USING DRONES TO IMPROVE THE QUALITY CONTROL OF MASONRY IN AFFORDABLE HOUSING CONSTRUCTION

by

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DECLARATION

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ABSTRACT

The increasing housing backlog present in South Africa has resulted in the need for housing to be delivered with urgency. Attempting to deliver houses in a quantitative manner has led to quality being overlooked, although key role players have made it clear that there should be a shift towards qualitative delivery of housing. Research has found that quality concerns are recurring in affordable housing projects and therefore the need for improved quality control is evident. Motivated by the need to address these recurring problems, this study aims to investigate using a drone to improve the quality control on affordable housing projects, limited to the quality control of masonry works.

Two affordable housing projects in the Western Cape were investigated over a period of two years to assist with achieving the aim of this study. The study seeks to improve aspects of dimensional quality control by firstly identifying the quality concerns on these projects by using traditional defect identification methods. A total of 1 048 measurements were taken on High Density Double Story (HDDS) units and 336 on Stand Alone Single Story (SASS) units. These measurements are compared to the specified dimensional requirements to identify which measurements do not adhere to the defined standards. Valuable findings are obtained and summarized from the data obtained using the traditional method.

The study then investigates using a drone through 2D and 3D analysis to find a practical and effective manner through which dimensional aspects of quality control can be improved. Measurements taken from 2D images are compared to the actual measurements taken on site to determine the accuracy and effectiveness of using a drone in this manner. A 3D model of a housing unit is then developed through photogrammetry and accompanying software to assist with quality control through defect identification. The practicality and effectiveness of both methods are discussed by comparing them to the traditional method.

From these findings it was determined that neither method would be practical and instead site progress monitoring through use of a drone is suggested to improve the dimensional aspects of quality control. A framework is then put forward as a recommendation to implement a drone on an affordable housing project.

OPSOMMING

Die toenemende tekort aan behuising in Suid-Afrika, lei daartoe dat behuising dringend gelewer moet word. Die poging om huise op 'n kwantitatiewe wyse te lewer het tot gevolg gehad dat kwaliteit oorgesien word alhoewel sleutelrolspelers dit duidelik gemaak het dat daar ‘n verskuiwing na kwalitatiewe lewering van behuising moet plaasvind. Navorsing het gevind dat kwaliteitsprobleme in bekostigbare behuisingsprojekte herhaal word en daarom is die behoefte aan ʼn verbeterde manier van gehaltebeheer duidelik. Gemotiveer deur die behoefte om hierdie herhalende probleme aan te spreek, ondersoek hierdie studie die gebruik van 'n hommeltuig om die kwaliteitsbeheer op bekostigbare behuisingsprojekte te verbeter, beperk tot die kwaliteitsbeheer van messelwerk.

Twee bekostigbare behuisingsprojekte in die Wes-Kaap is oor 'n tydperk van twee jaar ondersoek om die doel van hierdie studie te bereik. Die studie poog om kwaliteitsbeheer te verbeter deur eerstens die kwaliteitstekorte in hierdie projekte te identifiseer deur tradisionele identifikasiemetodes te gebruik. Altesaam 1 048 metings is geneem op hoëdigtheid, dubbelverdieping (afgekort as HDDS in hierdie studie) eenhede en 336 op alleenstaande enkelverdieping (SASS) eenhede. Dié word dan vergelyk met die projekspesifikasies om die metings te identifiseer wat nie aan die standaarde voldoen nie. Waardevolle uitkomstes word verkry en opgesom uit die data wat met die tradisionele metode geïdentifiseer is.

Die studie ondersoek dan die gebruik van 'n hommeltuig deur 2D- en 3D- analise om 'n praktiese en effektiewe manier te vind waardeur kwaliteitsbeheer verbeter kan word. Metings wat van 2D-beelde geneem word, word vergelyk met die werklike metings wat op die terrein geneem is om die akkuraatheid en doeltreffendheid van die gebruik van 'n hommeltuig op hierdie manier te bepaal. 'n 3D-model van 'n behuisingseenheid word ook ontwikkel deur fotogrammetrie en gepaardgaande sagteware om te help met kwaliteitbeheer deur defekidentifikasie. Die praktiese uitvoering en doeltreffendheid van beide metodes word dan bespreek deur dit met die tradisionele metode te vergelyk.

Uit hierdie bevindinge word daar vasgestel dat nie een van die metodes prakties sou wees nie, en daar word voorgestel dat kwaliteit eerder beheer moet word deur monitering van terreinvordering deur die gebruik van 'n hommeltuig. 'n Raamwerk word voorgestel as 'n aanbeveling vir die gebruik van ʼn hommeltuig op 'n bekostigbare behuisingsprojek.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

2D	2 Dimensional
3D	3 Dimensional
ASQ	American Society for Quality
BIM	Building Information Models
CAD	Computer Aided Design
CSIR	Council for Scientific and Industrial Research
DESC	Department Ethics Screening Committee
ECSA	Engineering Council of South Africa
GCC	General Conditions of Contract
HDDS	High Density Double Story
IDT	Independent Development Trust
LiDAR	Light Detection And Ranging
NBR	National Building Regulations
NCR	Non-Conformance Report
NHBRC	National Home Builders Registration Council
NHC	National Housing Code
NHF	National Housing Forum
PMBOK	Project Management Body of Knowledge
QA	Quality Assurance
QC	Quality Control
QP	Quality Plan
QMS	Quality Management System
SANS	South African National Standards
SASS	Stand-Alone Single Story
SBER	Social, Behavioural and Education Research
SCADA	Supervisory Control And Data Acquisition
SMMEs	Small Micro and Medium Enterprises
VLOS	Visual Line of Sight
VM	Visual Management

CHAPTER 1: INTRODUCTION

1.1. Chapter Overview

This chapter introduces the reader to the primary focus of the research, which is investigating the use of drones on affordable housing projects to assist with recurring quality problems. The chapter provides a background on the housing shortage in South Africa and the quality issues which are present on projects that were completed in an attempt to address the housing issue. This presents the reader with a motivation for the need for improved quality control through use of modern technologies such as drones. The aim of the study is described with the accompanying objectives which should be met to achieve this aim. The scope of the study is then defined before a describing how the study will be completed within this scope.

1.2. Background

In an effort to remedy South Africa's eminent housing shortage as the country transitioned from the Apartheid era into democracy, the National Housing Forum (NHF) was established together with South Africa's new affordable housing policy. The aim of the NHF's policy at that time was to put forward a vision and a goal for the delivery of affordable houses in South Africa to eradicate the housing backlog resulting from the Apartheid era.

In 1994, the NHF constructed a framework for the new "housing subsidy scheme" with a target deliverable of 350 000 affordable housing units per annum, aiming to fulfil the goal of eradicating the housing backlog; which was estimated to be around 1.5 million units at that time (Tomlinson, 2015). From the establishment of the scheme in 1994, more than 3 million housing units were delivered by the end of 2015 (Chakwizira, 2019). The housing backlog was re-evaluated in 2015 and reported a continual growth in housing shortage, far surpassing the initial count when the scheme was established in 1994. In spite of the 3 million units already delivered, the net housing backlog increased to 2.1 million units outstanding (Tomlinson, 2015; Chakwizira, 2019).

During the formulation of the initial housing policy, the NHF focused on delivering as many housing units as possible, rather than providing houses that were of a superior standard (Jeffery et al., 2015). The 'quantitative delivery of housing' approach seemed to be of good judgement at the time, as it was thought to be the most effective way to eliminate the housing backlog post-haste and provide a large number of beneficiaries with a serviced site and rudimentary structure to which they had a secure tenure.

However, by focusing mainly on quantitative delivery of housing, beneficiaries of the earliest rudimentary units quickly raised concerns about qualitative shortcomings (Tomlinson, 2015).

Consequentially, beneficiaries and their communities began placing pressure on the Government to provide housing that was sufficient with respect to size, location and quality. Backed by the communities, politicians moved to reject the NHF's initial policy and demanded an increase in subsidy grants in order to provide formal housing of higher standards. Owing to the persistent pressure placed on the Government, the original subsidy amount of R12 500 per unit has since increased to R168 853 (Department of Human Settlements, 2021); presenting an overall increase of 1350% over a span of 26 years. In addition to the increased subsidy amount, the housing policy was revised, to shift its focus from quantitative delivery to qualitative delivery. To this end, the new Comprehensive Plan, shifting the objective from quantitative delivery only, to a more sustainable quality orientated delivery, was approved by Cabinet on 1 September 2004 (Department of Human Settlements, 2009).

Following the implementation of the new comprehensive plan in 2004, a study conducted at Nyandeni Local Municipality reported that 85% of affordable-housing occupants maintained negative perceptions regarding the quality of their houses (Madzizela, 2008). Similarly, 74% of occupants in Pelindaba, Bloemfontein were displeased with the quality of their low-income houses (Mehlomakhulu *et. al*, 2010). It seemed that these incidents were not isolated, and the general consensus regarding low-cost housing in South Africa was that a large number of units were not conforming to general quality standards put forward by the National Home Builders Registration Council (NHBRC) (Madzizela, 2008; Mehlomakhulu and Marais, 2010; Chakwizira, 2019; Wium and Declerq, 2021). Naturally, tenants and politicians placed further emphasis on the need for a new quality improvement strategy to aid in the identification and resolution of quality concerns currently arising in affordable housing units (Minas, 2016).

Increasing qualitative delivery remains the main focus of the recent corrective action, however, a trade-off is required as South Africa's continual increase in housing backlog maintains the need for the quantitative delivery of houses. The goal is thus to bring forth an innovate solution whereby quality within affordable housing projects can be improved without delaying progress or introducing further costs. In an effort to promote both qualitative and quantitative delivery of housing units, an appropriate Quality Control (QC) method should be implemented as the foundation on which an innovative solution is developed, allowing for continuous monitoring and improvements throughout the project lifetime. Implementation of an appropriate QC method will ultimately ensure conformance to the customers' expectations, while allowing reasonable production targets to be met (Kutta and Nyaaga, 2014: 610).

Poor building quality caused by production targets and time constrained projects is a worldwide occurrence and not limited to South Africa and its affordable housing policy. The need for a practical solution to address the broader extent of quality limitations related to low-income housing projects is clear (Aigbavboa & Oke, 2019: 150). While this study will specifically investigate and address the quality limitations within the context of affordable housing in South Africa, the investigation and outcomes could provide valuable insight to affordable housing projects internationally.

Over the past few years, technological advances have increased the opportunities available to improve quality in construction. The solution to improving quality within the context of affordable housing projects could lie in taking advantage of modern technology not previously accessible to project stakeholders. By adapting modern technologies within the construction industry, current quality management can be improved in a multitude of ways, specifically by assisting with the development of a more effective QC framework that will allow project stakeholders to manage the risk of sub-standard quality issues, while effectively and continuously monitoring construction progress and completing required checks without disrupting production (Kutta et al, 2014: 610).

This study investigates if modern technology, specifically the use of drones and drone imaging, can be implemented in the construction of affordable housing units in a manner that will increase the efficiency of quality inspection of certain aspects of the construction process. Thereby, improving the overall quality, reducing the need for extensive supervision and decreasing the risk of extensive rework and the possibility of budget overruns.

1.3. Aim and Objectives

The study aims to determine how a drone can be used to improve quality control on affordable housing projects. Although the term “quality” can refer to a broad range of aspects, this thesis only focusses on the dimensional tolerances of masonry work, and aims to improve this aspect of quality in affordable housing.

In order to achieve the aim of this study, the following objectives must be met:

- Identify dimensional quality concerns in affordable housing projects.
- Employ the systems development cycle to assist with the development process of implementing a technological approach to current quality control methods.
- Develop and present a framework which integrates the use of drones and other quality control methods to identify dimensional quality defects, increase quality monitoring, assurance and control, decrease project schedule- and cost overruns and increase stakeholder satisfaction.

1.4. Scope

The scope of this study is limited to the construction of affordable housing in South Africa and focuses on improving the dimensional aspect of masonry within this sector. Quality issues are limited only to those that can be practically addressed by means of drone imaging. To this end, this study focusses on developing a method that will monitor and improve the dimensional quality, but also be more effective than traditional quality control methods with respect to cost and time.

The housing projects investigated in this study are based in the Western Cape and are limited to two projects for the Department of Human Settlements. Both of these projects implement the Preferential Procurement Policy Framework Act 5 Of 2000, and aim to empower emerging contractors or Small Medium and Micro Enterprises (SMMEs) by subcontracting a minimum of 30% of the value of the contract to SMMEs and the other individuals covered by the Act.

The study focusses on stand-alone single story (SASS) units and High Density Double Story (HDDS) units which have been built according to minimum specifications as set out in the National Housing Code (NHC) of 2009, the South African Bureau of Standards (SABS) and the South African National Standards (SANS).

Only the General Conditions of Contract (GCC) will be considered in this study as both projects investigated made use of this contract.

1.5. Approach

The study commences by reviewing literature applicable to the study. The literature review provides information to assist in understanding the origin and extent of the problem and subsequently developing a solution to address the problem. The literature review focuses on the history of affordable housing in South Africa, the current quality standards in low cost housing projects, parties responsible for quality assurance, current methods used for quality control, common reasons for quality shortcomings and emerging technologies in construction.

Subsequently, two affordable housing projects are identified as case studies. The affordable housing projects are required to be in the appropriate construction phase in order to collect useful data. The case studies form the basis of this study and provide the required measurement data to determine the outcome of quality improvement by means of drone technology.

In order to collect useful data from the identified projects, a data collection strategy is developed to ensure the collection of complete, comparable datasets for use in the selected data analysis method. Concurrent to development of the data collection strategy, various data analysis methods are investigated for their appropriate application to achieve the defined outcomes. The principal data is collected in the form of traditional on-site quality measurements, as well as, drone imaging to ultimately generate these measurements. The collected data is analysed by means of the pre-defined data processing software and appropriate models are generated.

In order to identify and conclude on the quality management improvements that result from drone technology, an iterative process is followed to determine how a drone can be used to improve aspects of dimensional quality on an affordable housing project. Various methods such as two-dimensional (2D) and three-dimensional (3D), or photogrammetric, methods are explored with the end goal of finding a practical method through which drones can be integrated into current quality control methods to improve quality. To this end, the limitations associated with integration of drone technology are also identified and discussed.

After establishing how drone technology could assist with quality control, the study continues to develop a framework which can integrate modern technology into project processes to improve the quality of affordable housing.

Finally, the practicality and effectiveness of the proposed drone implementation method is evaluated. The use of drone technology during the construction phase is reviewed and a conclusion is drawn on whether the use of drone technology contributes towards improving quality control on an affordable housing project.

1.6. Document Structure

This study consists of six chapters structured as follows:

Chapter 1: Introduction - the introductory chapter comprises the research background, aims and objectives, scope, approach and document structure.

Chapter 2: Literature review - the literature study section discusses the history of affordable housing in South Africa, quality management in construction, standards and specifications used on affordable housing projects, parties responsible for quality on affordable housing projects, aspects influencing quality on these projects, modern/emerging technologies in construction and the systems development cycle.

Chapter 3: Methodology - the research methodology is based on the systems development cycle and describes the two of the phases followed to complete the study namely, the conception-, the definition-, the execution- and the operation phase.

Chapter 4: Execution phase – this chapter elaborates on the execution phase by describing how applicable housing projects were identified. It provides a description of the projects used for this study. The data collection strategy and data processing methods are then discussed.

Chapter 5: Results and Discussions – the findings from the collected data is discussed in this chapter by presenting the data in the form of tables and charts.

Chapter 6: Framework to Improve Quality Control through drone technology – this chapter presents a framework as a recommendation which describes how drone technology can be integrated with a Quality Manager to increase the Quality Control on an affordable housing project

Chapter 7: Conclusion – the final chapter concludes the thesis by summarizing the findings and determining whether the aims and objectives of the study were met.

