points that were measured. As previously mentioned, when a report is generated, a measured value must be illustrated on a scanned image. In this case, not all the points were illustrated on the scanned image even though they were measured. Four circle points were shown in the statistical report, but only one circle point (circle point 4) was depicted in the scanned image, which made it difficult to determine where circle points 1-3 were located on the scanned image.



There are no readings available for the inside of the scan (the grey area).

Figure 28: A 3-D Scanned image of the inside of Sample A (38mm closure) of the circle points measured

Table 9: Statistical report of Sample A (38mm closure) circle points measured

Control View								
Control View Name		Circle Points						
Units		Millimeters						
Coordinate Systems		world						
Data Alignments		best-fit to ref 1						
All Statistics		Total: 18, Measured: 18 (100,000%), Pass: 18 (100,000%), Fail: 0 (0,000%), Warning: 0 (0,000%)						
Char No,	Object Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
	 circle 1	Diameter	29,414	29,201	±1,000	-0,213	Pass	
	 circle 1	X	0,000	0,028	±1,000	0,028	Pass	
	 circle 1	Y	11,850	11,361	±1,000	-0,489	Pass	
	 circle 1	Z	0,000	0,065	±1,000	0,065	Pass	
	 circle 2	Diameter	37,700	37,861	±1,000	0,161	Pass	
	 circle 2	X	0,000	-0,053	±1,000	-0,053	Pass	
	 circle 2	Y	6,175	5,682	±1,000	-0,493	Pass	
	 circle 2	Z	0,000	0,013	±1,000	0,013	Pass	
	 cylinder 1	Diameter	37,700	37,600	±1,000	-0,100	Pass	
	 circle 3	Diameter	38,873	38,007	±1,000	-0,866	Pass	
	 circle 3	X	0,000	-0,050	±1,000	-0,050	Pass	
	 circle 3	Y	0,269	0,344	±1,000	0,075	Pass	
	 circle 3	Z	0,000	0,013	±1,000	0,013	Pass	
	 circle 4	Diameter	40,600	40,052	±1,000	-0,548	Pass	
	 circle 4	X	0,000	-0,030	±1,000	-0,030	Pass	
	 circle 4	Y	0,000	0,344	±1,000	0,344	Pass	
	 circle 4	Z	0,000	0,039	±1,000	0,039	Pass	
	 cone 1	Included Angle	1,000	0,888	±1,000	-0,112	Pass	

4.1.2 Sample B1 and B2: 250ml Tub

Table 10 below is the statistical report of the 3-D scanned image generated for Sample B. Table 10 depicts that the 3-D scanner from Sample B captured fifteen surface points. However, only twelve of these surface points were measured. The image that accompanies the statistical report in Table 10 is Figure 30. When a report is created, it is expected to display a measured value on the scanned image. However, all the points that were measured, were not shown on the scanned image. The generated statistical report (Table 10) showed that twelve surface points were measured in Figure 29, and only nine surface points were illustrated (points 2, 3, 4, 6, 7, 8, 10, 12, and 15). The missing graphical representation of the measurements of the identified points on the scanned image made it difficult to correlate the data from the statistical report to the scanned image. Furthermore, even though surface points 2 and 6 were depicted in Figure 29, they were shown in grey, which means that no result was measured for that point, resulting in incomplete results for the scanned image.

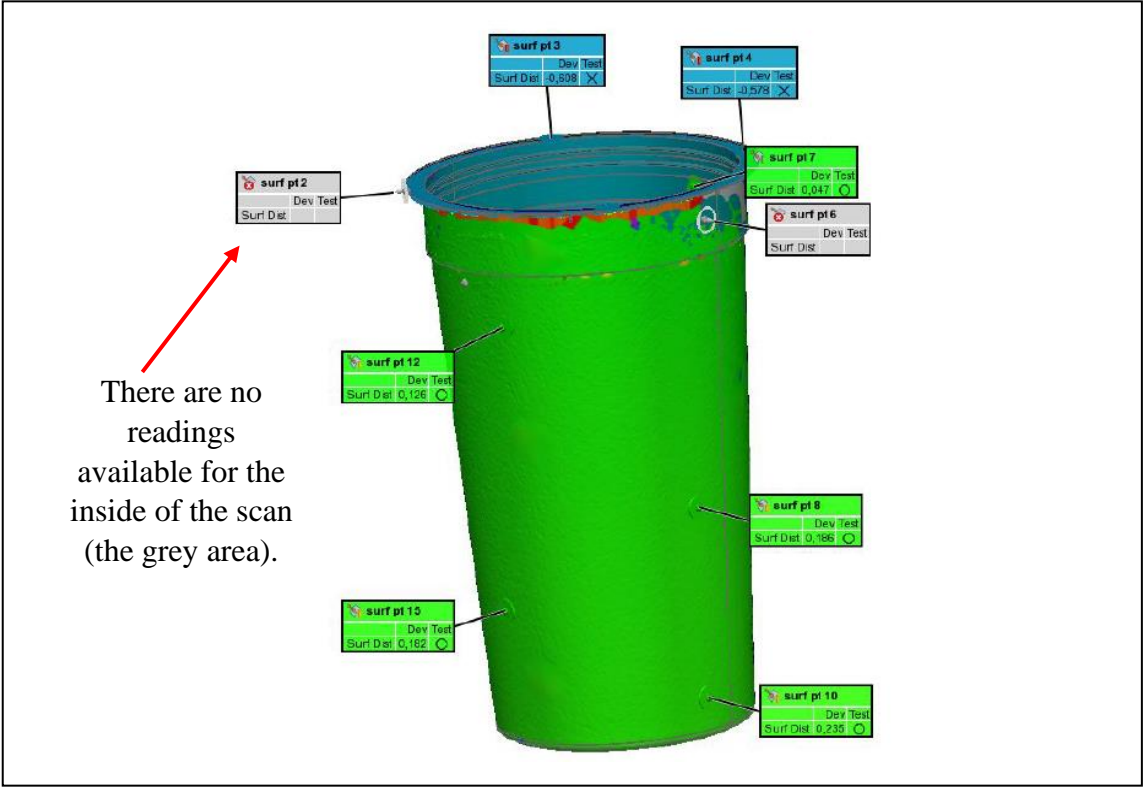


Figure 29: A 3-D scanned image of Sample B (250ml tub) of the surface points measured

Table 10: Statistical report of Sample B (250ml tub) surface points measured

Control View								
Control View Name		Surface Points						
Units		Millimeters						
Coordinate Systems		world						
Data Alignments		best-fit to ref 1						
All Statistics		Total: 15, Measured: 12 (80,000%), Pass: 9 (60,000%), Fail: 3 (20,000%), Warning: 7 (46,667%)						
Char No.	Object Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
	surf pt 1	Surface Distance		-0,544	±0,500	-0,544	Fail	-0,044
	surf pt 2	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	surf pt 3	Surface Distance		-0,608	±0,500	-0,608	Fail	-0,108
	surf pt 4	Surface Distance		-0,578	±0,500	-0,578	Fail	-0,078
	surf pt 5	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	surf pt 6	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	surf pt 7	Surface Distance		0,047	±0,500	0,047	Pass	
	surf pt 8	Surface Distance		0,186	±0,500	0,186	Pass	
	surf pt 9	Surface Distance		0,143	±0,500	0,143	Pass	
	surf pt 10	Surface Distance		0,235	±0,500	0,235	Pass	
	surf pt 11	Surface Distance		0,245	±0,500	0,245	Pass	
	surf pt 12	Surface Distance		0,126	±0,500	0,126	Pass	
	surf pt 13	Surface Distance		0,074	±0,500	0,074	Pass	
	surf pt 14	Surface Distance		0,171	±0,500	0,171	Pass	
	surf pt 15	Surface Distance		0,182	±0,500	0,182	Pass	

The statistical results of the coordinates on the X, Y, and Z planes of Sample B are represented in Table 11 below. Figure 30, the accompanying scanned image, illustrates which circle points were measured and where they are located on the scanned image. Table 11 shows that thirty-four points were taken, and twenty-six points were measured. There was a 76.5 percent pass of all twenty-six points that were measured. A measured value is supposed to be displayed on the scanned image when a report has been completed. However, not all measured points were visible in the scanned image. Eight circle points were shown in the statistical report, but only one circle point (circle point 5) was depicted in the scanned image, resulting in incomplete results for the scanned image.

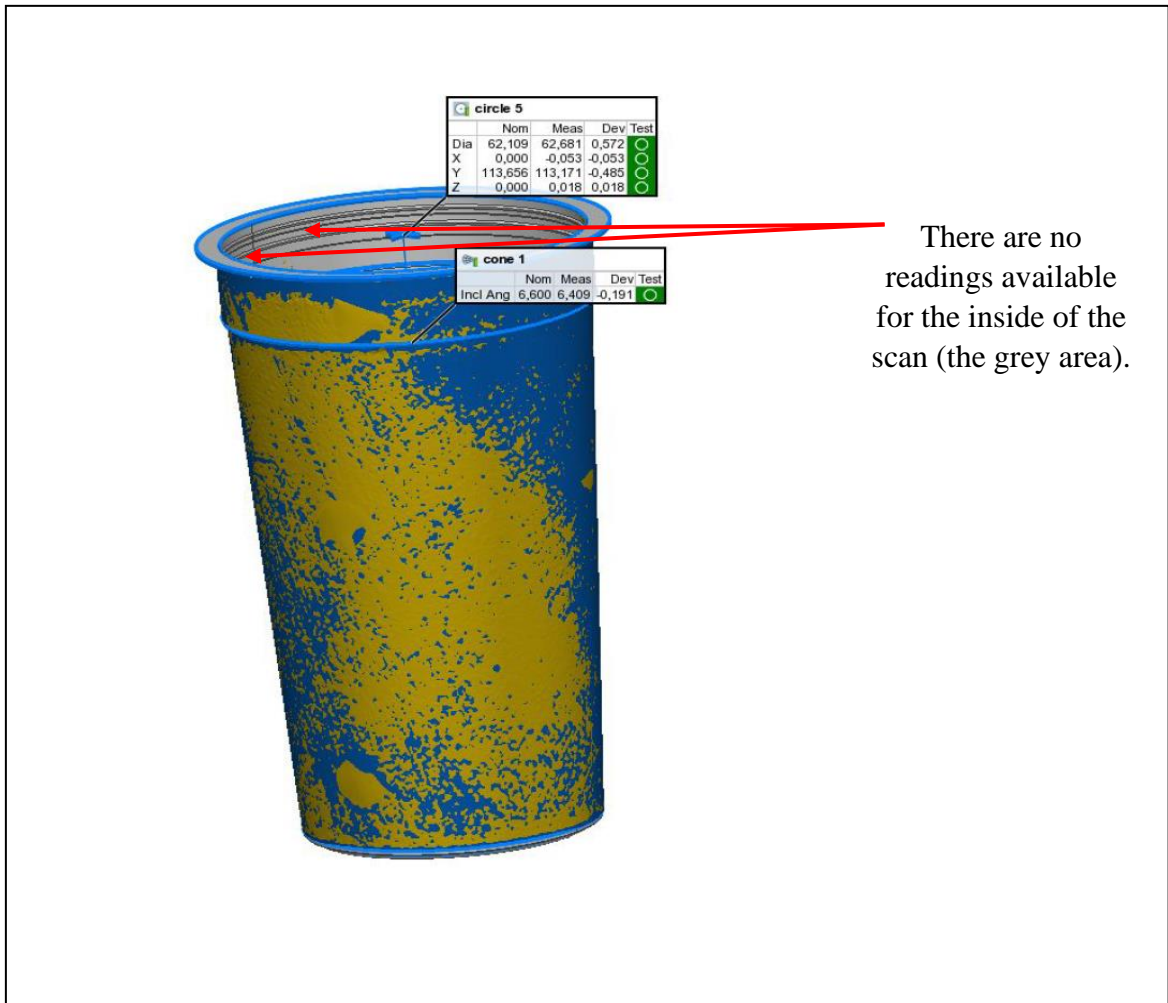


Figure 30: A 3-D Scanned image of the inside of Sample B (250ml Tub) of circle points measured

Table 11: Statistical report of Sample B (250ml tub) circle points measured

Control View								
Control View Name		Circle Points						
Units		Millimeters						
Coordinate Systems		world						
Data Alignments		best-fit to ref 1						
AI Statistics		Total: 34, Measured: 26 (76,471%), Pass: 26 (76,471%), Fail: 0 (0,000%), Warning: 0 (0,000%)						
Char No.	Object Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
	circle 1	Diameter	61,805	62,367	±1,000	0,562	Pass	
	circle 1	X	0,000	0,002	±1,000	0,002	Pass	
	circle 1	Y	100,549	99,731	±1,000	-0,818	Pass	
	circle 1	Z	0,000	0,162	±1,000	0,162	Pass	
	circle 2	Diameter	69,990	69,868	±1,000	-0,122	Pass	
	circle 2	X	0,000	-0,003	±1,000	-0,003	Pass	
	circle 2	Y	113,759	113,171	±1,000	-0,588	Pass	
	circle 2	Z	0,000	0,051	±1,000	0,051	Pass	
	circle 3	Diameter	N/A	N/A	N/A	N/A	N/A	N/A
	circle 3	X	N/A	N/A	N/A	N/A	N/A	N/A
	circle 3	Y	N/A	N/A	N/A	N/A	N/A	N/A
	circle 3	Z	N/A	N/A	N/A	N/A	N/A	N/A
	circle 4	Diameter	69,990	69,868	±1,000	-0,122	Pass	
	circle 4	X	0,000	-0,003	±1,000	-0,003	Pass	
	circle 4	Y	113,759	113,171	±1,000	-0,588	Pass	
	circle 4	Z	0,000	0,051	±1,000	0,051	Pass	
	circle 5	Diameter	62,109	62,681	±1,000	0,572	Pass	
	circle 5	X	0,000	-0,053	±1,000	-0,053	Pass	
	circle 5	Y	113,656	113,171	±1,000	-0,485	Pass	
	circle 5	Z	0,000	0,018	±1,000	0,018	Pass	
	circle 6	Diameter	62,300	62,383	±1,000	0,083	Pass	
	circle 6	X	0,000	0,002	±1,000	0,002	Pass	
	circle 6	Y	100,549	99,731	±1,000	-0,918	Pass	
	circle 6	Z	0,000	0,152	±1,000	0,152	Pass	
	circle 7	Diameter	63,300	62,732	±1,000	-0,568	Pass	
	circle 7	X	0,000	0,022	±1,000	0,022	Pass	
	circle 7	Y	100,097	99,732	±1,000	-0,365	Pass	
	circle 7	Z	0,000	0,050	±1,000	0,050	Pass	
	circle 8	Diameter	N/A	N/A	N/A	N/A	N/A	N/A
	circle 8	X	N/A	N/A	N/A	N/A	N/A	N/A
	circle 8	Y	N/A	N/A	N/A	N/A	N/A	N/A
	circle 8	Z	N/A	N/A	N/A	N/A	N/A	N/A
	cone 1	Included Angle	6,600	6,409	±1,000	-0,191	Pass	
	cone 2	Included Angle	2,000	1,697	±1,000	-0,303	Pass	

4.1.3 Sample C1 and C2: 125ml Tub

Table 12 below is the statistical report of the 3-D scanned image that was generated for Sample C. Table 12 depicts the seventeen surface points that were captured by the 3-D scanner from

Sample C. However, only fifteen of these surface points were measured. The image that accompanies the statistical report in Table 12 is Figure 31. When a report is generated, a measured value is expected to appear on the scanned image. However, the scanned image did not show all the measured points. The statistical report (Table 12) showed that fifteen surface points were measured, while Figure 31 only illustrated nine surface points (points 2, 3, 7, 8, 9, 11, 14, 15, and 17). As a result, connecting the data from the statistical report with the scanned image became problematic. In addition, surface point 11 was represented in Figure 31, but it was coloured grey, indicating that no measurement was taken at that spot.