CHAPTER 2: LITERATURE REVIEW

2.1. Chapter Overview

In this Chapter the history of affordable housing in South Africa is reviewed, from the origin of inadequate housing which was led by the discovery of diamonds and the progression to current state of affairs. Thereafter, Quality Management Systems (QMS) are briefly explained by making reference to Quality Planning, Quality Assurance and Quality Control. The standards and specifications being used for dimensional tolerances in affordable housing projects are reviewed, before considering which parties are responsible for quality within affordable housing projects by comparing literature findings to clauses in the General Conditions of Contract (GCC). Once general quality management has been discussed, the aspects influencing dimensional quality in affordable housing are addresses and an overview of modern/emerging quality control methods in the construction industry is also presented. The discussion on the uses of drones is limited to areas where dimensional quality can be assessed as this is what is applicable to this study. Other uses of drones within the construction industry are however also mentioned later in the chapter.

The Chapter is concluded by describing the four-phase systems development model which encompasses the total developmental life cycle of all human-made systems as the solution to addressing current quality control limitations within the affordable housing industry.

2.2. History of Affordable Housing in South Africa

2.2.1. Industrialization

Industrialisation in South Africa was set in motion in 1867 following the discovery of diamonds in the soil of dried out river beds (Tappan, 1914). As the mining industry in South Africa started to boom, so did the need for labour. Approximately 50 000 African men migrated from rural backgrounds to work for the industry during 1871 to 1875 (Tappan, 1914). During this period, white claimholders started to group together against Asian and black claimholders and by the end of the 1880s a worldwide monopoly had been established by white claimholders. Among the monopoly Cecil John Rhodes, as the prime minister of the Cape Colony in 1890, implemented the Glen Grey Act of 1894. Summarised, the act imposed taxes on adult men with the idea of reshaping gender and social roles for African men and women closer to British colonial roles (Redding, 1993). This pushed more African men towards leaving their homes to become wage labourers working in rural areas (Redding, 1993).

In order to provide housing for the increasing labour force, the mining companies introduced compounds. These barrack-type accommodations could provide housing for around 20 000 labourers (Turrel, 1984). Housing compounds were initially classified as open compounds, allowing free travel through the gates of the compounds. However, this increased the possibility of diamond theft and, as such, a closed compound labour housing plan developed by De Beers was adopted throughout mining centres in South Africa. This meant that labourers were not allowed to move freely through the gates of the compounds anymore and had to carry identification at all times stating their name and contract conditions (Turrel, 1984).

Industrialisation and associated increased labour need during 1904 to 1920 encouraged labourers to migrate to larger cities. This resulted in the introduction of the Urban Areas Act, which made it compulsory for natives to carry identification at all times and contained African settlements in rural areas through regulations such as influx control. Housing for the labourers became the responsibility of local authorities, who experimented with various housing models such as townships and satellite suburbs. However, insufficient housing was provided for the expanding mass of urban residents and by the 1980s the housing problem had become an extreme crisis (Tomlinson, 1999). Townships became overcrowded, resulting in the emergence of informal settlements which were not regulated by the local authorities.

2.2.2. Political progression to democracy

The mid 1980s saw the collapse of apartheid era ideologies, opening the door for the first government funded urbanisation programme aiming to address the increasing unregulated informal settlements. The programme, the Independent Development Trust (IDT), was established in 1990 and intended to service 100 000 sites with a subsidy of R7 500 (Tomlinson, 1999).

The income-based capital subsidy was introduced shortly thereafter (1994) by the NHF. This was introduced as a formulated housing policy whereby subsidies could be fairly distributed according to household earnings. Households earning less than R3 500 per month would receive subsidies as a once-off payment, and households earning less than R1 500 per month would receive the largest subsidies Tomlinson, 1999). The idea of this initial policy was not to guarantee a complete family dwelling, but was rather seen as an incremental housing approach which could provide beneficiaries with a foundation for improving their housing through future subsidies (Jarbandhan, Viljoen, de Beer, Blaauw, 2016). Therefore, the focus of the initial housing policy was placed on quantitative delivery of housing, rather than qualitative (Tomlinson, 2007). Consequently, more than 3 million fully subsidised housing units were provided over the past 20 years (IRR 2016).

2.2.3. Affordable housing challenges

As mentioned, the housing backlog was estimated to be around 2.4 million units at the end of 2015, proving to be a major challenge for the South African Government to address (Chakwizira, 2019). Notwithstanding statements that some beneficiaries have been on the waiting list for longer than 10 years, reports also found that beneficiaries often reject houses as a result of quality not meeting requirements (Windapo and Goulding, 2013). This was substantiated by Jay and Bowen (2011), who found that beneficiaries of these units regularly reported significant dissatisfaction in the delivered product.

A general consensus developed regarding the lack of quality within housing units being delivered, and studies found that incidents were not isolated (2008; Mehlomakhulu et al., 2010; Chakwizira, 2019; Wium et al., 2021). Apart from physical safety concerns arising from sub-standard housing, it was found that low quality within housing is linked directly to the mental well-being of inhabitants (Connoly, Dermot & Rosato, 2010).

2.2.4. Current quality improvement initiatives

The Government attempted to address the quality concerns by developing The Comprehensive Plan for the Creation of Sustainable Human Settlements, which was approved by Cabinet on 1 September 2004. This plan also known as the Breaking New Ground (BNG) plan, advocates for the enhancement of the National Norms and Standards for housing products to be delivered through the National Housing Programme. It expresses the need to deliver sustainable housing through increased quality insurance, rather than focussing solely on the quantitative delivery of housing (Department of Human Settlements, 2009). In addition, the Minister of Housing introduced revised National Norms and Standards with full effect from 1 April 2007 to attempt to improve the standard of quality within affordable housing (Department of Human Settlements, 2009).

Nevertheless, a study subsequently conducted by Manomano and Tanga (2018) reported that more than 90% of beneficiaries still had negative perceptions of various quality components in their housing units as presented in Table 1:

Table 1. Quality Perceptions of Beneficiaries of Affordable Housing Units (Adapted from: Manomano)

Quality component	Poor quality	Fair quality
Windows	91.2%	8.8%
Roofs	91.2%	8.8%
Doors	93.6%	6.4%
Walls	93.6%	6.4%

Quality component	Poor quality	Fair quality
Floors	93.6%	6.4%

Findings from various other sources also found that there are still a large number of units not conforming to general quality standards put forward by the National Home Builders Registration Council (NHBRC) (Mehlomakhulu et al., 2010; Chakwizira, 2019; Wium et al., 2021).

2.3. Quality Management in Construction

2.3.1. Quality Management Systems (QMS)

2.3.1.1. Overview

A Quality Management System (QMS) is described as a continual process of improvements encompassing all aspects of the business with the wider aim of identifying and preventing mistakes as proactively as possible. A QMS is successful if it can manage the outcomes of a process and achieve maximum customer satisfaction, while regulating the overall cost and continuously improving the process (American Society for Quality (ASQ), 2019).

The concept of QMS was originally developed on assembly line productions, with identical products being manufactured repeatedly. Quality for these processes was reflected in the end product and to assure repeated quality, a proposed QMS was applied throughout each different phase of the manufacturing process (Islam, Islam & Gupta, 2017). To aid in the application of QMS within this context, international standards were developed by the International Organization for Standardization (ISO) (International Organization for Standardization, 2015). These general standards can be adapted to align with the focus of each company and ultimately demonstrate the intent of the company to achieve the highest level of quality while continuously improving the actions and processes through well-defined strategies aimed to achieve specific goals.

Quality relates to the reasonable, pre-defined standard to which certain aspects are delivered in the project. Often, the exact expectations are not clear or can develop over the execution phase of the project. If quality is not clearly defined initially it could develop to encompass greater deliverables over time, which could adversely affect the project cost and schedule.

Project quality management generally focuses on three main aspects: (1) Quality Planning, (2) Quality Assurance (QA), and (3) Quality Control (QC) (Mane and Patil, 2015). Planning quality management requires identifying quality requirements and establishing the standards of the project deliverables, i.e., planning process. To perform quality assurance, the quality requirements and quality control results are continually audited to ensure the use of appropriate quality standards throughout, i.e., executing process. Finally, quality control is responsible for monitoring and recording of useful quality activities and parameters that assess the performance and introduces recommended changes, i.e., monitoring and control process.

2.3.1.2. Implementation in Construction

Implementing a QMS requires additional resources, however, the benefits outweigh the associated cost and time associated with implementing the QMS. To support of this argument, Chung (1999) conducted a study comparing seven building projects of different sizes and reported that the costs associated with implementation of a QMS across these different building projects was significantly less than the received savings. A study done by Roberts (1991) reported that the implementation costs associated with a proactive QMS, resulted in about 1% of the project value, reducing the expenditure associated with the repair, rework and rejections significantly from what was previously reported at 10% of the project value, to 2% of the project value. Figure 1 depicts a visual comparison between a project without a QMS, and the same project with a QMS:

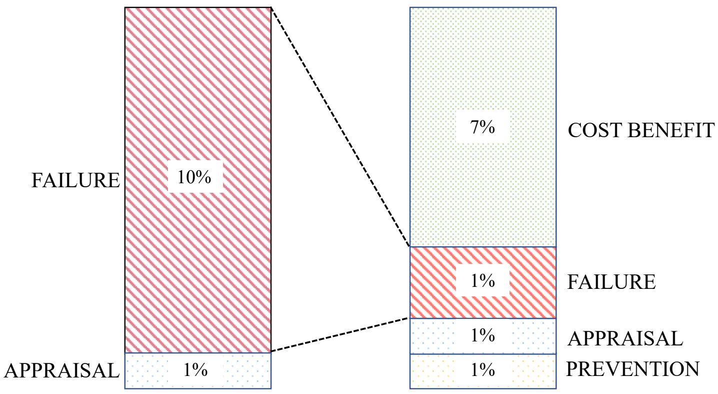


Figure 1: Cost and failure rate associated with implementing a QMS (Adapted from Roberts, 1999).

Additionally, the use of a certified QMS can be used as marketing tool for companies in the construction industry. In the context of construction, a well-established QMS incorporates third party certification as a means to solidify commitment to quality (Chung, 1999).

2.3.2. Quality Planning (QP)

2.3.2.1. Overview

The concept of quality planning encompasses a systematic process where quality policies are interpreted into measurable objectives and requirements (Rumane, 2013 & Nyakala, Romoroka & Ramdass, 2021). According to ASQ, a QP encompasses a specific document, or a number of documents, that collectively specify the agreed-upon standards and practices, resources, relevant specifications, and the sequential nature of any activities relating to the relevant project, product or service, or contract. The usefulness of quality planning lies in assurance to conform to the expectations of the customer, to facilitate traceability of quality, and to classify gaps that can be filled within the quality team (Kutta and Nyaaga, 2014).

2.3.2.2. Implementation in Construction

In the context of construction, clear objectives must be defined and stipulated with supporting documentation providing specific standards and operating procedures. Both Contractors, and project managers, are responsible for the aforementioned documentation, and must ensure that all employees adhere to, and follow, stipulated standards and operating procedures during the construction process (Jumah, Faithy, Rami & Jamal, 2015). This documentation forms the general Quality Plan (QP).

QP within construction projects is critical in stipulating policies and procedures, relevant internal guidelines and appropriate practices, quality standards and practices, and the general structure and resources relating to the relevant activities of a specific job (Yalengama, Chileshe & Ma, 2016; Zhang, 2000). Furthermore, this documentation will promote authority, ensure responsibility and allocate resources in the different phases of the project (Jumah, Faithy, Rami & Jamal, 2015).

2.3.3. Quality Assurance (QA)

2.3.3.1. Overview

As the second component of quality management, Quality Assurance (QA) increases confidence that the quality requirements as set out in the QP, will be met. QA can be viewed as the activity of providing evidence that requirements will be met. Alternatively, QA can be seen analogous to the concept of a financial audit, whereby financial integrity is assured through an independent audit, that the accounting plan will result in (1) the correct reflection of the financial position of the company if followed correctly, (2) ascertain that the plan is being followed at that time (Frank M. Gryna, 2001). Therefore, QA can be defined as the activity of increasing confidence, through evidence based methods, that effective quality-related activities will be performed as stipulated in the QP.

The demand for QA within the construction industry is increasing as stakeholders want to be assured, prior to commencement, that quality will be maintained throughout the project and carried through to delivery of the end-product (Landin, 2001).

2.3.3.2. Quality assurance in construction

The application of quality assurance within the construction of affordable housing is important as its absence can easily lead to project failure under the already present budget- and time constraints. In addition, dissatisfaction from end users can negatively impact the Client as delivery of poor quality housing could cause loss of confidence from the public, in turn, negatively impacting both the Employers Agent and the Contractor, as they will lose stakeholder satisfaction.

Non-conformance to quality can negatively impact the Contractor further by increasing the amount of rework, which will directly influence the amount of cost- and schedule overruns (Zunguzane, Smallwood et al. and Emuze, 2012). To this end, assurance of quality within the context of affordable housing projects will have a dual purpose of improving the social-economic condition of communities, as well as support quality conformance to the stipulated standards as defined in the QP (Nyakala, Romoroka & Ramdass, 2021).

2.3.4. Quality Control (QC)

2.3.4.1. Overview

The final component of quality management, the component that relates the closest to the product level, is effective Quality Control (QC). QC involves the practical implementation of QA (Arditi and Gunaydin, 1997). QC is predominantly enforced through real-time onsite QC methods. While the application of these methods is essential to reduce project schedule- and cost overruns, it has been found that real-time methods currently followed are time-consuming and ineffective (Wang et al., 2015). To limit variations in quality and avoid mistakes such that the waste amount is reduced to zero, QC needs to be executed efficiently (Arditi and Gunaydin, 1997).

The Project Management Body of Knowledge (PMBOK) refers to QC as a process of continual monitoring and recording of quality activity outcomes to evaluate performance and provide necessary recommendations for changes. Through quality control, the focus is placed on the project results and ensures their compliance with the relevant defined project standards, further reducing the risk of unsatisfactory performance. Potential problems are identified and prevented before they can impact the process by following the QC process effectively.

2.3.4.2. Implementation in Construction

According to Salvi (2021) the QC process in the context of construction projects should include training of labour and managers, continuous knowledgeable supervision, revision of all completed activities at regular intervals for accuracy and completeness and adequate documentation of all decisions, assumptions, and recommendations. Implementation of QC means that the project should meet the desired specifications and standards and ensure the satisfaction of end users and clients.

Salvi (2021) states that quality does not merely happen by chance and that it needs to managed at every stage of the project. If management effectively implements QC within a project, it should filter down to all other levels of the project organogram and result in efficient and continuous quality control throughout the project life cycle.

2.4. Standards and specifications of affordable housing projects

2.4.1. Overview

Ensuring quality conformance within the affordable housing sector can be done in various ways, some focus on prescriptive dictates, while others merely provide a broad parameter for guidance (Norms and Standards for Social Housing, 2019).

Without some instance of the quality conformance guidelines, there will always be a possibility of relativity and room for dispute regarding conformance. Requirements that are stipulated clearly, will leave no opportunity for varied interpretations of requirements (Smallwood and Haupt, 2005). Aigbavboa and Oke (2019) state that a large portion of defects found within new houses are caused by non-conformance to the building code or other existing rules and regulations.

As this study focuses on improving masonry within affordable housing by means of drone imaging, only the standards and specifications for blockwork and walls will be reviewed, since drone imaging cannot assess the structural integrity of materials used. As such, to determine whether use of drone imaging is successful, it is necessary to establish the prescriptive and general guidelines used for affordable housing, focusing mainly on physical dimensions and physical construction errors, not on compliance of quality of materials used.

2.4.2. Mechanisms used to measure conformance

The mechanisms discussed below can be used to measure conformance: (1) Design guidelines, (2) Norms and Standards, (3) Technical specifications, and (4) Statutory compliance (Norms and Standards for Social Housing, 2019:9).