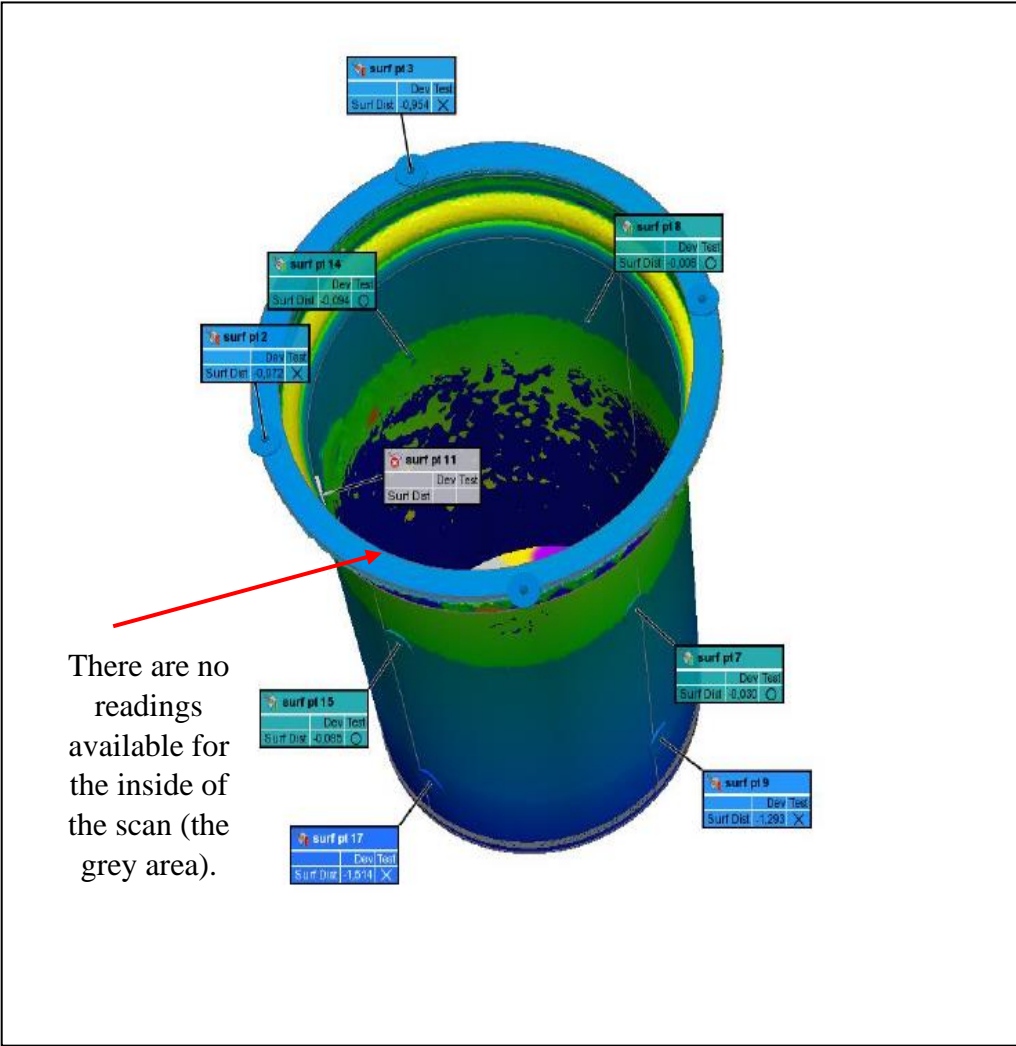


Figure 31: A 3-D scanned image of Sample C (125ml tub) of the surface measured

Table 12: Statistical report of Sample C (125ml tub) surface points measured

Control View								
Control View Name		Surface Points						
Units		Millimeters						
Coordinate Systems		world						
Data Alignments		best-fit to ref 1						
All Statistics		Total: 17, Measured: 15 (88,235%), Pass: 6 (35,294%), Fail: 9 (52,941%), Warning: 0 (0,000%)						
Char No.	Object Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
	surf pt 1	Surface Distance		-1,006	±0,500	-1,006	Fail	-0,506
	surf pt 2	Surface Distance		-0,972	±0,500	-0,972	Fail	-0,472
	surf pt 3	Surface Distance		-0,954	±0,500	-0,954	Fail	-0,454
	surf pt 4	Surface Distance		-0,939	±0,500	-0,939	Fail	-0,439
	surf pt 5	Surface Distance		-0,011	±0,500	-0,011	Pass	
	surf pt 6	Surface Distance		-2,284	±0,500	-2,284	Fail	-1,784
	surf pt 7	Surface Distance		-0,030	±0,500	-0,030	Pass	
	surf pt 8	Surface Distance		-0,008	±0,500	-0,008	Pass	
	surf pt 9	Surface Distance		-1,293	±0,500	-1,293	Fail	-0,793
	surf pt 10	Surface Distance		-1,489	±0,500	-1,489	Fail	-0,989
	surf pt 11	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	surf pt 12	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	surf pt 13	Surface Distance		0,008	±0,500	0,008	Pass	
	surf pt 14	Surface Distance		-0,094	±0,500	-0,094	Pass	
	surf pt 15	Surface Distance		-0,085	±0,500	-0,085	Pass	
	surf pt 16	Surface Distance		-1,486	±0,500	-1,486	Fail	-0,986
	surf pt 17	Surface Distance		-1,514	±0,500	-1,514	Fail	-1,014

Table 13 displays the statistical results of Sample C's coordinates on the X, Y, and Z planes. Figure 32 illustrates the measured circle points and where they are located on the scanned image. Table 13 demonstrated that thirty points in all were collected, and all thirty points were measured. Of the thirty points that were measured, 60 percent of them were within the specification and had passed. Although seven circle points were shown in the statistical report, only one circle point (circle point 5) was depicted in the scanned image, resulting in incomplete results for the scanned image. When generating a report, the scanned image should display all measured points, but it failed to do so.

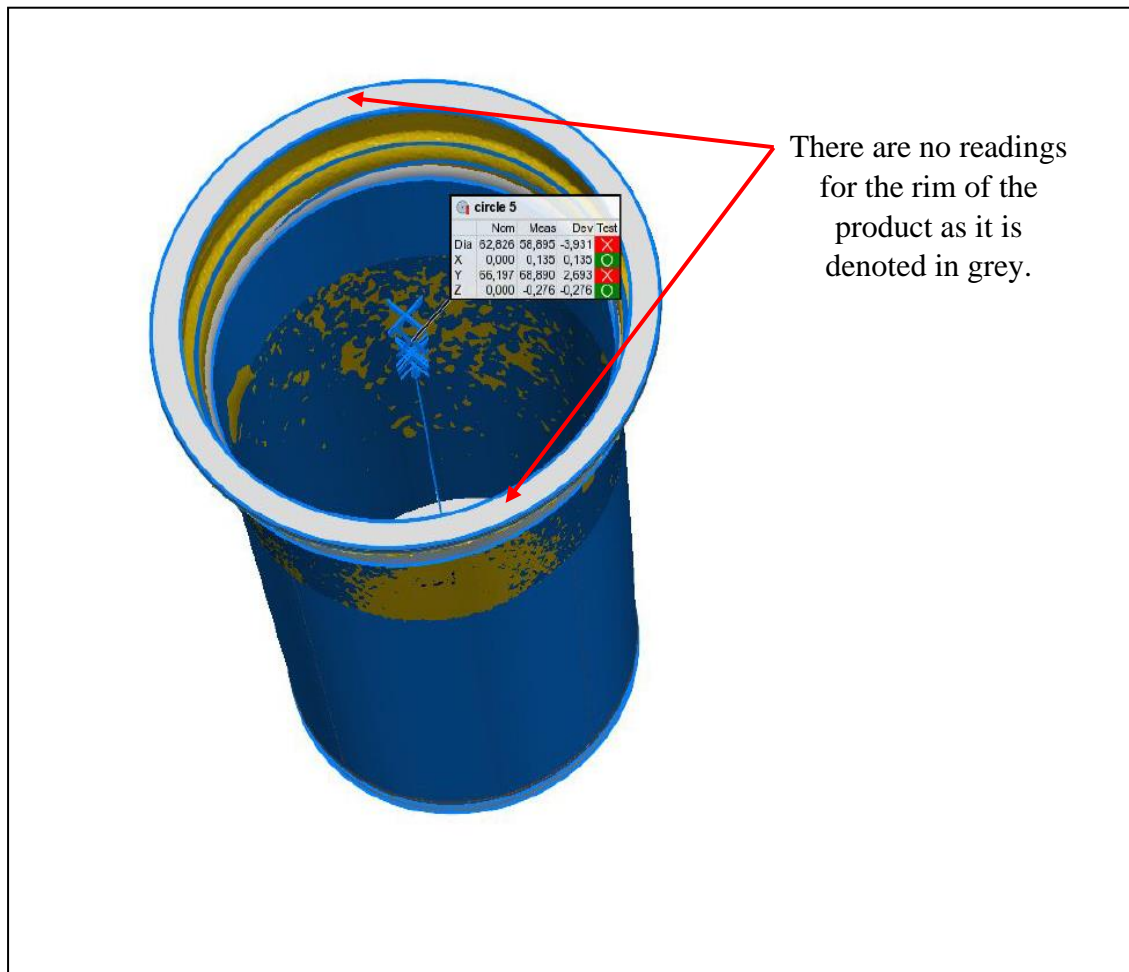


Figure 32: A 3-D Scanned image of the inside of Sample C (125ml tub) of circle points measured

Table 13: Statistical report of Sample C (125ml tub) circle points measured

Control View								
Control View Name		Circle Points						
Units		Millimeters						
Coordinate Systems		world						
Data Alignments		best-fit to ref 1						
All Statistics		Total: 30, Measured: 30 (100,000%), Pass: 18 (60,000%), Fail: 12 (40,000%), Warning: 0 (0,000%)						
Char No.	Object Name	Control	Nom	Meas	ToI	Dev	Test	Out Tol
○	circle 1	Diameter	69,600	69,787	±1,000	0,187	Pass	
○	circle 1	X	0,000	-0,095	±1,000	-0,095	Pass	
○	circle 1	Y	75,000	74,092	±1,000	-0,908	Pass	
○	circle 1	Z	0,000	-0,064	±1,000	-0,064	Pass	
○	circle 2	Diameter	61,640	62,068	±1,000	0,428	Pass	
○	circle 2	X	0,000	0,042	±1,000	0,042	Pass	
○	circle 2	Y	75,000	74,097	±1,000	-0,903	Pass	
○	circle 2	Z	0,000	0,048	±1,000	0,048	Pass	
○	circle 3	Diameter	62,040	58,884	±1,000	-3,156	Fail	-2,156
○	circle 3	X	0,000	-0,070	±1,000	-0,070	Pass	
○	circle 3	Y	67,200	68,889	±1,000	1,689	Fail	0,689
○	circle 3	Z	0,000	-0,089	±1,000	-0,089	Pass	
○	circle 4	Diameter	55,373	56,725	±1,000	1,352	Fail	0,352
○	circle 4	X	0,000	0,062	±1,000	0,062	Pass	
○	circle 4	Y	63,903	65,562	±1,000	1,659	Fail	0,659
○	circle 4	Z	0,000	0,122	±1,000	0,122	Pass	
○	circle 5	Diameter	62,826	58,895	±1,000	-3,931	Fail	-2,931
○	circle 5	X	0,000	0,135	±1,000	0,135	Pass	
○	circle 5	Y	66,197	68,890	±1,000	2,693	Fail	1,693
○	circle 5	Z	0,000	-0,276	±1,000	-0,276	Pass	
○	circle 6	Diameter	47,350	43,821	±1,000	-3,529	Fail	-2,529
○	circle 6	X	0,000	0,123	±1,000	0,123	Pass	
○	circle 6	Y	0,000	-1,356	±1,000	-1,356	Fail	-0,356
○	circle 6	Z	0,000	-0,096	±1,000	-0,096	Pass	
○	circle 7	Diameter	47,577	44,014	±1,000	-3,563	Fail	-2,563
○	circle 7	X	0,000	0,108	±1,000	0,108	Pass	
○	circle 7	Y	1,644	-1,356	±1,000	-3,000	Fail	-2,000
○	circle 7	Z	0,000	-0,092	±1,000	-0,092	Pass	
⊢	cone 1	Included Angle	7,900	12,585	±1,000	4,685	Fail	3,685
⊢	cone 2	Included Angle	7,900	12,326	±1,000	4,426	Fail	3,426

4.1.4 Sample D1 and D2: 1kg Tub

Table 14 below is the statistical report of the 3-D scanned image generated for Sample D. Table 14 depicts that the 3-D scanner from Sample C captured twelve surface points. However, only eight of these surface points were measured. When compiling a report, it is essential that the scanned image accurately displays all measured points. However, it has been noted that not all measured values were depicted on the scanned image. The image accompanying the statistical report in Table 14 is Figure 33. While the statistical report (Table 14) showed that eight surface points were measured, Figure 34 only identified four surface points (points 1, 4,5, and 8). As a result, connecting the data from the statistical report with the scanned image became problematic.