2.4.2.1. Design guidelines

Design guidelines identify the broader qualitative parameters that are required to design developments and are inter-related to the norms and standards. The following list provides the general design guidelines commonly utilized for masonry works within affordable housing projects:

- The National Home Builders' Registration Council's (NHBRC) Home Building Manual (1999)
- SANS 10400-K: The Application of The National Building Regulations Part K: Walls
- SANS 10249 2012: Masonry Walling
- SANS 2001-CM1 2012: Construction Works Part CM1: Masonry Walling.
- Council for Scientific and Industrial Research (CSIR) Guidelines for Human Settlement Planning and Design (2000)

2.4.2.2. Norms and standards

Norms and standards can be referred to as any document or collection of documents that specify and pre-define a common set of criteria, methods and/or procedures to be followed or used to achieve the relevant compliance benchmark. The main norms and standards for affordable housing projects are adapted from The National Housing Code (NHC) (Department of Human Settlements, 2009) and the National Home Builders Registration Council (NHBRC) Home Building Manual (NHBRC, 1999).

National Housing Code (NHC)

According to the Housing Act of 1997, the National Norms and Standards for housing developments are determined by the Minister of Housing. These Norms and Standards were subsequently improved in the NHC of 2009. (Department of Human Settlements, 2009).

The improved NHC of 2009 supersedes all prior documentation regarding policy principles, guidelines and norms and standards which apply to Government's housing programmes introduced since 1994. Instead of being prescriptive, the NHC merely aims to provide clear guidelines whereby the implementation of housing projects can be simplified (Norms and Standards for Social Housing, 2019). The General Principle of the Housing Code is stated in Clause 2.1.3. of the code, as per the Department of Human Settlements (2009):

> "*Any specification or definition of norms and standards for affordable housing should ideally be performance based. This encourages innovation by allowing a variety of building systems, materials or techniques to be combined to meet the set performance requirements. While there are many technologies that can be used to produce a house that will meet a performance*

specification, it is essential that the resulting structure is acceptable to the community members who are the potential buyers of the housing products."

Appearance is often used as the framework to measure quality in affordable houses, therefore there needs to be a way to determine what is defined as adequate with respect to quality. The Clause above and Chung (1999, 4) state that a building can be regarded as conforming to quality requirements if it will function as intended for its design life, nothing more, nothing less.

NHBRC Home Building Manual

The NHBRC was established with the objective of regulating the building industry to provide consumer protection and, according to the Housing Consumers Protections Measures Act of 1998, all houses constructed through the application of the housing subsidy amount must be enrolled with the NHBRC (Department of Human Settlements, 2009). Therefore, all houses constructed in affordable housing projects are subject to the Norms and Standards put forward in the NHBRC Home Building Manual.

2.4.2.3. Technical specifications

Technical specifications are defined as a range of standards typically used for materials of construction, the quality of workmanship, the methodologies and quality tests to be performed. The main aim of referring to technical specifications and the application thereof, is to achieve compliance with the defined core standards.

According to the defined design guidelines all required building tolerance for affordable housing projects investigated are Grade II as per SANS 10155: 1980 (2000). The allowable Permissible Deviations (PD) for this Grade are defined in Appendix A.

2.4.2.4. Statutory compliance

Statutory compliance means complying to the predefined rules and regulations. Therefore, statutory compliance within the affordable housing sector is made up of a series of documentation and is achieved by adhering to the previously mentioned design guidelines, norms and standards and specifications (see Figure 2).

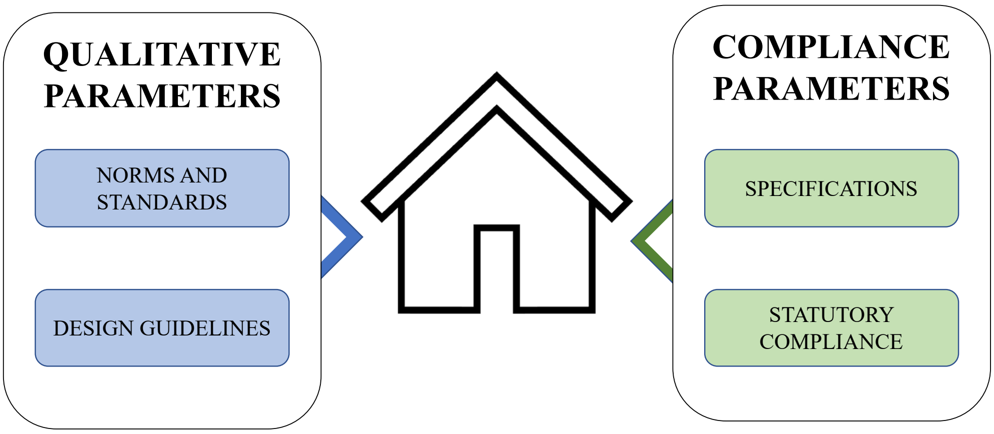


Figure 2. Qualitative and Compliance Parameters (Adapted from: Norms and Standards for Social Housing, 2019).

2.5. Parties Responsible for Quality on Affordable Housing Projects

2.5.1. Overview

Meeting the design guidelines, Norms and Standards and technical specifications described in the previous section becomes the responsibility of parties involved in the construction process. If quality chains become too long, they become limiting. When problems arise, long quality chains can complicate the process of determining causes and responsibilities of each of the parties involved (Dubas and Paslawaski, 2018).Therefore, it is necessary to clarify to which extent certain parties are responsible for certain aspects of quality to mitigate the risk of blame shift. Clearly defining which parties are responsible for which aspects can change blame shifting to accountability.

There are generally three parties involved in the quality chain: (1) the Contractor, (2) the Employer, and (3) the Employer's Agent. The responsibilities of the aforementioned parties will be discussed below by discussing what was found in literature as well as the clauses set out in the General Conditions of Contract (GCC) (2015).

2.5.2. The Contractor

The Contractor has been named in the Contract Data as the party whose offer has been accepted to complete the Works set out in the Contract's Scope of Works (GCC, 2015). Once the Contractor signs the Acceptance Letter they agree to complete the Works for the Contract Sum set out in their Form of Offer as broken down in their submitted Bill of Quantities.

2.5.2.1. Literature findings

Sources state that the Contractor must be kept accountable for providing all specified documents indicating which operating procedures and construction processes are to be followed by all employees (Jumah, Faithy, Rami & Jamal, 2015).

Through these procedures and processes the Contractor should create authority and take responsibility for all aspects relating to quality in all the different phases of the project (Jumah, Faithy, Rami & Jamal, 2015). (Nyakala, Romoroka & Ramdass, 2021). Different initiatives that could be taken to minimise non-conformance to quality of low-income housing in South Africa include evaluating the contractors' knowledge of the National Building Regulations before contract award (Aigbavboa et al., 2019: 3; Zunguzane et al., 2012).

Chung (1999) argues that it is sometimes impossible for inspectors to pick up on all quality defects, and states that supervision by the Contractor's staff is the key to quality. This is substantiated by findings that problems related to quality often arise as a result of deliberate non-compliance to specifications by the Contractor (Shittu et al 2013). Salvi (2021) argues that the Contractor should take full responsibility of QC as the majority of works are done by this party, and he says that the Contractor should be responsible to the designer and the owner.

Acknowledgement has been made that perception of quality from the perspective of the Contractor varies as the Contractor has to carefully balance quality and cost associated therewith (Standing, 2001). In some instances the Contractor insists that the quality of the finished product is not simply profit motivated, but is rather a value indicator of their involvement (Kelly, Morledge and Wilkonson, 2002).

2.5.2.2. General Conditions of Contract

Clauses from General Conditions of Contract (2015) which are applicable to the Contractor have been listed in Appendix E. In summary, the Contractor is mainly responsible for ensuring that they have a deep understanding of all the standards, specifications and guidelines applicable to the project while they are carrying out the works. The Contractor must either be certain of what is expected of them to meet the defined quality standards, or request for additional information regarding this if unclear.

The Contractor then has a direct responsibility to ensure that the Works are completed according to these standards and specifications. According to the Contract, they are responsible for providing sufficient and adequate supervision which is capable of implementing defined quality standards and specifications (GCC, 2015).

The Contractor is also held responsible for any Works that has been covered up without inspection (such as blockwork which has been covered by plaster). According to the Contract, the Contractor has to allow the Employer's Agent or their Representative to inspect all such Works, and are responsible for requesting inspection from these parties (GCC, 2015).

The Contractor is held accountable for remedying all quality defects which may occur as a result of negligence of any of the aforementioned, as well as purposeful negligence of the defined quality standards and specifications (GCC, 2015).

2.5.3. The Employer

The Employer is the person for whom the Works are to be carried out (GCC, 2015). The Western Cape Government and Department of Human Settlements are regarded as the Employer for the purpose of the case studies considered in this study and will hereafter be referred to as such.

2.5.3.1. Literature findings

Section 26 (1) and (2) of the Constitution of 1996 (Bill of Rights) states that "everyone has the right to have access to adequate housing" and "the state must take reasonable legislative and other measures within its available resources to achieve the progressive realisation of this right" (Constitution of the Republic of South Africa, 1996). Adequate housing could be an objective term, nevertheless responsibility is clearly placed on the Employer to ensure that efforts are being made to address the quality of affordable housing together with the delivery thereof.

The list compiled by Aigbavboa et al. (2019) and Zunguzane et al. (2012) mentions that monitoring, and sufficient inspection of work in progress by stakeholders such as municipal inspectors and NHBRC officials could also minimise non-conformance to quality. This suggests that there should be a collaborative effort towards the improvement of quality and that the Employer should also take responsibility to ensure that adequate inspections are done at key phases of the project.

Chung (1999) found that in some instances the Employer, following a political agenda, places pressure on the Contractor to meet production targets which are very difficult to meet. If this is the case, the Employer must show commitment to quality by providing adequate resources that can reduce the risk of attempting to meet these production targets at the expense of quality (further discussed in 2.6.1).

The Employer is responsible for ensuring that policies, rules, regulations etc. favour the development of a sustainable affordable housing project. The needs of the end-user should be taken into consideration together with the realization that these beneficiaries cannot afford to maintain and uphold the condition of their houses with low levels of income and, as such, all measures must be taken to provide housing that will not require excessive maintenance as a result of construction defects (Windapo et. al, 2013). Chohan, Che-Ani, Shar and Awad (2015) underlined the importance of the implementation and facilitation of effective quality management by the Employer.

2.5.3.2. General Conditions of Contract

Clauses from General Conditions of Contract (2015) which are applicable to the Employer have been listed in Appendix F. According to these clauses, the Employer should ensure that the Contract is set up in such a manner that the defined Clauses and/or Contract Data encourage conformance to quality standards and specifications.

Although the Contractor and the Employer's Agent should ensure adequate supervision and inspections, the Employer also has a responsibility to ensure that inspections, examinations and tests are adequate to achieve the required quality standards. The Employer should also arrange for independent inspections, examinations and tests to show commitment to conformance to these quality standards.

The Employer must keep the Employer's Agent accountable for implementing QC by requesting proof of documentation of compliance.

2.5.4. The Employer's Agent

The Employer's Agent is the natural person who has been appointed to administer the Contract as an Agent of the Employer (GCC, 2015). Although the Employer's Agent has been appointed by the Employer, they should act impartially towards the Contractor and the Employer to ensure that the interests of the project are kept at the forefront of their decisions.

2.5.4.1. Literature findings

According to the Engineering Council of South Africa (ECSA) the designer should have two separate Contracts with the Employer, one for the design phase and one for the construction phase (ECSA, 2021). During construction the designer is known as The Employer's Agent and will hereafter be referred to as such.

The Employer's Agent has a contractual responsibility to ensure that the project is completed as requested by the Client, but he/she is also held accountable by his/her profession to ensure that the standards and specifications stipulated by the ECSA are met. This makes it sensible for this party to fill the role Project Manager (Chung, 1999). The Employer's Agent must delegate responsibilities appropriately between stakeholders involved to ensure that quality standards are standards are met.

According to Zunguzane et al. (2012), the Employer's Agent must be closely involved with the project by creating weekly plans and scheduling daily or monthly meetings to exercise proactiveness with regards to any quality concerns that have arisen or may arise.

Failing to ensure that quality standards are maintained will inevitably lead to Client and stakeholder dissatisfaction. This could tarnish the image of not only the Employer's Agent, but also the image of all other professionals involved (Aigbavboa et al., 2019).

2.5.4.2. General Conditions of Contract

Clauses from General Conditions of Contract (2015) which are applicable to the Employer's Agent are listed in Appendix G. The responsibility of the Employer's Agent is to provide clarification when any discrepancies between documents are found (GCC, 2015). Other than this, the Employer's Agent is responsible for administering the Contract as impartially as possible to ensure that the Works are completed within the specified budget and time frame and according to specifications (GCC,2015).

The Employer's Agent should have a deep understanding of the Contract as well as all the standards and specifications which are applicable to the project. Only in doing so can the Employer's Agent effectively ensure that quality standards are upheld throughout the project. The Employer's Agent should also take responsibility for ensuring that all plans issued clearly define quality standards which to be adhered to (GCC, 2015).

The Employer's Agent has a direct responsibility to the Contract and the Employer to conduct regular inspections of the Works. If the Employer's Agent identifies any defects or part of the Works that do not adhere to the specified quality standards, they have a responsibility to issue clear and concise instructions to the Contractor on how to remedy these defects (GCC, 2015). The Employer's Agent should keep records of all quality defects and should keep the Contractor accountable for remedying these defects. According to the clauses in the Contract, the Employer's Agent can keep the Contractor accountable by providing instruction to remove the Works, and/or by withholding/removing interim payments of such Works until defects have been remedied as per the instruction (GCC, 2015).

2.5.5. Summary

It can be concluded that the accountability for ensuring quality conformance lies not with only one specific party, instead, it requires active engagement, collaboration and communication between the key decision making stakeholders (Lizarralde and Massyn, 2008; Emmett, 2000; Windapo et. al, 2013).

External/independent authorities should be appointed to monitor, evaluate and assist with construction processes carried out by these key-stakeholders (Nyakala, Romoroka & Ramdass, 2021). The key-stakeholder could then, together with the unit responsible for quality control, determine whether the beneficiaries (customers of low-income housing) will be satisfied with the delivered end-product (Emuze & Mhlwa, 2015).

According to the Guide to the Project Management Book of Knowledge (PMI, 2004) varying amounts of effort are required during the different stages of the project life cycle (see Figure 3).

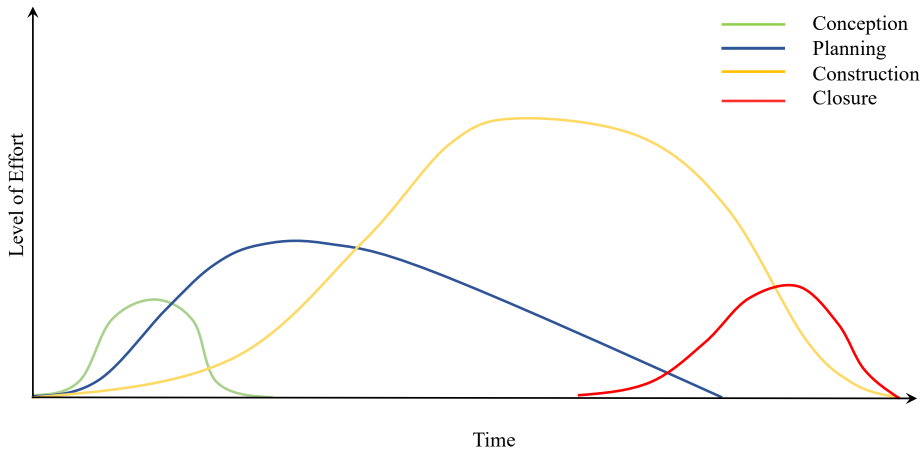


Figure 3. Level of Effort Required During Project Life Cycle (adapted from PMBOK, 2004)

From the findings above it was found that responsibility towards QC associated with parties discussed also varies during the different stages of the project life cycle. However, the largest amount of effort occurs during the construction phase and as such, this is where parties should implement continuous QC to achieve QA of the end-product.

2.6. Aspects Influencing Quality on Affordable Housing Projects

2.6.1. Contradiction between Time, Cost and Quality

Inherent to all projects which have to be managed is a model of three constraints, namely: time, cost and quality. Projects are generally expected to create a balance between these constraints in such a manner that all three are optimised. It is sometimes necessary to evaluate certain situations and decide which aspect is most important. For example, it is possible to have high quality and low cost, but at the expense of time, and conversely to have high quality and a fast project, but at a cost (Chung, 1999). It is not, however, possible to have high quality, low cost in a short time.