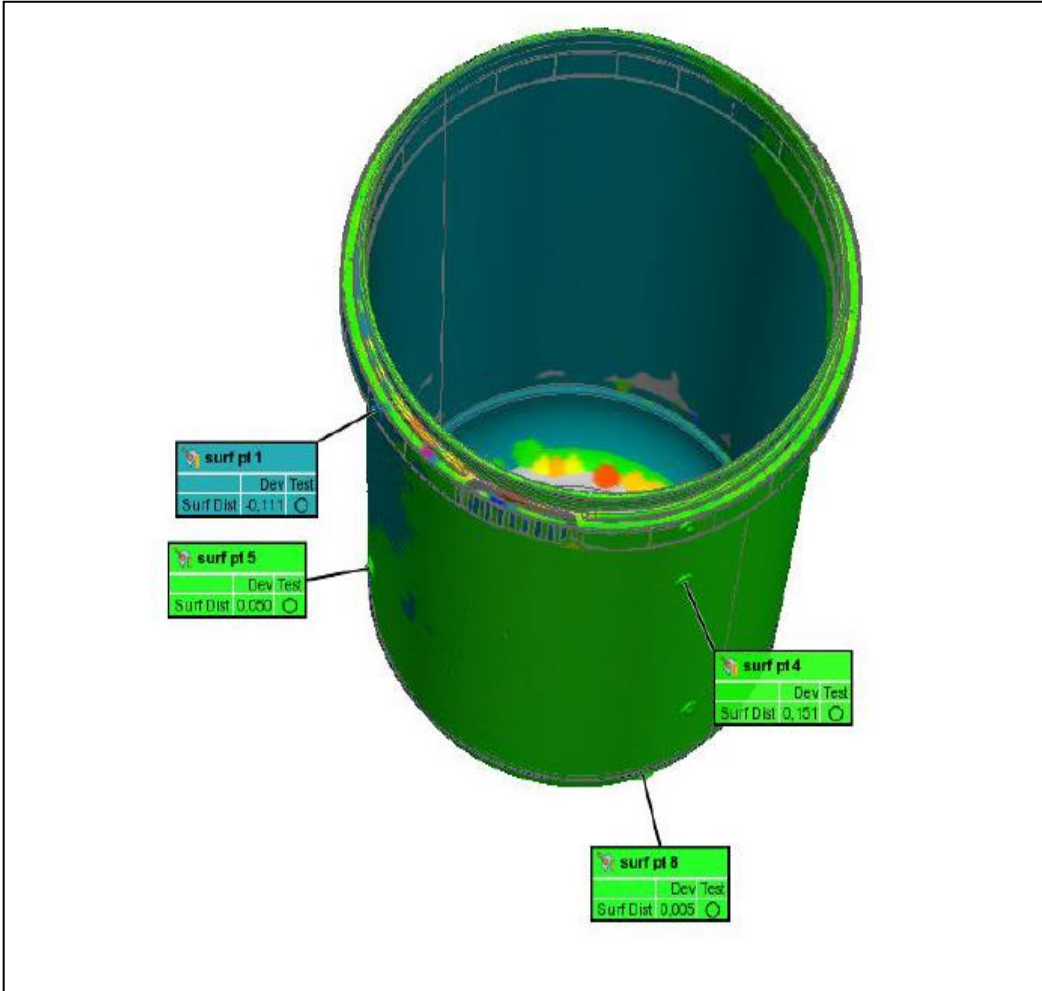


Figure 33: A 3-D scanned image of Sample D (1kg tub) of the surface points measured

Table 14: Statistical report of Sample D (1kg tub) surface points measured









Control View Name	Surfaces							
Units	Millimeters							
Coordinate Systems	world							
Data Alignments	best-fit to ref 1							
All Statistics	Total: 8, Measured: 7 (87,500%), Pass: 7 (87,500%), Fail: 0 (0,000%), Warning: 5 (62,500%)							
Char No.	Object Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
	 surf pt 1	Surface Distance		-0,111	±0,500	-0,111	Pass	
	 surf pt 2	Surface Distance		0,217	±0,500	0,217	Pass	
	 surf pt 3	Surface Distance		-0,119	±0,500	-0,119	Pass	
	 surf pt 4	Surface Distance		0,151	±0,500	0,151	Pass	
	 surf pt 5	Surface Distance		0,050	±0,500	0,050	Pass	
	 surf pt 6	Surface Distance		0,122	±0,500	0,122	Pass	
	 surf pt 7	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	 surf pt 8	Surface Distance		0,005	±0,500	0,005	Pass	

Table 15 displays the statistical results of Sample D's coordinates on the X, Y, and Z planes. Figure 34 illustrates the measured circle points and their locations on the scanned image. Table 15 demonstrated that twelve points were collected, and eight points were measured. 58 percent of the eight measured points were within the specification and had passed. Although eight circle points were shown in the statistical report, zero circle points were depicted in the scanned image, resulting in incomplete results for the scanned image.

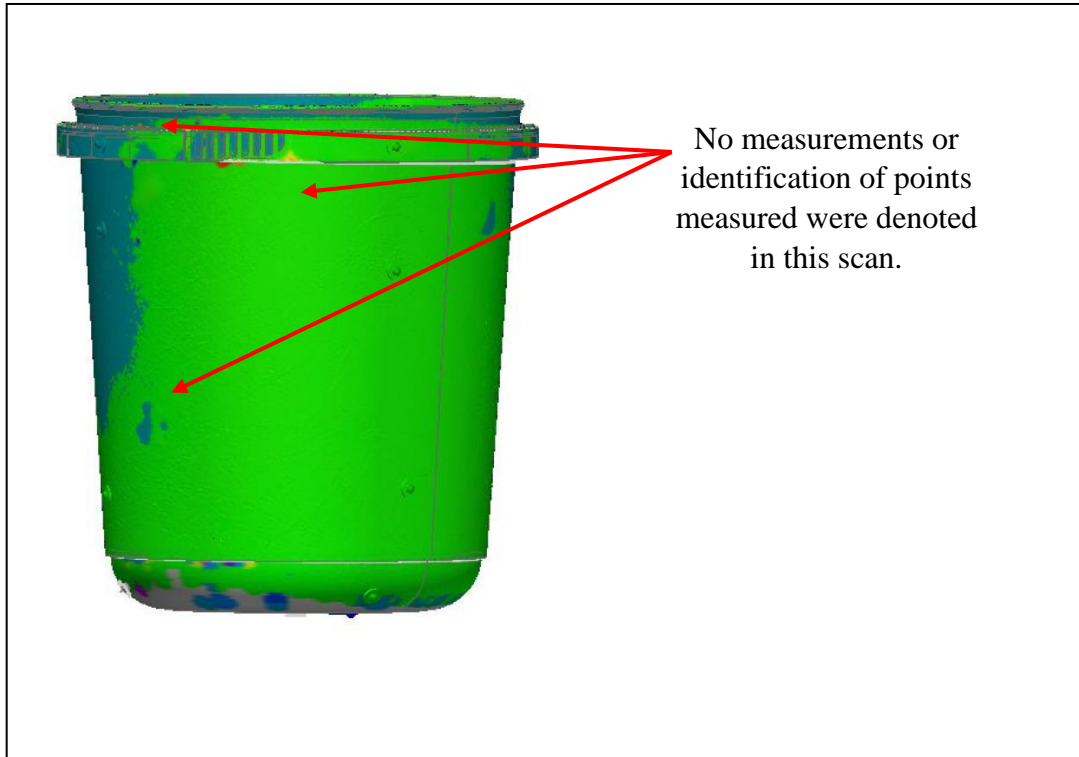


Figure 34: A 3-D Scanned image of the inside of Sample D (1kg tub) of circle points measured.

Table 15: Statistical report of Sample D (1kg tub) circle points measured

Control View								
Control View Name		Circles						
Units		Millimeters						
Coordinate Systems		world						
Data Alignments		best-fit to ref 1						
All Statistics		Total: 12, Measured: 8 (66,667%), Pass: 7 (58,333%), Fail: 1 (8,333%), Warning: 0 (0,000%)						
Char No.	Object Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
	circle 1	Diameter	94,694	94,659	±1,000	-0,035	Pass	
	circle 1	X	0,000	0,015	±1,000	0,015	Pass	
	circle 1	Y	14,219	13,829	±1,000	-0,390	Pass	
	circle 1	Z	0,000	0,043	±1,000	0,043	Pass	
	circle 2	Diameter	112,271	112,261	±1,000	-0,010	Pass	
	circle 2	X	0,000	-0,051	±1,000	-0,051	Pass	
	circle 2	Y	119,570	118,529	±1,000	-1,041	Fail	-0,041
	circle 2	Z	0,000	-0,004	±1,000	-0,004	Pass	
	circle 3	Diameter	N/A	N/A	N/A	N/A	N/A	N/A
	circle 3	X	N/A	N/A	N/A	N/A	N/A	N/A
	circle 3	Y	N/A	N/A	N/A	N/A	N/A	N/A
	circle 3	Z	N/A	N/A	N/A	N/A	N/A	N/A

4.1.5 Discussion of the Surface Points Measurements of the 3-D Scanned Images and Statistical Reports

The measurements in this section represent surface points. Each sample was scanned ten times. Therefore, there was a cumulative number of one hundred scans for all the samples in the experiment. A total of 1207 surface points were taken; however, from the 1207 surface points that were taken, only 1029 surface points were measured by the 3-D scanner, and 665 surface points were illustrated. Table 16 presents the summarised average number of surface points scanned and measured for each sample by the 3-D scanner. As shown in Table 16, an average of 12.32 surface points were captured by the 3-D scanner, and an average of 6.7 points were illustrated for each sample measured. Of these points, only 88.1 percent of the surface points were measured. The points measured were then categorised into passes or failures. Failures occur when the scanned image and the original drawing (CAD control) do not match when superimposed. Only, 72.4 percent of the surface points had passed, 15.3 percent of the surface points failed, and 36.6 percent of the surface points were marked as a warning. The warning

category is for those points within the specification that were either at the bottom end or top end of the specification. The 3-D scanner failed to measure all surface points captured with the scanner in all scanned samples.

Table 16: Average results of the number of surface points scanned with the 3-D scanner

Sample	Surface Points					
	Average number of points taken	Average number of points measured	Average number of points illustrated	Average number of points passed	Average number of points failed	Average number of points in warning
A1 (inside)	10	9	3.4	9	0	4
A 1 (outside)	8	4	2.6	4	0	4
A 2 (inside)	11	10	4	9	1	5
A 2 (outside)	11	10	6.3	9	1	5
B 1	15	15	8.9	14	1	7
B 2	16	16	10	16	0	6
C 1	16	13	8.4	6	8	3

C 2	16	14	9.6	6	8	3
D 1	10	9	6.2	8	1	4
D 2	11	10	7.1	10	0	6
Average	12.32	10.85	6.65	8.92	1.89	4.51
Average % of points from the number of points taken		88.07	53.98	72.40	15.34	6.61

4.1.6 Discussion of the Circle Points (X, Y, and Z Planes) Measurements of the 3-D Scanned Images and Statistical Reports

The measurements in this section represent the circle points. There was a total of two thousand three hundred eleven circle points taken; however, from the two thousand three hundred eleven circle points taken, only two thousand eighty circle points were measured, and scanner and 180 circle points were illustrated.

The consolidated average number of circle points that the 3-D scanner scanned and measured for every sample is shown in Table 17. The 3-D scanner recorded an average of 23.2 circle points and an average of 2.3 points were illustrated for each sample measured. for every sample, as indicated in Table 17. Ninety-two percent of the 21.4 circle points that were recorded were measured. Thereafter, the measured points were divided into passes and failures.71.8 percent

of the circle points measured had passed, 16.5 percent had failed, and zero percent had been flagged as a warning out of the total number of points tested. Failure in the context of circle points is the same as indicated for the surface points in the preceding section.

The 3-D scanner failed to measure all circle points captured in all samples scanned.

Table 17: Average results of the number of circle points scanned with the 3-D scanner

Sample	Circle Points					
	Average number of points taken	Average number of points measured	Average number of points illustrated	Average number of points passed	The average number of points failed	Average number of points in warning
A1 (inside)	20	18	5	18	0	0
A 1 (outside)	12	7	3	6	1	0
A 2 (inside)	15	15	1	13	2	0
A 2 (outside)	15	15	3	13	2	0
B 1	27	25	2	24	1	0
B 2	27	25	2	23	1	0

C 1	28	27	2	17	10	0
C 2	28	27	2	16	11	0
D 1	22	21	1	17	4	0
D 2	36	36	2	30	6	0
Average	23.19	21.44	2.26	17.58	4	0
Average % of points from the number of points taken		92.45	10.54	75.81	16.47	0.00

4.2 Evaluation of Results of the 3-D Scanner, Vernier, and CMM Measurements

There are certain variables of products that are critical for the functioning of the product. These include but are not limited to the height, thickness, orifice, width, depth, thread, and diameter. These variables are essential and measured as routine quality control checks to ensure that the product manufactured always conforms to specifications and tolerances (as determined by the product manufacturer) to function. These critical variables differ for each type of product manufactured. The exterior diameter, minor thread, internal clip diameter, and height were the variables considered for sample A (closures). The variables considered were the height, orifice, and diameter of samples B (250 ml tub) and C (125 ml tub). For sample D (1 kg tub), the

variables considered were the height, neck ring, clip ring, and diameter. These factors were chosen due to the manufacturer's criteria, which were essential for routine quality testing.

Tables 18-25 compare the average results for each variable taken for each sample using the three different measuring devices (the 3-D scanner, vernier, and CMM) and the manufacturer's specifications of the samples.

4.2.1 Sample A1 and A2: 38mm Closure

As shown in Tables 18-19 (samples A 1 and A 2), the vernier and CMM measuring devices obtained results for external diameter, minor thread, internal clip diameter, and height. The 3-D scanner could not obtain actual measurements and illustrations on the scanned image for the external diameter, minor thread, and height for both Sample A 1 and Sample A 2.

Table 18: Average measurement results of Sample A1 (38mm closure)

Instrument of Measurement	Sample A 1				
	External Diameter	Minor Thread	Internal Clip Diameter	Height	Time
	Specification				
	39,8-41,8	35,55 - 35,95	37,2 - 37,6	16,15 - 18,15	
	mm	mm	mm	mm	secs
Vernier	40,331	35,938	37,242	16,542	17,956
CMM	40,283	35,944	37,342	16,57488045	183,719
3-D Scanner	no result	no result	37,596	no result	203,28

Table 19: Average measurement results of Sample A2 (38mm closure)

Instrument of Measurement	Sample A 2				
	External Diameter	Minor Thread	Internal Clip Diameter	Height	Time
	Specification				
	39,8-41,8	35,55 - 35,95	37,2 - 37,6	16,15 - 18,15	
	mm	mm	mm	mm	secs
Vernier	40,32	35,94	37,10	16,58	17,99
CMM	40,32	35,91	37,24	16,53	183,72
3-D Scanner	no result	no result	37,5757	no result	128,82

4.2.2 Sample B1 and B2: 250ml Tub

The findings of the vernier and CMM measuring instruments for the variable's height, orifice, and diameter are displayed in Tables 20–21 (samples B 1 and B 2). The 3-D scanner failed to obtain precise measurements and visual representations of the orifice for both Sample B1 and Sample B2. When the diameter was measured using a vernier and a CMM, the average result was within the required standard; however, when the 3-D scanner was used, the measurement was slightly below the requirements, at 0.28mm and 4mm for samples B 1 and B 2, respectively.