Keeping in mind that pressure derived from the increasing demand for houses in South Africa sometimes cause stakeholders of affordable housing projects to favour speed at the expense of quality. The time and cost of such projects are then controlled by the government (the Employer), who have already increased subsidies and set intensive construction and quality requirements to benefit the low-income groups. However, the triple constraints imposed through these requirements hugely contradict each other with there being a relatively short time allowed to construct adequate housing with a low budget (Wang, He and Zuo, 2018). Stakeholders sometimes realize the difficulty of the expected task and as such condone instances of poor workmanship to allow the Contractor to reach productivity targets (Chung, 1999).

The Preferential Procurement Policy Framework Act 5 Of 2000 further adds to the conundrum. Through this Act, 30% of the project must be allocated to local emerging Contractors/Small Medium and Micro Enterprises (SMMEs). A paper by Nyakala (2021) highlights findings from Statistics South Africa (2015) which state that there are currently skills shortages, limited quality Contractors and inappropriate management in the affordable housing sector. This makes it difficult to find a local SMME with adequate experience and results in the workforce of the Contractor existing partially of unskilled and inexperienced labour that require basic qualitative training (Department of Public Works, 2004). However, managers/owners of these emerging businesses still require training of their own on human resource-, cash-flow- and time management. Lack of experience in these management fields causes a high turnover of labourers, and requires continuously repeating the cycle of basic training for new labour. This incurs additional costs and directly influences productivity. These external factors all influence the time, cost and quality model typically used on construction projects (see Figure 4).

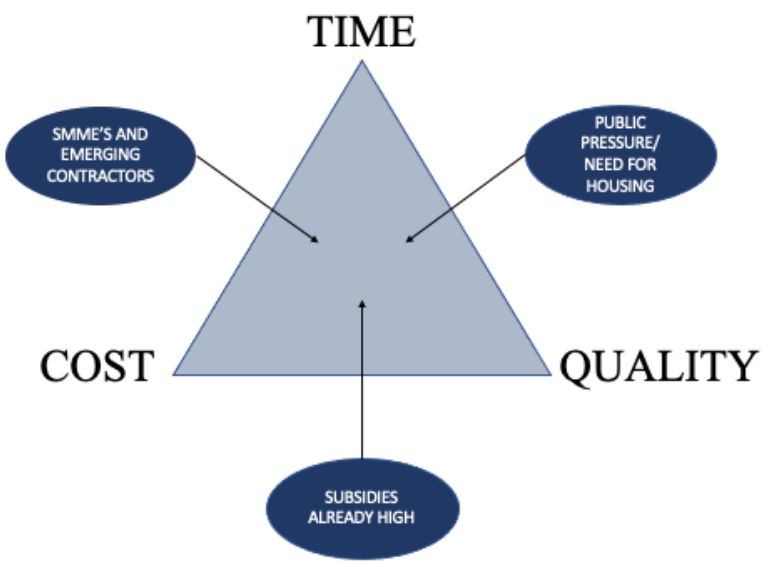


Figure 4. Time, Cost, Quality Contradiction

The need for housing in South Africa means that the Employer is under constant pressure to provide housing of good quality as quickly as possible at the lowest price possible. This pressure filters down to the Contractor and the Employer's agent who are expected to meet stringent completion- and quality targets with a partially inexperienced workforce.

2.6.2. Supervisors

Contractual requirements clearly stipulate the need for adequate and sufficient supervision, however, literature has found that cost and time overruns regularly occur as a result of lack of supervision (Marosszeky and Davis, 2006). According to Marosszeky and Davis (2006) a supervisor is someone who helps to coordinate construction activities while attempting to control quality by systematically implementing QC during the construction process. Not enforcing adequate supervision typically leads to errors being overlooked. As a result, the cost of rework is far beyond what it would have been, had there been a supervision in place which could have detected the issues earlier (Chung, 1999).

Kutta and Nyaanga (2014) define rework of defects as the redundant process of redoing an activity that was erroneously implemented the first time. In an ideal scenario, rework should not exist as defects should not be present. Sommerville (2007) found that a great number of the defects in affordable housing projects are due to poor communication and inadequate checks and controls.

Wang, He and Zuo (2018) found that insufficient and/or inadequate supervision in the present affordable housing market is very common. Wang, He and Zuo (2018) also found that low project budgets result in low salaries for supervisors, which directly influences the standard of the supervisor's service and ultimately leads to quality concerns (Wang, He and Zuo, 2018).

2.6.3. Other challenges

Apart from the contradiction between time, cost and quality and the lack of adequate or sufficient supervision, literature mentions a few other aspects which influence quality in construction projects. A study by George (2016) found that most defects were owing to either deliberate non-compliance to specification by the Contractor, defective material being used, bidding processes which have become to competitive or poor communication during construction. Wai-Kiong (2005) also highlighted that the majority of errors in construction projects are attributed to willingness of the Contractor.

Chung (1999) found that companies often lose sight of savings that will accrue when implementing a proper quality control system. He states that the construction industry has been slow and reluctant to embrace concepts of QA in practice and argues that implementation of such a systems will significantly reduce the incidents of rework, but finds that companies are not willing to make the initial investments which are required to implement such a systems. Salvi (2020) also states that quality doesn't happen by chance, instead the implementation QA and QC systems have to be implemented and managed at every stage of the project life cycle.

A study conducted by Wium and Declerq (2019) found that construction sites which implemented a QC system with adequate supervision had noticeably better quality when compared to sites which did not have sufficient and adequate supervision. Thereby proving that the implementation of a QC system together with supervision was effective towards ensuring improved quality of the end product (Wium et al., 2019).

According to Sommerville (2007), a large number of defects in affordable housing projects occur as a result of inadequate checks and controls. However, Chung (1999) argues that it is not the inadequate checks or controls that are the issue, but rather the fact that the current inspectorial systems only identify a mistake after the event has occurred. As this is usually difficult to repair afterwards, the end product typically ends up as a patched up version of the intended product and requires expenditure which was not budgeted for (Chung, 1999). Additionally, many defects are merely covered up during subsequent construction activities (covering blockwork defects with plastering) and become a source of recurring trouble in the future (Chung, 1999).

In summary, factors such as lack of supervision, inadequate management and –monitoring of builders and ineffective manpower allocation are among the primary concerns directly related to lack of quality, and construction cost- and time overruns in affordable housing projects (Marosszeky and Davis, 2006; Romeo, Andrew, Sarich & Michael, 2014; Riaz, Din & Aftab, 2015). Instead of placing focus on implementing systems which could assure quality, project stakeholders are still in a state of mind previously enforced by the NHF's initial housing policy, focussing on quantitative delivery of houses, meeting stringent production targets and consequently cutting costs where possible (Aigbavboa *et al.* 2019; Zunguzane *et al.* 2012; Hong, 2012; Mac-Barango, 2017). Stakeholders seem to lack commitment to enforcing qualitative delivery, not realizing that this could essentially reduce the amount of cost- and time overruns in the long run (Aigbavboa *et al.* 2019; Zunguzane *et al.* 2012).

2.7. Modern/Emerging Quality Control Methods

2.7.1. Overview

Technological advancements are occurring at a rapid pace as a result of the fourth industrial revolution. Naturally, advancements have to be made in the construction industry in order to keep up with improved quality, reliability and finishing requirements being imposed as a result (Salvi, 2020).

Over the past few years, many opportunities have arisen to upgrade and improve construction processes, promoting the change from a traditional, reactive approach to a modern, proactive approach. According to Dubas et al (2018:1), the use of sensors, mobile devices, wireless communication and other modern technologies have the ability to drastically improve quality within the construction industry. The use of technological advancements is being considered within the affordable housing sector to improve the efficiency of product delivery through continuous QC at each stage of the project life cycle (Salvi, 2020).

2.7.2. Quality Control and Quality Assurance Systems

The current version ISO 90001 was only introduced in 2015, making it a relatively new Quality Management System. According to Salvi (2020), a quality system is analogous to a financial control system and serves as a mechanism which can optimize the construction process to achieve the best quality at the lowest cost. According to him, management should view quality systems as a philosophy which must be strictly committed to.

Chung (1999:8) also found there has been a progressive need towards making the implementation of quality systems a contractual requirement on affordable housing projects. The challenge associated with these systems is that they must continuously change to improve, and therefore they require a two-way flow of information (Salvi, 2020).

Through the use of modern technology, Mahachi (2021) examined the development of a quality assessment tool which can measure and quantify the construction quality of low-income houses in South Africa. He concluded that use of such a tool, if implemented correctly, could improve the quality of houses being delivered. This is only one example, but various other methods of QC and QA can be explored if modern technology is taken advantage of.

2.7.3. New Technology

According to Deloitte's Engineering and Construction Industry Outlook (Meisels, 2021), 76% of executives in the field of engineering and constructions indicated that they had either already invested in technology within the field, or are planning on doing so within the next year. According this study, Deloitte identified some key fields of technological advancement:

- Building Information Models (BIM)
- Digital supply networks
- Digital twin technologies
- Autonomous rovers and drones

In themselves, each of the fields listed above can contribute to improving the quality of construction in various areas. However, for the purpose of this study, only the use of drones during the construction phase of affordable housing units is focussed on.

2.7.4. Drone Technology in Construction

2.7.4.1. Overview and application

DeYoung (2018) eloquently states that centuries of habitual norms have beset the construction industry and as a result, the industry has become ineffective and unsustainable (Ikuabe, Aigbavboa, Akinradewo, Adekunle & Adeniyi, 2022), state that it is advisable to integrate innovative technologies such as drones to abate some of the problems which are encountered in the delivery of construction projects and allow the industry to evolve accordingly.

The use of drones has become a fast-growing trend and the projections over the next ten years indicate an increase in the use of drones in construction. Rentz (2018) reports a 239% development in utilization of drones in the construction industry, year-on-year; a developmental rate far greater than in any other commercial zone.

In light of the potential improvements that drones could introduce to the construction industry, Korody & Snow (2017) stated that: *"..demand for commercial drones is moreover projected to exceed all other industries by a factor of x10 being the cornerstone of a $100 billion drone-market into 2020"*. Goldman Sachs also forecasted the construction industry as the largest consumer of commercial drones for the year 2020 (DeYoung, 2018).

This is validated by an extensive study conducted by Mahajan (2021) over a 10 year period that found that studies on the use of drones for commercial reasons are increasing exponentially. The same study found that the Architecture, Engineering and Construction industries are among those that predominantly benefit through implementation of drones.

Previous studies which reported on the use of drones within the construction industry include:

- Inspecting highways and bridges for crack identification or any other structural defects (Seo, Duque & Wacker, 2018),
- Inspecting road systems and traffic monitoring (Bisio, Garibotti, Haleem & Sciarrone, 2017),
- Damage inspection of transmission towers (Wang, Zhou, Liu, Huang & Feng, 2012),
- Wind turbines surface damage detection (Shihavuddin, Chen, Federov, Christensen, Riis, Branner, Dahl & Paulsen, 2019),
- Building façade and roof inspection for performance inspections and structural defects (Chen, Reichard & Xu, 2019)
- Surveying and geo-referencing (Motavwa & Kardakou, 2018),
- Wetland/environmental inspections (Nitha, Syeeda, & Maroua, 2022) etc,

The use of drones in construction can be incorporated in a multitude of ways. Using drones to mitigate construction sites with the aim of avoiding potential delays and overruns, or reducing waste, is one example of its application (DeYoung, 2018: 22). After reviewing more than 100 sources, Mahajan (2021) summarized the potential use of drones in pre-construction; construction, through to post-construction stages (see Table 2).

Table 2. Applications of Drones in the Construction Industry. Adapted from Mahajan (2021)

Stage		Application tested
Pre-Construction	Planning	Site Selection
		Topographic Maps
		Zoning
	Decision making	Site Location
		Site barriers
		Aerial Images and videos
	Site Mapping	Contour mapping
		Surveying
		Live imagery
Construction	Inspection	Concrete or masonry Works
		Material Inspections
		Installation Inspections
	Progress Tracking	Real time progress monitoring
		Decision making
		Increasing effectivity of handling multiple sites
	Labour and Safety	Increase safety of construction works
		Monitor dangerous works
		Increase productivity
	Document measurement of actual site data	Precise aerial photogrammetry
		2D and 3D for measurement
		Increase RFI validity
Post-Construction	Evaluation	Capture final finsihed work
		As builts
		Evaluate from start to finish
	Maintenance	Assist with operation & management inspections
		Easily detect defects

In comparison to conventional methods, John (2017) found that drones are able to execute the same activities with minimal risk and increased accuracy, ultimately reducing the manpower requirements.

2.7.4.2. Real-time data capture

One major advantage of drones and their ability to collect real-time site data, is increased accountability across contractual parties. Due to the mobile nature of construction, the varying environment and various unknowns distributed across the different contractual parties, control of accountability is often limited (DeYoung, 2018: 28). With the drone collection of real-time data during the construction phase, measurements in progress can easily monitored by comparing the status of the site to the baseline accurately, and in real time. Where discrepancies arise, they are quickly observed and can be addressed sooner, given the real-time changes reported by the data. The availability of this data, and ease of access, allows for expedited comparison to the project's contractual documents and specified requirements amongst teams, with fewer disputes and minimal loss of time (DeYoung, 2018:27).

2.7.4.3. Construction Site Monitoring and Visual Management (VM)

Project monitoring and assessment was found to be one of the prevailing issues effecting delivery of construction projects, making construction site monitoring using drones one of the most apparent uses for the technology (Ikuabe et al. 2022). With the introduction of drone imaging and real-time site data, an umbrella of Visual Management (VM) results, providing the construction industry with a major advancement in its proactive capabilities (DeYoung, 2018). VM has become the latest industrial standard where lean construction is concerned. Any aspect of site operation can now be addressed by both the project team and the employees by looking at the live data from drones.

Data models associated with VM are replacing historical randomness and limitations throughout the construction industry (Tezel, & Aziz, 2017). Through this, the construction industry is advancing into a formal adaption of Supervisory Control And Data Acquisition (SCADA) systems, with the end goal of one standard system to unify all its operations (DeYoung, 201).

Construction site monitoring is becoming effortless through use of drones and software which implements autonomous flying of pre-programmed flight paths. According to various sources, site monitoring by means of a drone has been found to alleviate complexities associated with construction projects and assist quality management through early defect detection (Goessens, Mueller & Latteur, 2018, Li & Liu, 2014 and Dupont, Chua, Tashrif & Abbott, E. 2017).

Site monitoring through use of drones can provide the project stakeholders with a proactive, in depth analysis of site conditions without affecting the project schedule (Cajzek & Klanšek, 2016).

2.7.4.4. Photogrammetry

Photogrammetry, which is defined as a method of extracting information about the position of points in space from photographic images (Siewczyńska & Zioło, 2022), is not a particularly new method. However, the technology which is being used to performed photogrammetry is rapidly advancing.

Photogrammetric technology can be used to make a model (either 2D or 3D) of an object by analysing a capturing a set of 2D images and analysing them through photogrammetric algorithms. According to a manual published by Agisoft Metashape (a photogrammetry software used in this study) (Agisoft, 2022) the best results are achieved if images overlap at least 60% on the side and 80% on the forward overlap (see Figure 5).