Table 20: Average measurement results of Sample B1 (250ml tub)

Instrument of Measurement	Sample B 1			
	Height	Orifice	Diameter	Time
	Specification			
	113-115	62,4 - 62,6	70 - 70,6	
	mm	mm	mm	s
Vernier	114,02	62,42	70,38	19,27
CMM	114,012	62,40	70,37	64,15
3-D Scanner	113,70	no result	69,72	107,64

Table 21: Average measurement results of Sample B2 (250ml tub)

Instrument of Measurement	Sample B 2			
	Height	Orifice	Diameter	Time
	Specification			
	113-115	62,4 - 62,6	70 - 70,6	
	mm	mm	mm	s
Vernier	114,04	62,44	70,488	19,29
CMM	114,02	62,41	70,48	64,10
3-D Scanner	215,82	no result	66,00	138,78

4.2.3 Sample C1 and C2: 125ml Tub

Tables 22–23 (samples C 1 and C 2) present the vernier and CMM measuring device results for the variable's height, orifice, and diameter. The 3-D scanner was unable to capture precise measurements and illustrations of the orifice for both Sample C1 and Sample C2. The average measurement obtained from using a vernier and a CMM to measure height was within the required specification; however, the measurement obtained from using a 3-D scanner was two-point eighty-three millimetres and two-point ninety-seven millimetres for Sample C1 and C2, respectively, which is below the specification of the samples.

Table 22: Average measurement results of Sample C1 (125ml tub)

Instrument of Measurement	Sample C 1			
	Height	Orifice	Diameter	Time
	Specification			
	77-79	61,75-61,95	69,6-70,4	
	mm	mm	mm	s
Vernier	78,24	61,85	70,33	17,15
CMM	78,19	61,84	70,31	63,49
3-D Scanner	74,17	no result	69,88	133,56

Table 23: Average measurement results of Sample C2 (125ml tub)

Instrument of Measurement	Sample C 2			
	Height	Orifice	Diameter	Time
	Specification			
	77-79	61,75-61,95	69,6-70,4	
	mm	mm	mm	s
Vernier	78,27	61,85	70,33	17,16
CMM	78,261	61,84	70,31	63,26
3-D Scanner	74,03	no result	69,79	138,30

The results for the 3-D scanner were incomplete and varied from those obtained by the vernier calliper and the CMM.

4.2.4 Sample D1 and D2: 1kg Tub

The findings of the vernier and CMM measuring instruments for the variable's height, clip ring, diameter, and neck ring are shown in Tables 24–25 (samples D 1 and D 2). The 3-D scanner could not obtain definite measurements and illustrations on the scanned image for the clip ring and neck ring for both Sample D 1 and Sample D 2. The average measurement obtained from using a vernier and a CMM to measure diameter was within the required specification; however, the measurement obtained for Sample D 1 from the 3-D scanner was zero-point ninety-seven millimetres below the specification. The height obtained for Sample D2 was within the specification when measured with the vernier and CMM. However, it was below the required specification by fifteen-point seventeen millimetres when measured with the 3-D scanner.

Table 24: Average measurement results of Sample D1(1kg tub)

Instrument of Measurement	Sample D 1				
	Height	Clip Ring	Diameter	Neck Ring	Time
	Specification				
	133 - 135	116,7-117,5	98,2-99	124,6 - 125	
	mm	mm	mm	mm	s
Vernier	133,75	117,24	98,347	124,958	26,34
CMM	133,73	117,23	98,35	124,96	105,33
3-D Scanner	133,76	no result	97,23	no result	265,68

Table 25: Average measurement results of Sample D2 (1kg tub)

Instrument of Measurement	Sample D 2				
	Height	Clip Ring	Diameter	Neck Ring	Time
	Specification				
	133 - 135	116,7-117,5	98,2-99	124,6 - 125	
	mm	mm	mm	mm	s
Vernier	133,76	117,12	98,26	125,02	26,38
CMM	133,75	117,11	98,27	125,02	105,12
3-D Scanner	117,83	no result	98,67	no result	346,80

4.2.5 Discussion of the Results of the 3-D Scanner, Vernier, and CMM

Due to the failure of the ability of the scanner to measure all surface points, the data for the critical variables required for quality control testing of the samples measured were incomplete, and the scanned images could not determine if those critical variables were within the prescribed specification or not. Even though each surface point consisted of over a million scanned points, the scanned image, once aligned with the original CAD drawing, had incomplete data thus, all quality checks were not completed. However, the vernier and the CMM measuring devices produced results and values for all the critical variables for quality control purposes and matched CAD drawings.

4.3 Time Study Comparison of the 3-D Scanner, Vernier, and CMM

A time study was conducted on all three measuring devices to determine if the 3-D scanner captured the critical quality control data much quicker than the vernier and the CMM and if it could save time during routine quality control checks.

A stopwatch was used to time each occurrence or each time a sample was measured with each device. Ten cycles were monitored for each sample. Table 26 shows the time study comparison between the three measuring devices. It contains the average time taken to measure each critical variable of each sample and the cumulative average time taken for the routine quality control checks of all the measured samples.

Table 26: The average time taken for the measurement conducted on each measuring device

Time taken to conduct measurements (seconds)				
Sample	ID	3-D Scanner	CMM	Vernier
A	1	203,28	183,719	17,917
	2	128,82	183,72	17,955
B	1	107,64	64,15	19,27
	2	138,78	64,10	19,28
C	1	133,56	63,49	17,15
	2	138,30	63,26	17,16
D	1	265,68	105,33	26,34
	2	346,80	105,12	26,38
Total Time Taken (seconds)		1462,86	832,894	161,465

Once the time study was conducted to determine how long each measuring device took to collect measurements from the sample, a comparison of the time taken to measure each sample with each measuring device was calculated.

4.3.1 Evaluation and Discussion of the Results of the Time Study Comparison of the 3-D Scanner, Vernier, and CMM

Table 27 summarises the time taken to collect data from the 3-D Scanner compared to the CMM and vernier. The results show that the 3-D scanner took longer to obtain results for the samples measured than the CMM and the vernier. Based on the cumulative average time to conduct the routine quality tests on the samples provided, the CMM took one-point seventy-six times longer than the CMM and nine-point zero-six times longer than the vernier to obtain the required results. Thus, the 3-D scanner was less efficient in obtaining the results than the CMM and vernier.

In retrospect, it was observed that the 3-D scanner and the CMM required only one scan or one measurement to obtain all the critical quality variables for each sample. In contrast, the vernier required measurements to be taken separately or manually for each variable. Even though the vernier required each variable to be measured individually for each sample, it was still the fastest or least time-consuming measuring device in obtaining the measurements needed for the routine quality control test.

Table 27: Comparison of time taken to collect data from the 3-D scanner, CMM and vernier

Comparison of Time Taken to Collect Data				
Samples (Optical)	CMM		Vernier	
	Is the 3-D Scanner faster at taking measurements than the CMM? (yes = ✓ and no = x)	How many times quicker or slower is the 3-D Scanner than the CMM at taking measurements?	Is the 3-D Scanner faster at taking measurements than the vernier? (yes = ✓ and no = x)	How many times quicker or slower is the 3-D Scanner than the vernier at taking measurements?
A1 (203,28)	x	1.11 slower	x	11.35 slower
A2 (128,82)	✓	0.70 quicker	x	7.17 slower
B1 (107,64)	x	1.68 slower	x	5.59 slower
B2 (138,78)	x	2.17 slower	x	7.20 slower
C1 (133,56)	x	2.10 slower	x	7.79 slower
C2 (138,30)	x	2.19 slower	x	8.06 slower
D1 (265,68)	x	2.52 slower	x	10.09 slower

D2 (346,80)	x	3.30 slower	x	13.15 slower
Average	x	1.76 slower	x	9.06 slower

Although the 3-D scanner was touted to be the quicker measurement device, it was the slowest of the three. The vernier calliper was a manual measurement device, the fastest and most accurate of the three. Therefore, the vernier calliper was the most reliable and effective measurement device.