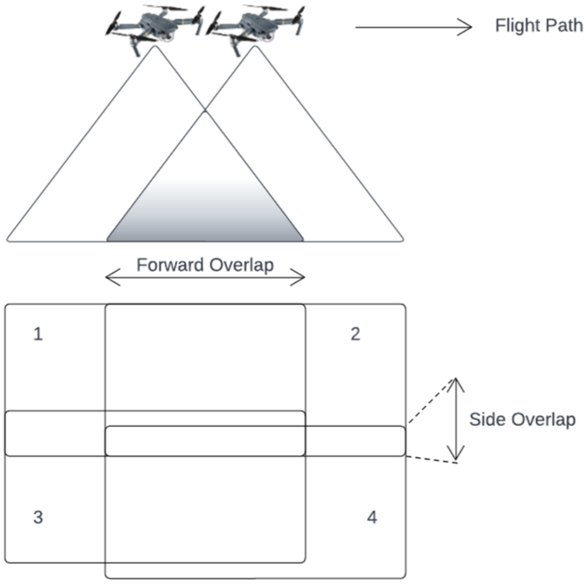


Figure 5. Overlapping of Drone Images

The software then finds corresponding points that appear in the overlapping 2D images and positions these points relative to each other in the defined space to create what is called a tie point cloud (see Figure 6) (Siewczynska and Ziolo, 2022).

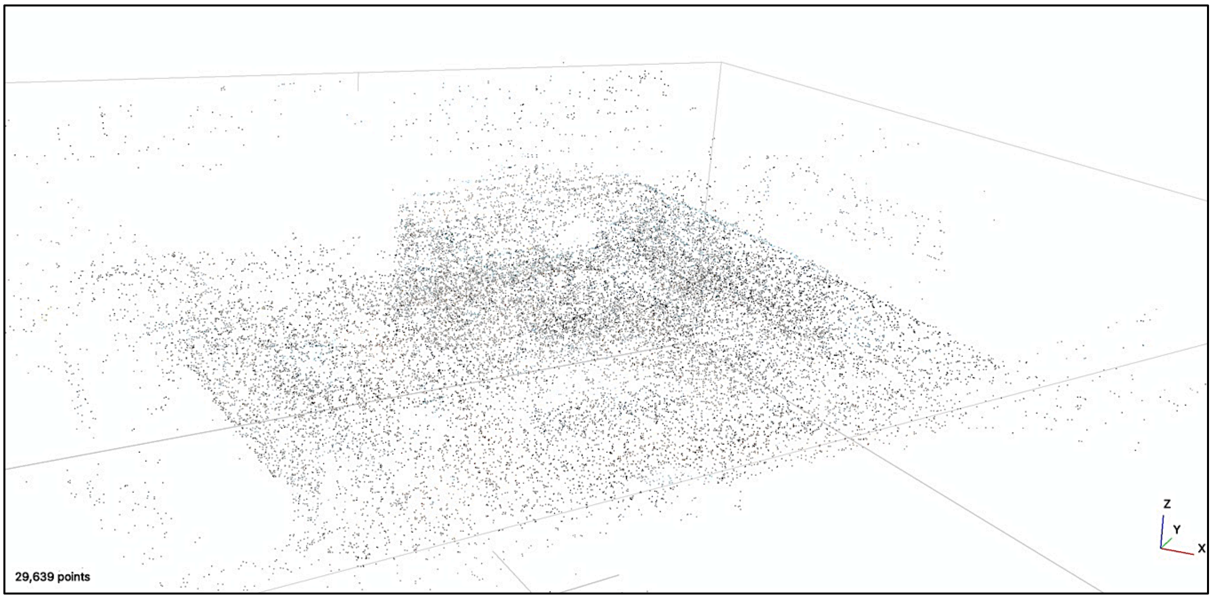


Figure 6. Example of a Tie-Point Cloud Generated on Agisoft Metashape

2.7.4.5. 3D Modelling of an Object Using Agisoft Metashape

Various types of software is currently available that can assist with generating 3D models from 2D images. The majority of these produce similar results, but for the purpose of this study a stand-alone software product called Agisoft Metashape was used. Building a 3D model with the data processing software consists of two main parts:

1. **Alignment:** This is where the software analyses the images which have been imported into the workspace to search for feature points across images in order to tie them together (called stitching). The camera positions of each image is also extracted during this step to produce a tie point cloud and set of camera positions (Agisoft, 2022).
2. **Mesh generation**: A dense point cloud is created by using the tie point cloud and estimated camera positions to ultimately generate a surface in 3D (mesh). This mesh is then textured to produce a photorealistic 3D model of the object which can be exported to numerous post-processing Computed Aided Design (CAD) software (Agisoft, 2022).

These two parts are completed by following the steps discussed below (see Figure 7):

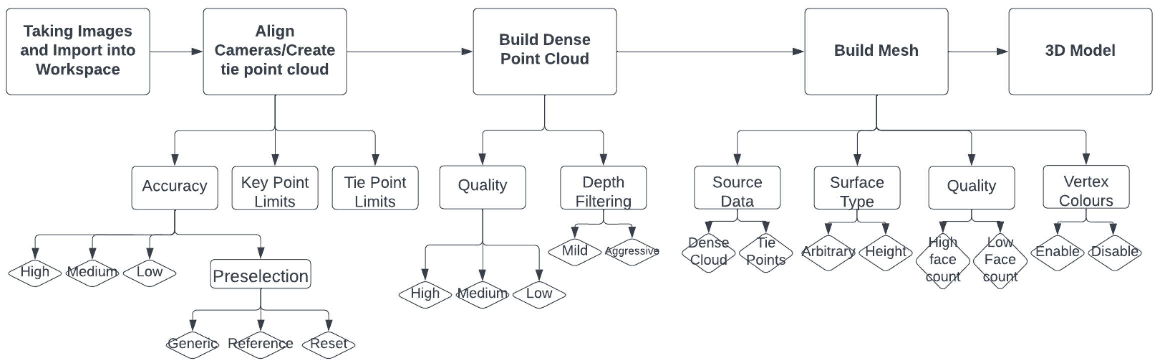


Figure 7. Steps to be Followed to Produce 3D Model of an Object

1. Take aerial images using a drone and import these images into the software workspace.
2. Align cameras/Create Tie point cloud. This requires selecting a number of parameters (see Figure 8 for Graphical User Interface and Figure 9 for descriptions of parameters):

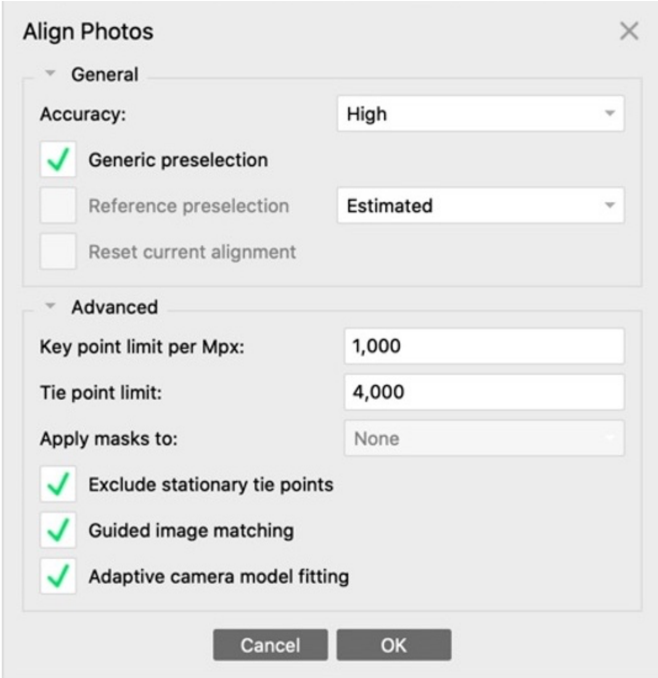


Figure 8. Agisoft Metashape Graphical User Interface (GUI) used to choose photo aligning parameters (Agisoft,2022)

Align Photos GUI		
Preference	**Function**	**Processing Period**
Accuracy	Improves the camera position estimates. Improved camera position estimates provide high quality models	Longer if increased
Generic Preselection	Used when starting with a new model, reference preselection is and reset current alignment	Standard Selection
Reference Preselection	Used when a model has already been generated using images and the user want to re-render the model with other parameters	Shorter than standard
Reset Current Alignment	Starts the alignment procedure from the beginning if favourable results weren't achieved after the first render.	Same as standard
Key Point Limit	Sets the upper limit of the number of feature points analysed on each individual image.	Longer if increased
Tie Point Limit	Sets the upper limit of the matching points used to tie images together.	Longer if increased
Apply Masks	Used to exclude certain previously masked areas from the alignment process.	Similar
Exclude Stationary Tie Points	Excludes tie points that remain stationary and eliminates false tie points related to the camera sensor	Similar
Guided Image Matching	Assists by increasing the key points per image but is mostly used for objects/scenes that include high resolution scanning of areas such as vegetation or forests.	Longer
Adaptive Camera Model Fitting	This enables automatic selection of camera parameters	Longer

Figure 9. Align Photos Preference Descriptions

3. Build Dense Point Cloud (see Figure 10 for Graphical User Interface and Figure 11 for descriptions of parameters):

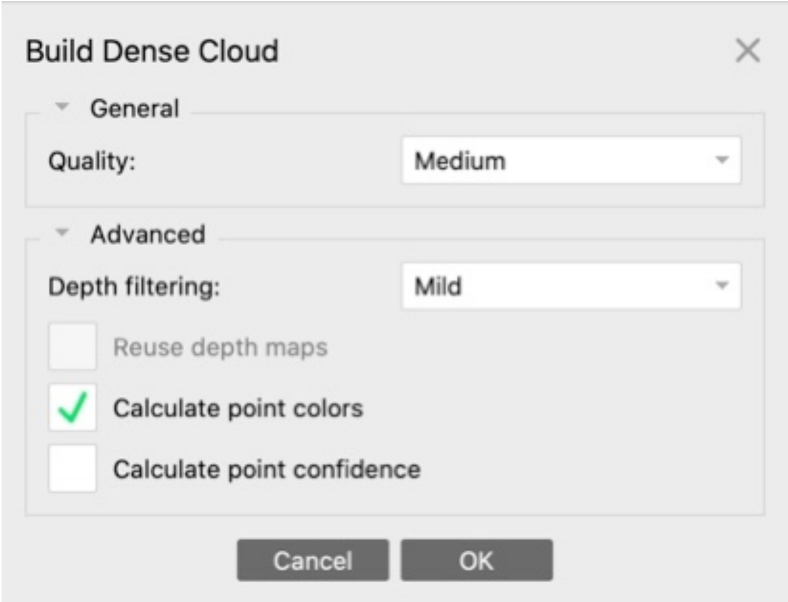


Figure 10. Agisoft Metashape Dense Point Cloud GUI

Dense Point Cloud GUI		
Preference	**Function**	**Processing Period**
Quality	Produces a more detailed and accurate geometry	Significantly increases
Depth Filtering	Built-in algorithm which sorts through the tie cloud points and filters outliers which will not produce accurate models as a result of noisy or badly focused images. Aggressive depth filtering means that all of the outliers are filtered out and is mostly used for distant aerial imagery such as mapping.	Aggressive = Longer
Colour points	Can be disabled if the colour of the point is not of interest for the model and can save processing time if disabled.	Shorter tif disabled
Point Confidence	Calculates how many depth maps have been used to generate each dense cloud	Same as standard

Figure 11. Dense Point Cloud Preference Descriptions

4. Build Mesh/3D polygonal model (see Figure 12 for Graphical User Interface and Figure 13 for descriptions of parameters):

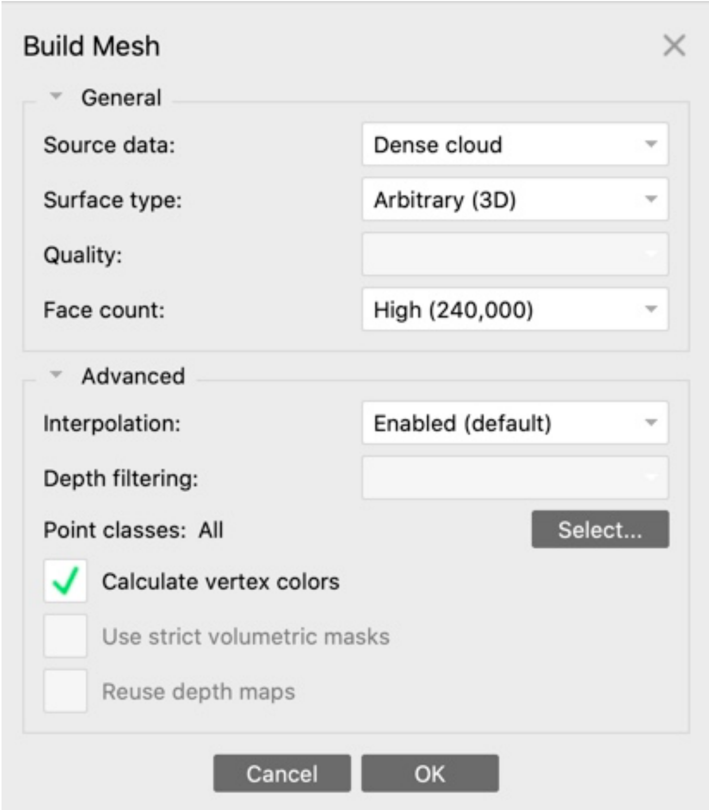


Figure 12. Agisoft Metashape Build Mesh GUI

Build Mesh GUI		
Preference	**Function**	**Processing Period**
Source Date	Either Tie Points or Dense Cloud. Tie Points allows the user to quickly generate a 3D model based solely on the tie points (low quality), whereas using the previously generated Dense Cloud results in a higher quality model which takes longer to process.	Tie Points = Short Dense Cloud = Long
Surface Type	Either an Arbitrary or a Height field surface type can be selected. The former doesn't make any assumptions on the object being analysed and is typically used on closed objects such as buildings or statues. The latter is typically used for planar surfaces.	Arbitrary = Long Height = Short
Quality	Dependent on the face count. The face count specifies the upper limit to the number of polygons which can be present in the final mesh.	Larger face count = Longer
Interpolation	If disabled the program will only reconstruct areas which correspond to the dense point cloud.. If enabled, the software will automatically interpolate surfaces and close any holes which are present.	Disabled = Shorter Enabled = Longer
Vertex Colours	If vertex colours are calculated the software will use colour information which is available from the source data to calculate colours for the mesh vertices	No significant change
Strict Volumetric maps and reuse depth maps	Not available on demo	N/A

Figure 13. Build Mesh Preference Descriptions

Once the preceding steps have been completed the user should have generated a 3D model of the desired object (see Figure 14 for Agisoft Metashape example) which can either be analysed on Agisoft Metashape or be exported to the desired CAD software for analysis.

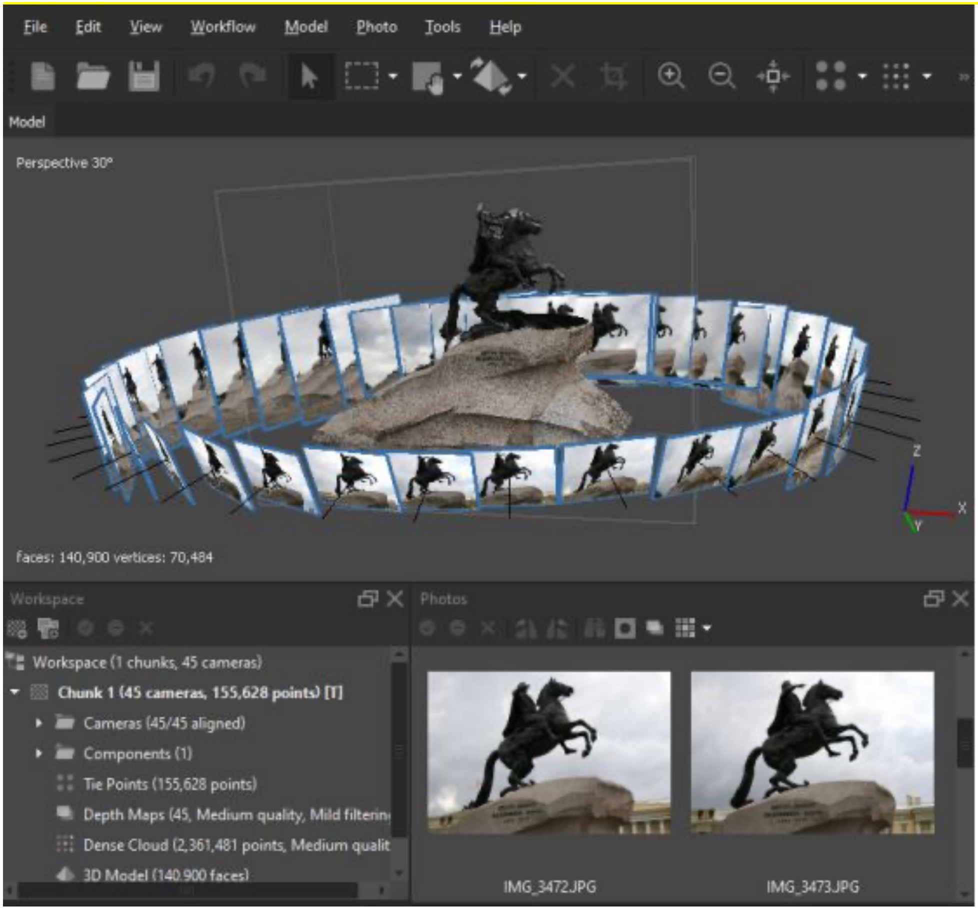


Figure 14. Example of 3D Model Generated on Agisoft Metashape (Agisoft, 2022)

2.7.4.6. Limitations

Performing photogrammetry through autonomous flight paths on affordable housing projects was found to be quite challenging from a spatial, sensor and photographic point of view, as units are constructed very close to one another (discussed in section 4.4.3.). Sensors on most drones will not be able to detect all of the obstructions present and therefore multiple solutions are often combined in an effort to implement site monitoring.