The literature reviewed indicated that advances in optical metrology could deliver more accurate measurements and expedited quality control processes compared to conventional tactile measurements. This indicated the benefits of incorporating a 3-D scanner as a tool in routine quality control testing and provided the impetus for the experiment's anticipated success. Moreover, studies involving both the automotive and aerospace industries have successfully integrated optical metrology into their quality control procedures. With the advent of Industry 4.0, there has been a notable proliferation of optical metrology across diverse industrial sectors, as an increasing number of production processes are being reengineered to encompass in-process measurement and control. However, this was not the case for this study because the results show that the use of 3D scanning for injection moulded plastic products is limited.

4.4. Summary of the Chapter

Chapter Four presented the data and findings from the three measurement tools (vernier, CMM, and 3-D scanner) used to conduct the study. The data consisted of the measurements taken from each measuring instrument and a time study comparison of the three different measuring instruments. From the results presented, the 3-D scanner failed to capture all measurement points in some of the measured samples. These scanned images were, therefore, incomplete, and the results were inconclusive. The time study comparison showed that the vernier was the quickest measurement instrument, the CMM the second quickest, and the 3-D scanner was the slowest of all 3 measurement instruments.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Overview of Chapter Five

This final chapter summarises the conclusions reached from the study and offers recommendations for further research, all based on the findings from Chapter Four. The utilisation of optical metrology in plastic injection moulding was investigated in this research. In this study, an experimental and quantitative research design methodology was adopted. Three distinct measurement instruments (a vernier, CMM and a 3-D scanner) were used to get the data.

5.2 Conclusion

Chapter Five summarises how each of the objectives outlined in Chapter 1 has been addressed.

The first objective was to investigate and optimise optical metrology, such as a 3-D scanner, as an alternative tool for measurements in injection moulding.

Outcome: The 3-D laser scanner tested during the study showed that it was ineffective as a measuring device for quality control testing. It was unable to capture comprehensive images of the injection-moulded plastic products with critical measurements absent from the statistical reports generated by the 3-D scans of each sample.

The second objective was to determine the efficacy of a 3-D scanner as a quality check tool on injection moulded plastic products.

Outcome: The 3-D laser scanner was touted to be faster and more time-efficient than traditional routine quality control testing. However, compared to the contact measuring devices, the vernier, and the CMM, the 3-D scanner was less efficient and took much longer to measure the tested samples. The protracted scanning duration of the 3-D scanner can be attributed to its inability to capture the entire injection moulded plastic sample, necessitating multiple scans of each tested sample. This indicated that the 3-D scanner was inefficient as a quality tool for this material.

The third objective was to establish the benefits (if there were any) of using a 3-D scanner as a measuring tool over traditional contact metrological measuring equipment.

Outcome: According to the study, the use of 3-D scanners did not yield any significant benefits in comparison to contact measuring devices. The 3-D scanners produced incomplete results due to inadequate scans, and the process of scanning samples and obtaining relevant measurements for critical quality variables was more time-consuming. This was attributed to the 3-D scanner's inability to effectively scan products made from plastic material, stemming from the light-refractive properties of the injection-moulded plastic samples (Mitchell, 2003). It is possible that the 3-D scanner failed to measure the samples effectively due to the material composite of the samples. The samples are made of polymer polypropylene. According to Mitchell (2003), polypropylene has a refractive index of 1.47. The lower the refractive index, the faster light passes through the material. The 3-D scanners use light technology to capture their scans. From the above information, it can be postulated that light passing through the samples impeded a full scan of the samples from being captured by the 3-D scanner. Therefore, aspects such as product size, material composition and colour of the products must be considered when conducting these studies to determine if they affect the results achieved.

The study adds to the body of knowledge that 3-D scanners are currently ineffective or inadequate for routine quality control testing on selected injection-moulded plastic products. This point has not been driven adequately in the injection-moulding, optical metrology fraternity and literature and can significantly inform other researchers and industries that would anticipate using such a device. Further advancements and improvements in 3-D scanning technology, in the future, could have the potential to establish them as valuable measurement instruments for routine quality control testing.

5.3 RECOMMENDATIONS

Prior studies indicate that 3-D scanning technology is not confined to any specific industry; rather, it is recognised as a versatile tool with wide-ranging applications across the automotive, aerospace, and medical industries. Within the automotive and aerospace sectors, 3-D scanning is frequently utilised for dimensional measurements on metal surfaces and is increasingly gaining traction within the medical field for part inspection and measurement.

Notably, its versatility is evident in the medical industry where it plays a crucial role in the customization of wearable devices such as implants and braces. The continual advancements in speed and efficiency are driving the widespread adoption of this technology, positioning 3-D scanning as an indispensable tool across various industries.

With the advent of technology, various types of 3-D scanners have been developed by different manufacturers. The technology, software, and capabilities of 3-D scanners may differ between manufacturers. In this study, only 1 type of 3-D scanner was utilised (from 1 manufacturer). Therefore, it is recommended that further studies be required using multiple 3-D scanners from different manufacturers to determine if the type of 3-D scanner used may affect the results achieved.

Arising from these results, there is a need for developers to consider these constraints so that these scanners can be developed to save time and costs and are aligned with the changing industrial revolutions and technological paradigms.

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7. APPENDICES

7.1 GATEKEEPER'S LETTER



Polyoak Packaging (Pty) Ltd
Waterford Road, Diep River
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Cape Town, South Africa
Tel: +27 (021) 710-9200
Fax: +27 (021) 712-1342
info@polyoak.co.za
www.polyoakpackaging.co.za

22nd June 2021

To whom it may concern

Dear Sir / Madam

PUBLICATION OF THESIS

I confirm that Veradana Maharaj is an employee at Polyoak Packaging.

The results generated by her anticipated research study on optical metrology at the Durban University of Technology may be published as a Masters thesis.

Yours sincerely

Alan Caldwell
Regional Director

7.2 PLAGIARISM SUMMARY

Similarity Report

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Using Optical Metrology in Injection Moulding short one	-
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7.3 EDITOR'S CERTIFICATE

CERTIFICATE OF LANGUAGE EDITING

This is to certify that the paper titled:

Using Optical Metrology in Injection Moulding

study submitted in complete fulfilment for the degree: Master of Philosophy Management Sciences: Department of Quality in the Faculty of Management Sciences

By

VERADANA MAHARAJ

Student number: 20924674

Has been edited for language by PEACE OASIS INTERNATIONAL, Language Editor. Neither the research content nor the author's intentions were altered. The editor guarantees the quality of the English Language in this paper. The following issues were corrected: grammar, spelling, punctuation, sentence structure, and phrasing.

Date issued. 09 September 2024

Dr. K. Shonhiwa: Head

POII004
Certificate number



7.4 FREC ETHICS APPROVAL



MANAGEMENT SCIENCES: FACULTY RESEARCH ETHICS COMMITTEE (FREC)

5 October 2022
Student No: 20924674

Dear Ms V Maharaj

MASTER OF PHILOSOPHY: QUALITY MANAGEMENT

TITLE: Use of optical metrology to assess injection moulds at a selected plastic manufacturer

Please be advised that the FREC Committee has reviewed your proposal and the following decision was made: **Approved – Ethics Level 1**

Date of FRC Approval: 8 September 2021

Approval has been granted for a period of two years from the above FRC date, after which you are required to apply for safety monitoring and annual recertification. Please use the form located at the Faculty. This form must be submitted to the FREC at least 3 months before the ethics approval for the study expires.

Any adverse events [serious or minor] which occur in connection with this study and/or which may alter its ethical consideration must be reported to the FREC according to the FREC SOP's. Please note that ANY amendments in the approved proposal require the approval of the FREC as outlined in the FREC SOP's.

Yours sincerely

Dr G Murwirapachena
Chairperson: Faculty Research Ethics Committee