This limits the autonomy of drone flights and instead requires the pilot of the drone to manually capture images of the desired object while keeping in mind the amount of overlap required to produce an accurate 3D model. Operating a drone within small spaces is time consuming in itself as it requires direct attention to the drone and its manoeuvring capabilities. Without pre-programmed flight paths and automatic image capturing the pilot is required to pay attention to the drone as well the images which are being taken.

Additionally, the market for drones in construction is relatively new, therefore software required to make full use of the drone's photogrammetry capabilities is still expensive and require either purchasing the software or making monthly payments (see Figure 15).

	Photogrammetry Software	Ground Control Points	LiDAR	2D mapping	3D model generating software	Cost/month	Comments	
PIX4D Mapper	YES	Yes	YES	YES	YES	R 5 305.48		
PIX4D Survey	Requires CAD additionally	Yes	YES	YES	Requires CAD additionally	R 2 273.75		
		No						
PIX4Dreact	NO		NO	YES	NO	R 1 062.30		
Drone Deploy	YES	Yes	YES	YES	YES	R 5 984.51		
Agisoft Metashape Standard	YES	NO	NO	YES	YES	R 3 256.01	Once-off	Demo can be used for free but projects cannot be saved

Figure 15. Costs of Popular Drone Software according to their websites (accessed March 2022)

2.8. The Systems Development Cycle

2.8.1. Overview

In this study, the integration of drone technology and quality management within the construction industry can be seen as an improved quality management "system". To this end, the systems development cycle developed by Nicholas & Steyn (2008) is used to assist with developing a framework which describes how drone technology can be integrated on affordable housing projects to improve QC during construction. Nicholas & Steyn (2008) state that this four-phase model encompasses the total developmental life cycle of all human-made systems (*see* Figure 16).

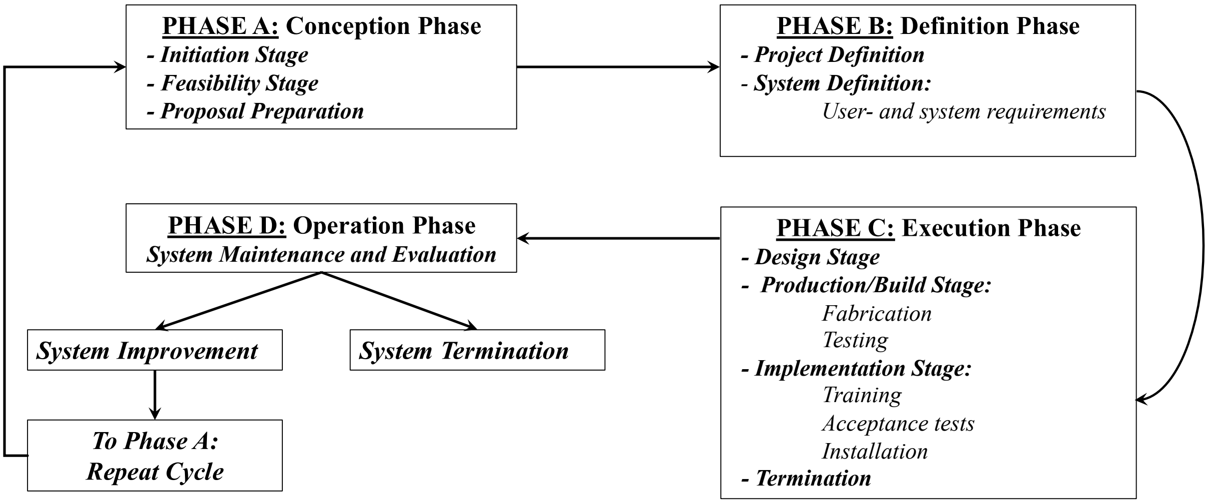


Figure 16. Four-phase model and stages of the systems development cycle adapted from Nicholas & Steyn (2008:77)

This development cycle can be implemented in two manners, either through a stepwise approach called *phased project planning* which follows the phases exactly, or through an overlapping and iterative practice called *fast-tracking* (Nicholas & Steyn, 2008).

This study makes use of the *fast-tracking* approach, as it requires considering the drone's quality improvement capabilities concurrently with the development of an effective and practical framework for implementation. This means that the phases and steps are not always performed in sequence, and that there are overlapping iterations occurring within the systems development cycle above.

2.8.2. The Conception Phase

According to the four-phase model in Figure 16, the conception phase can be split into two stages (Nicholas & Steyn, 2008):

1. **The initiation stage** occurs when a problem is identified together with a need or opportunity to solve the problem in a manner which could result in benefits accruing if a solution to the problem is found.
2. **The feasibility stage** then occurs after establishing that there is a need to further investigate the problem.

A detailed investigation of problem, user requirements and possible solutions are discussed during the feasibility stage of the cycle, before concluding this phase with a proposal which will aim to solve the problem (Nicholas & Steyn, 2008).

2.8.3. Definition Phase

During this phase the functional requirements of the system have to be considered. As illustrated in Figure 16, two main definitions are required during this phase (Nicholas & Steyn, 2008):

1. **The project definition**, which details what needs to happen in order to produce the end-item and
2. **The system definition**, which aims at detailing the capabilities of the end-item to ensure that it meets the defined user requirements.

The project and system definitions occur concurrently as the work to be done must meet the system requirements, but the systems requirements are also restrained by the method of work (Nicholas & Steyn, 2008).

2.8.4. The Execution Phase

The Execution Phase according to the model by Nicholas and Steyn (2008) includes the design stage, the production/build stage (known as the development stage in this study), the implementation stage and the termination stage.

The design stage occurs when conceptual ideas become actual representations or models showing the system components (Nicholas & Steyn, 2008). Various possibilities are reviewed here to determine which variation would best meet the required specifications.

Once the design has been finalized the subsequent stages include developing the system (end-product) which will be implemented. As discussed later (section 4.3.1), this process is an iterative approach which requires concurrent development and testing. This determined how the drone was used to improve the quality of masonry in affordable housing projects.

The final developed system is then implemented in practise and operated during the life cycle of the project. Improvements to the system are encouraged during this process until the end of the project when the system is terminated.

2.9. Synthesis of Literature Review

Factors which influence quality within the affordable housing sector of South Africa stem from the formation of the initial housing policy which aimed to reduce the housing backlog post haste. This meant that parties initially involved with affordable housing projects focussed mainly on quantitative delivery of housing instead of qualitative delivery of housing.

In spite of shifting focus to the latter, this problem seems to be recurring nearly 28 years later. Literature has thus indicated the need for the implementation of more than just traditional management methodologies. Instead, the construction industry should embrace the technological revolution and take advantage of the modern and emerging technologies which could assist with alleviating these recurring issues.

Quality is the result of a continuous effort towards the implementation of QC and QA systems. Implementation of these systems together with the use of modern and emerging technologies could provide a solution to the contradiction between time, cost and quality currently being imposed by affordable housing projects.

As the level of effort required varies during the project life cycle, so does the responsibility associated to parties involved. Parties such as the Contractor, the Employer and the Employer's Agent should have a clear understanding of their responsibilities towards quality and should be held accountable when defects occur as a result of negligence towards these responsibilities. During the construction phase these parties should be dedicated to provide QA through the implementation of a continuous QC system.

The use of drones within the construction industry is growing faster than any other field of application. After the limitations of using drone on affordable housing projects have been identified it is still apparent through the research that project monitoring through means of a drone can be an effective method to improve quality. The need for a framework which describes how a drone can be used to improve QC on an affordable housing project has been corroborated through the findings in the literature review.

CHAPTER 3: METHODOLOGY

3.1. Chapter Overview

This section describes the methodology followed in this study. The diagram in Figure 17 (which is based on Nicholas & Steyn's (2008) approach) provides a visual representation of the methodology and the structure thereof.

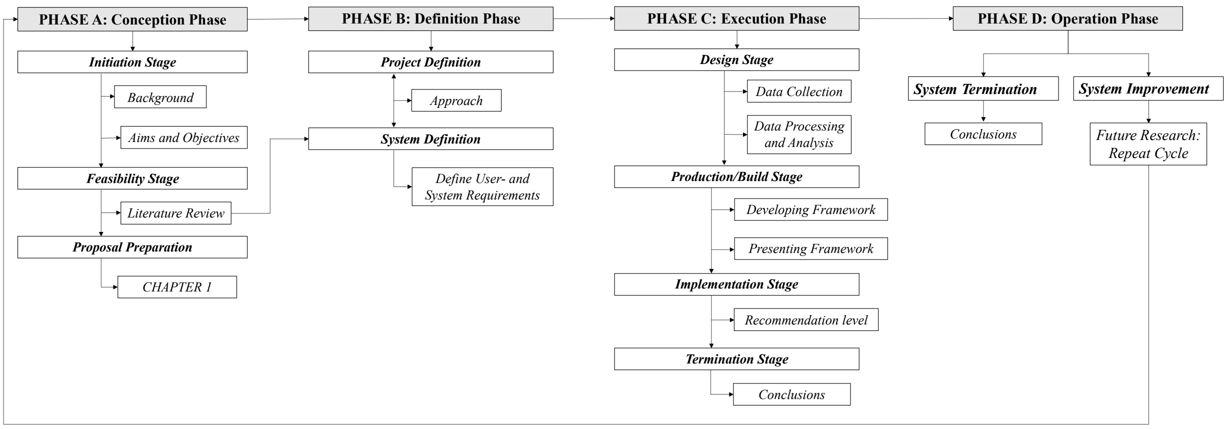


Figure 17: Logic diagram of the methodology.

3.2. Conception phase

The conception phase involved the project initiation, referring to the problem statement and impact of the problem; and the feasibility phase, investigating the feasibility of the study and the possible solutions.

3.2.1. Project Initiation

The initiation stage of this phase occurred in Chapter 1 where a clear statement of the problem regarding quality concerns in affordable housing was developed. The following problem was identified: current quality control methods are inefficient or outdated as they continue to yield unsatisfactory quality within housing units and stakeholders continue to focus on quantitative delivery of housing, irrespective of the fact that the NHF has required a shift towards qualitative delivery of housing units.

Solving this problem would result in the following benefits for the end users:

- **Beneficiaries** would receive units with improved quality. Improving their housing would directly benefit their overall livelihoods.

- **The Client**, being the Western Cape Government and Department of Human Settlements, would benefit by receiving increased public support for improving the livelihoods of beneficiaries by delivering housing which is of superior quality.
- **The Contractor** would benefit by reducing the need for rework which would in turn reduce the risk of cost- and budget overruns. Furthermore, by delivering high quality affordable housing units the Contractor will improve stakeholder satisfaction and increase the probability being awarded future Contracts.

The identified problem together with the opportunity of accrued benefits supports the need for further investigation into the problem.

3.2.2. Feasibility

The problem was then addressed in chapter 1 and 2 to understand the needs of the users and to determine whether a solution is worth developing. The following was found:

- A detailed investigation determined that there is indeed an overall consensus regarding poor quality in affordable housing projects (Mehlomakhulu et al., 2010; Chakwizira, 2019; Wium et al., 2021).
- Beneficiaries are continuously emphasising the need for a new quality improvement strategy which can identify and resolve quality concerns currently arising in affordable housing units (Minas, 2016).
- Stakeholders lack commitment to enforcing qualitative delivery and do not realize that this could reduce the cost- and schedule overruns (Aigbavboa *et al.* 2019: 3; Zunguzane *et al.* 2012).
- Continuous inspections, audit programmes and examinations at appropriate stages can increase the effectiveness of quality control methods in affordable housing projects (Jogdand and Deshmukh, 2017).

Possible solutions discussed were the following:

- The need for increased effectiveness in QC methods was highlighted and this led to the proposal of using modern technologies such as drones to assist in this regard.
- The development of a framework that describes how this technology could be implemented is suggested.

3.3. Definition Phase

3.3.1. Project Definition

The approach (Chapter 1) briefly addresses the processes that need to be followed to produce the final product. The aim and how it was achieved is now expanded upon in order to complete the project definition.

3.3.1.1. Identify common dimensional quality concerns in affordable housing projects

From literature it was found that there is still a problem regarding quality on affordable housing projects. In order to further research this, on-site inspections of two current affordable housing projects were used to identify common dimensional quality concerns. Data was collected from these affordable housing projects to identify and confirm the dimensional quality concerns being raised.

3.3.1.2. Explore different methods of using drones to improve quality concerns

The drone used for this study is a DJI Mavic Pro Platinum. The drone makes use of two satellite positioning systems, namely GPS and GLONASS, giving it a maximum transmission distance of 7km. According to the specifications, the drone has a maximum flight time of 30min

The drone comes standard with a 3-axis gimbal and a camera which is capable of shooting 4K 30p. The drone has sensors in the front and bottom which allow obstacle avoidance in these directions together with autonomous tracking.

Research regarding the use of drones within the construction industry was used to determine how a drone can be used to improve the quality in the affordable housing project. The drone was then used on site during the identification of common quality concerns to explore various methods of using it to assist with improving the identified concerns.

Different software, image processing and image/video analysing techniques were investigated to find the most practical way to use the drone in this regard.

3.3.1.3. Developing a framework which improves QC through the use of drones

The concerns identified as well as the capabilities of the drone and drone software are used to develop the framework. The aim of this framework is to provide a basic approach through which a drone can be used to identify quality defects, increase quality monitoring, -assurance and -control, decrease project schedule- and cost overruns and increase stakeholder satisfaction. This framework will look at quality management aspects beyond only dimensional quality tolerances.

3.3.2. System Definition

The systems definition stage requires firstly determining the requirements of the users, as this will define the system and which capabilities it must meet (Nicholas & Steyn, 2008). The requirements of the beneficiaries, the Client and the Contractor are also considered to ensure that the system produces the required end-product (affordable housing units which adhere to quality standards and specifications).

Considering the project definition and research into the problem, it was determined that the end-item would need to be practical, effective and inexpensive to meet the user requirements. These three user requirements were then translated into system requirements to determine the specifications of the system (see Figure 18):

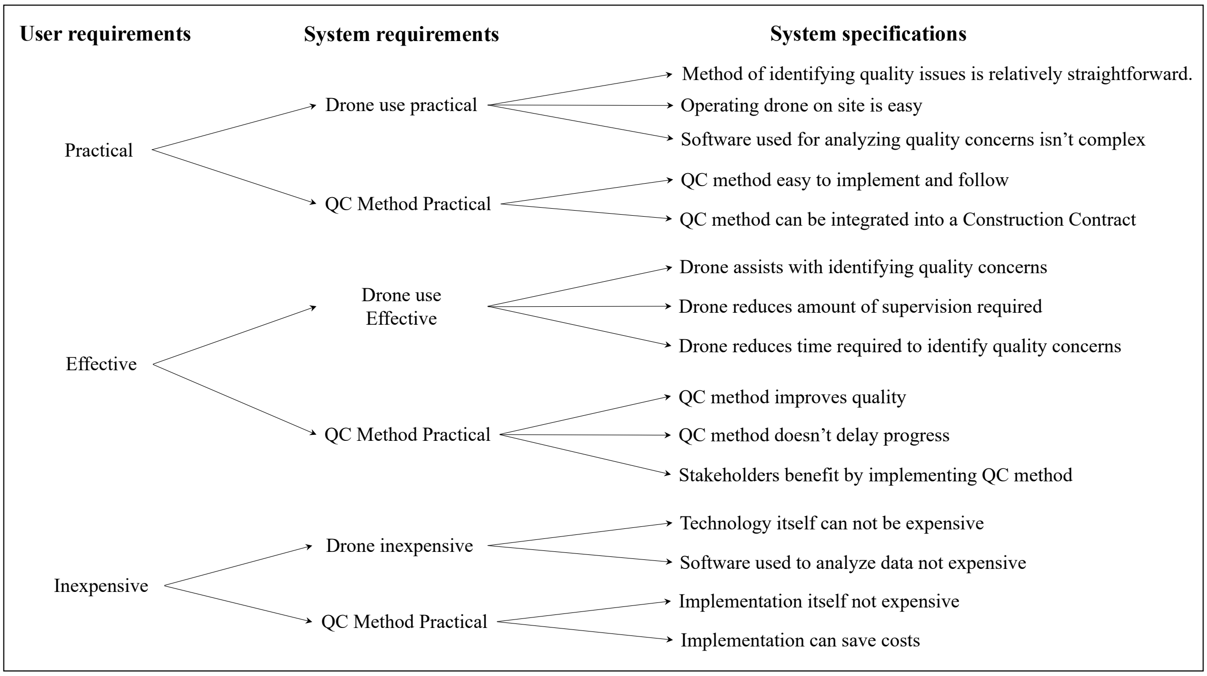


Figure 18: User requirements for a system (Adapted from: Nicholas & Steyn, 2008).

Developing a method to implement the drone in practise was guided by continuously considering what is required to meet the specifications. Simultaneously, the specifications where guided by considering practicality of the method which would be implemented (i.e. the practicality specification is governed by the method through which the drone can implemented).

3.4. Execution and Operation Phase

The bulk of this study is comprised of the execution and operation phases which are discussed in detail in Chapter 4, 5 and 6. These stages include development and implementation of the drone technology which will aim to improve quality control of masonry in affordable housing.

In order to collect data for the study it was firstly necessary to obtain Social, Behavioural and Education Research (SBER) permission from the Department Ethics Screening Committee (DESC) of Stellenbosch University. The data collection strategy together with the aims and of objectives of the study was reviewed by the DESC who then classified the project as low risk and provided ethics clearance for this study with Project ID no. 25902 (see APPENDIX B). Gatekeeper permissions were also obtained from the stakeholders involved in the affordable housing projects, however, these are not attached to the document to protect the identity of these parties.

CHAPTER 4: EXECUTION PHASE

4.1. Chapter Overview

The preceding chapter addressed the problem, possible solutions, requirements and specifications before the study progresses to the execution phase. This phase now describes the process which was followed to develop a framework (system) which describes how drones can be used to improve the quality in affordable housing projects, starting by identifying common dimensional quality concerns on two affordable housing projects. The data collection strategy, data processing software used and analysis of data are discussed before concluding with results obtained and discussions on insights gained from following the steps set out in this chapter. See the process flow diagram in Figure 19 for a visual representation of the chapter which follows.

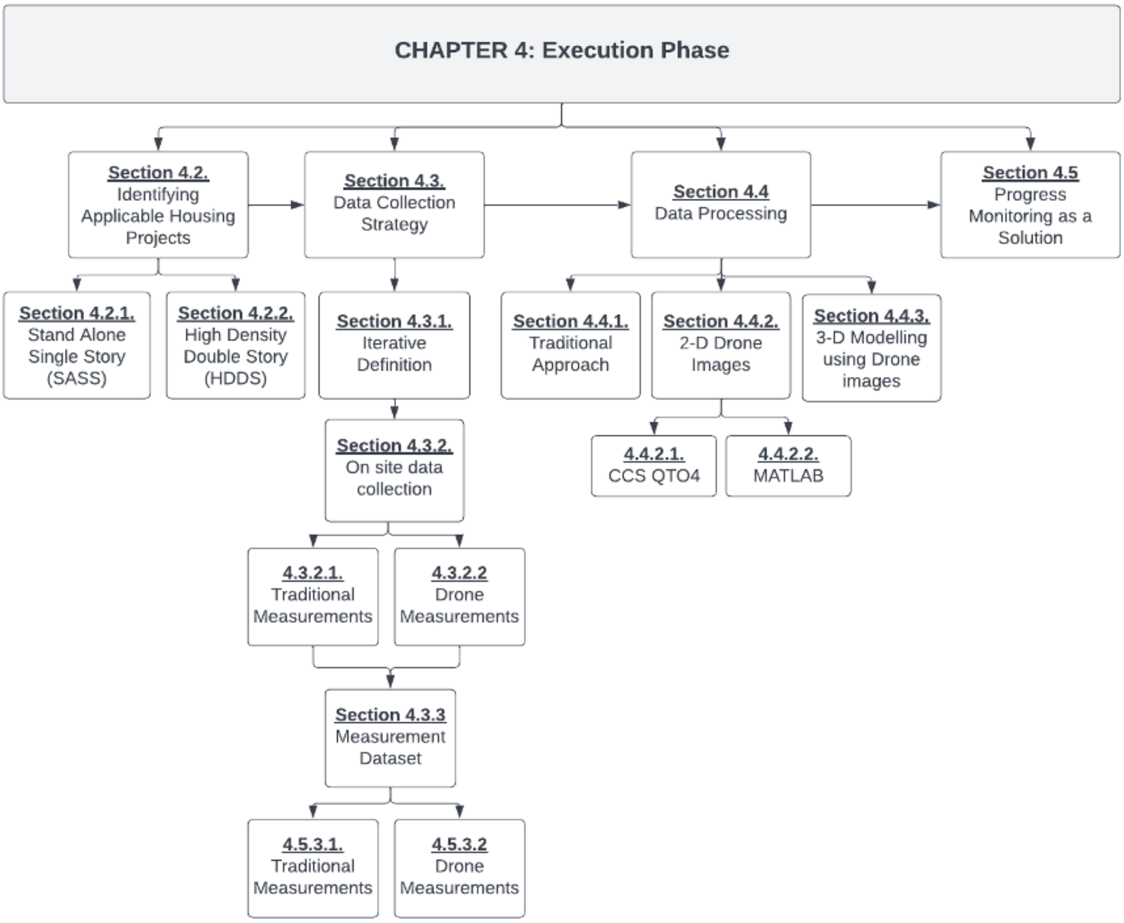


Figure 19. Chapter 4 Structure

4.2. Identifying Applicable Housing Projects

In order to identify applicable housing projects that would generate useful data for the investigation in this study, the following requirements were defined:

- Housing projects had to be in the construction phase while observations and measurements were being recorded.
- The projects had to be relatively close to one another to assist with logistics.
- One simple project and one complex project were to be identified for comparison, as a multi case study improved the quality and generalising of the study results.

The two affordable housing projects identified which met the requirements above were both allocated in the Western Cape, South Africa. However, to protect the identity of stakeholders the exact location of these projects will not be disclosed. One project consists of Stand-Alone Single Story (SASS) housing units, while the other consists of High Density Double Story (HDDS) housing units.

The time frame of this study occurred over a two year period during which the quality of specific units in both projects were monitored and documented to assist with achieving the goals and objectives of this study, while also determining which areas could practically be focused on through use of a drone. During this time frame the insights gathered from measurements and observations assisted with developing the final framework for drone implementation on an affordable housing project.

4.2.1. Stand-Alone Single Story (SASS) Units

The layout of Stand-Alone Single Story Units of Project 1 are relatively straight forward. These units are constructed on their own raft foundations with manageable block work, dimensions and finishing (*see Figure 20*).

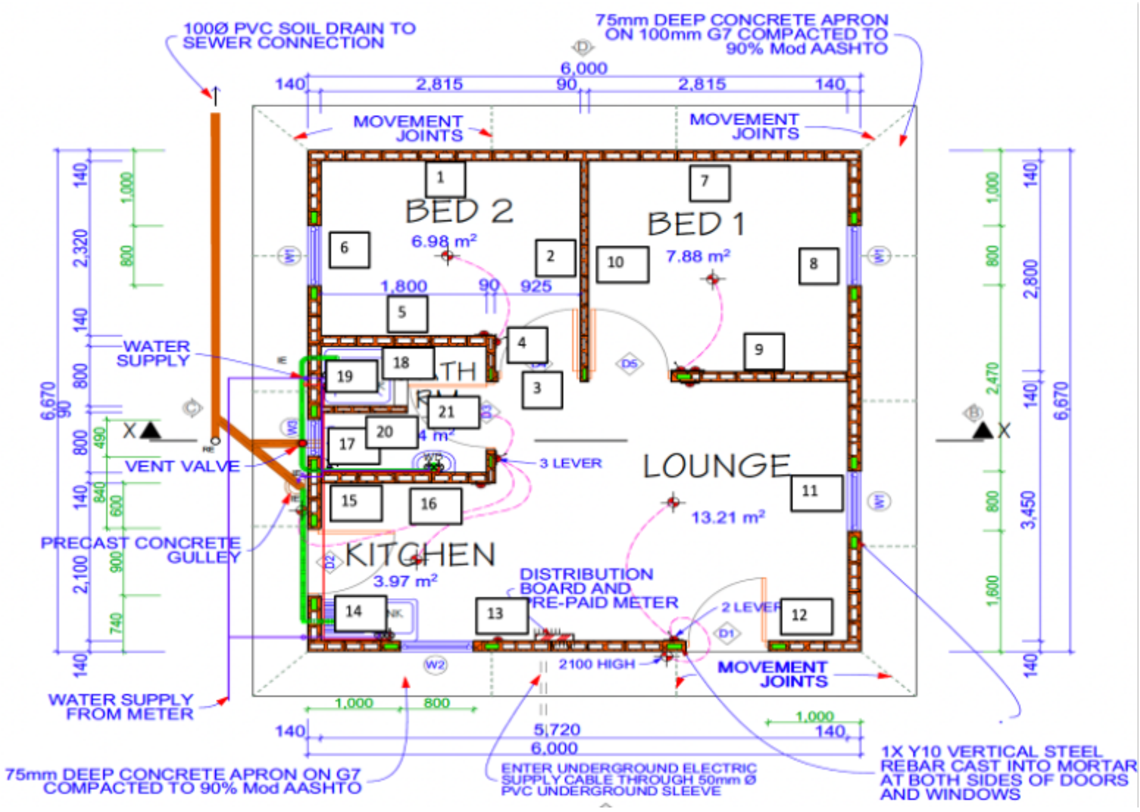


Figure 20. Layout of SASS units (used with permission of gate keeper)

The simple, single story layout limits the possibility of major errors occurring and in turn makes inspection and quality control easier. The simpler design provides a great starting place for SMMEs to learn the basics as emerging Contractors in the construction industry.

4.2.2. High Density Double Story (HDDS) Units

In contrast to the SASS units, the High Density Double Story (HDDS) units constructed on Project 2 were not as straightforward, with multiple units being constructed on a single raft foundation known as a block (see Figure 21 and Figure 22). Each block has two types of units:

1. The units in the centre, which are double story units (living room and bathroom downstairs and bedrooms upstairs).
2. The units on the outside, which have one complete unit on ground level (meant for disabled beneficiaries) and another complete unit built above it (accessed by external staircase).

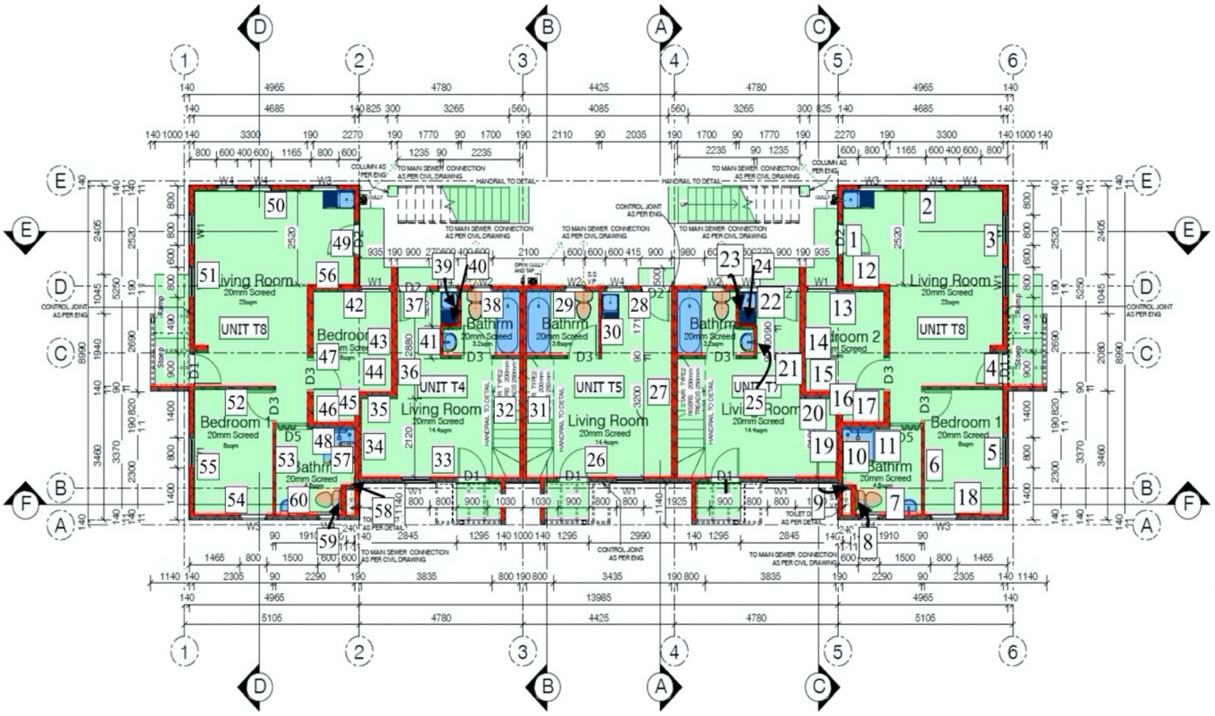


Figure 21. Layout of HDDS Units Ground Floor (used with permission from gate-keeper)

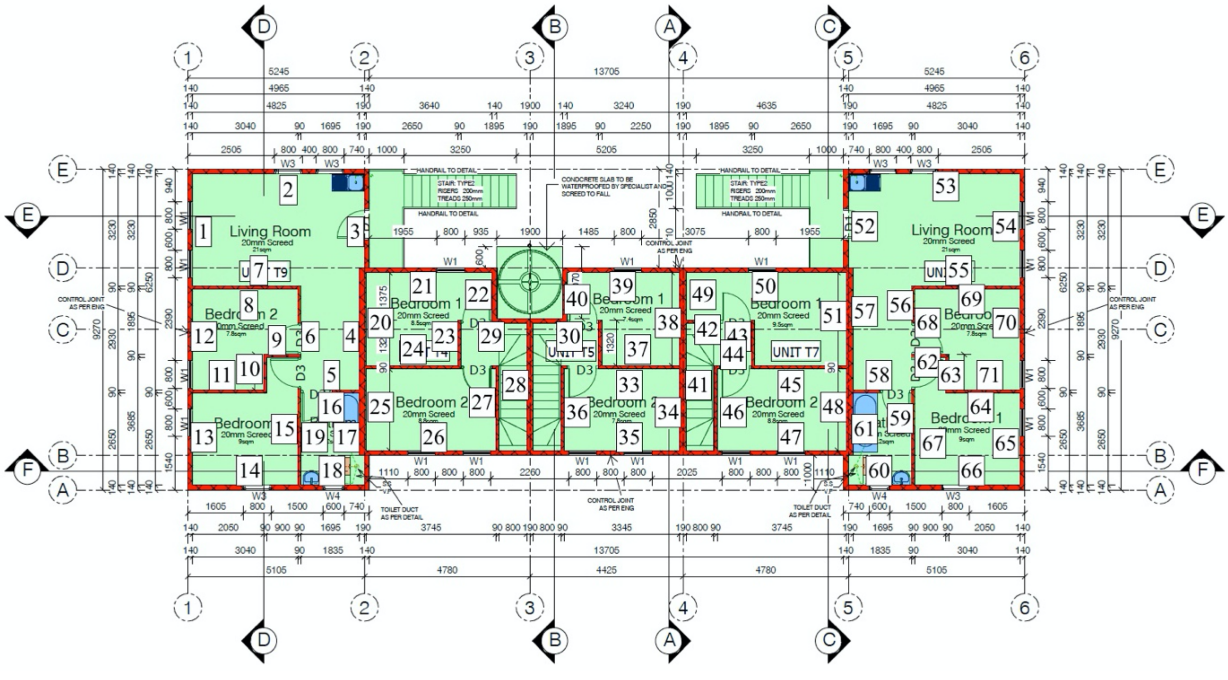


Figure 22. Layout of HDDS Units First Floor (used with permission from gate-keeper)

The construction of units in Project 2 is not as straightforward as that of Project 1. Apart from the layout being more complex, these units also require the construction of a suspended slab in order to complete the upper level. This is classified as specialized works, which limits the opportunities for emerging contractors and causes problems for the Contractor who is expected to allocate 30% of the works to local, emerging Contractors/SMMEs. As mentioned in section 2.5.1. emerging Contractors/SMMEs will typically experience difficulty finding local labour which can complete these specialized works.

Construction on the second story presents its own challenges as the precast staircases are only installed at a later stage to reduce the risk of damage to staircases. This makes inspections and quality control of the upper level difficult.

4.3. Data Collection Strategy

4.3.1. Iterative Definition: Design-Testing Process

The first step under data collection was to determine how the data would be collected while considering that the requirements for implementation of a drone to improve QC included effectiveness and practicality when compared to traditional methods.

The method through which a drone is used to assist with QC (i.e., through 2D analysis, 3D analysis or progress monitoring) could not be determined without on-site testing of the drone capabilities. Practicality and effectiveness of the various methods had to be reviewed on “prototype” ideas before the framework, which outlines the end-user requirements, could be completed. Therefore, the data collection strategy was an iterative process that was repeated until the requirements were met. The framework could then be developed if a method was found which could meet the requirements (Figure 23 provides a visual representation of the process followed).

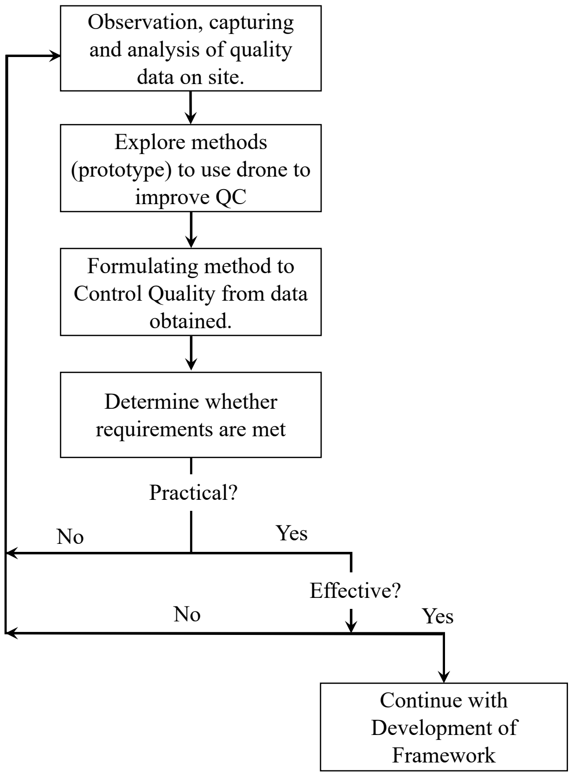


Figure 23. Iterative Process Followed to Collect Data

4.3.2. On-site data collection

During the construction phase of both projects, it was observed that many units were being constructed and completed (including all finishes such as plastering, painting, bathroom fittings, electrical fixtures, and ceilings) only for the Employer's Agent or other supervision to identify walls which did not adhere to the guidelines thereafter. This either resulted in the problem being overlooked or resulted in rectifying these defects after finishes had been completed, which resulted in rework being significantly more than if the defect had been identified earlier.

4.3.2.1. Traditional Measurements

To determine the scope of this quality problem, physical measurements of masonry walls were taken (using a measuring tape) on site on both Project 1 and 2 to compare the actual measurements to the dimensions specified in drawings. Figure 20, Figure 21 and Figure 22 show allocated IDs (wall numbers) for the different units in Project 1 and Project 2.

The next step was to determine how a drone could be used to either identify these defects or assist with continuously monitoring these dimensions as the construction of units progressed.

4.3.2.2. Drone Measurements

Three different methods were investigated which use a drone to identify measurements that do not adhere to the specifications:

- Using Construction Computer Software's Quantity Take Off (V4) (CCS QTO4) to measure walls off a 2D image taken with the drone directly from above (see Figure 24).
- Using code generated in MATLAB to measure walls off a 2D image taken with the drone directly from above.
- Developing a 3D model of a unit using photogrammetry software and then analysing the model in post-processing software.

Figure 24. Picture of HDDS units taken from above with Drone

The following was considered during this data collection process:

- Images had to be captured before successive works such as plastering, or roofing occurred.
- Depth within 2D images plays a role in accuracy (i.e., the user cannot calibrate the image at the top of the wall and take measurements at the bottom). Therefore, all measurements must be taken at the top of walls. Measurements taken by hand should also be taken as close to the top of the wall as possible to produce accurate results.
- The time taken for recording actual measurements on site should also be documented to compare to the time taken to get measurements from drone image.

4.3.3. Measurement Datasets

4.3.3.1. Traditional Data

In order to produce useful, comparative data, multiple HDDS and SASS units were measured. Measurements were taken on 8 different HDDS units and 16 different SASS units. The HDDS units consisted of a ground floor and first floor on which total of 60 and 71 measurements were taken, respectively. The SASS consisted of 21 measurements per unit. A total of 1 048 measurements were taken on HDDS units and 336 on SASS units (see Appendix C).

The logic diagram in Figure 25 provides a visual representation of the traditional data measurements and the analysis process that follows:

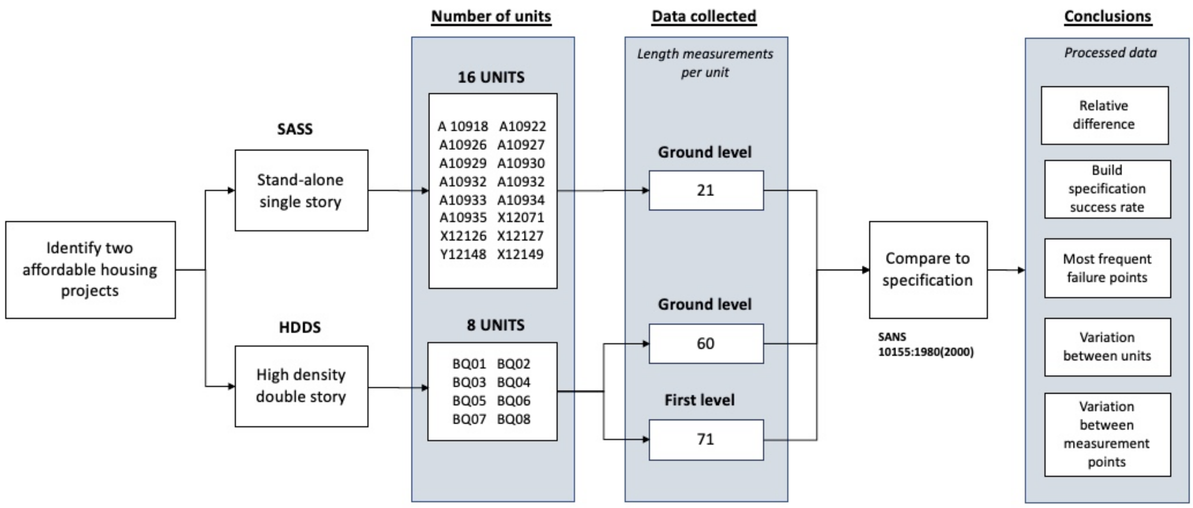


Figure 25. Logic diagram representing the traditional measurement data collection and process of analysis.

4.3.3.2. Drone Data

The same HDDS and SASS units that were measured using the traditional method were then measured using a photo analysis software and images taken by the drone. This meant that measurements using this technology were also taken on the 8 different HDDS units and 16 different SASS units. Measurements were only taken on the first floor of HDDS units using this software. The reference length (discussed below) used to calibrate the images isn't considered and as such, a total of 560 and 320 measurement were taken on the HDDS and SASS units, respectively (see Appendix D).

The logic diagram in Figure 26 provides a visual representation of the drone data measurements generated through QTO4 and MATLAB, and the process of analysis that follows:

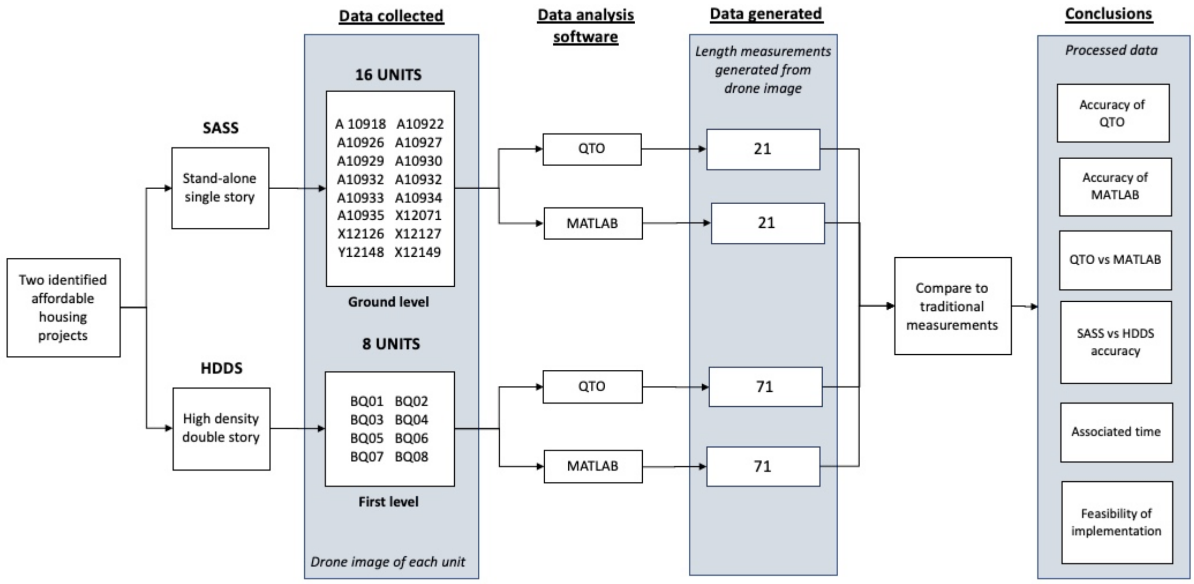


Figure 26. Logic diagram representing the drone data collection and process of analysis.

4.4. Data Processing

4.4.1. Traditional approach using Microsoft Excel

The data collected on site was captured in Excel as can be seen in Appendix C. These actual measurements could then be compared to the specified dimensions to draw conclusions regarding the quality on the two projects.

MS Excel, which was used as an analysis tool for the traditional measurements provided the following which will be discussed under the results and discussions (chapter 5):

- The number of measurements which did not adhere to the PDs stipulated in SANS 10155:1980(2000).
- Box and whiskers diagrams which assist with visually depicting the errors found.
- Measurement IDs which consistently produce defects. This allows supervision to be proactive by continuously monitoring these "critical" measurement IDs.

4.4.2. 2 Dimensional (2D) Drone Image Analysis Software

4.4.2.1. CCS QTO4

Construction Computer Software (CCS) has a Quantity Take-Off (QTO) feature which allows users to measure dimensions from 2D images. This is done by providing the software with one known reference measurement which calibrates the remainder of the image accordingly. Therefore, this analysis method still requires on-site measurement of at least one measurement ID traditionally. Measurement ID no. 1 measured on site was used as the reference length on all of the units.

Once the image has been calibrated, other measurements can be obtained from the 2D image by selecting which two points need to be measured (see Figure 27 for a visual example of the software with measured lengths given on the left after the image had been calibrated using measurement ID no. 1).

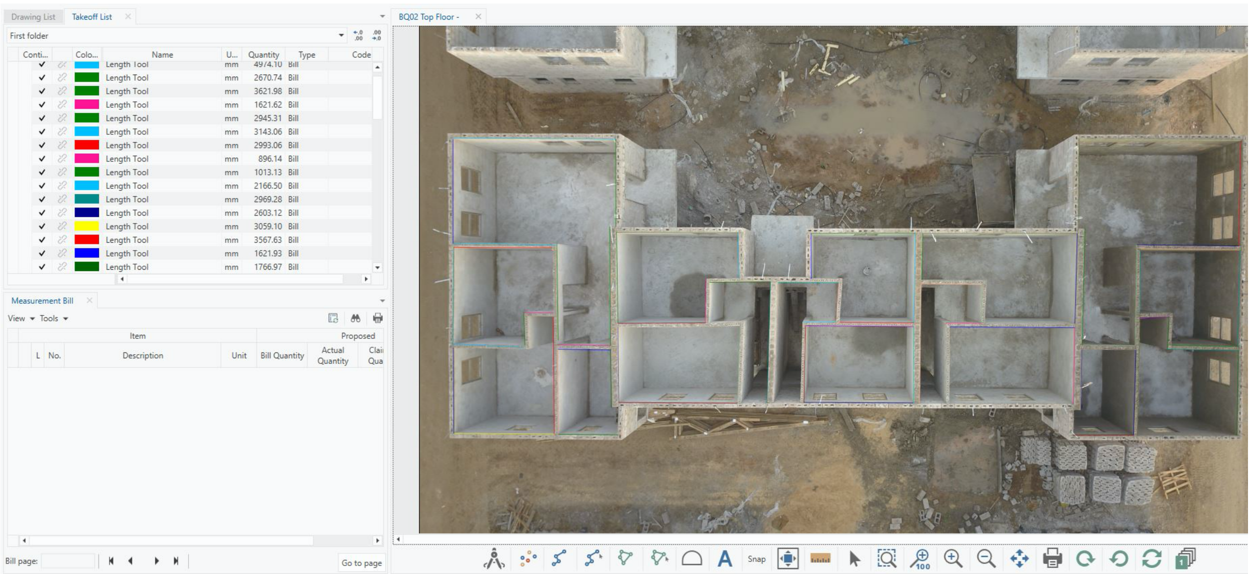


Figure 27. 2D drone image analysed in CCS QTO4 software (colours indicate walls which were measured).

4.4.2.2. MATLAB

Use of CCS QTO4 requires a substantial subscription fee and as such, MATLAB was investigated to determine whether code could be generated to replicate CCS QTO4 (QTO4 for short), and whether this can be used an alternate data processing software to compare generated measurements to the traditional measurements. The code (see Appendix H) was adapted from pre-existing code within the MATLAB library, but works on the same principle as QTO4 where the 2D image is calibrated according to a known dimension (reference length) given by the user. The code requires the user to specify the length between two points and then calculates the number of pixels present between these points. The code uses the reference length given by the user to calculate the ratio between the reference length and the number of pixels between the two points to provide the user with the “real length” between any other two points on the 2D image (assuming they are on the same plane) (see Figure 28 - Figure 30 showing the MATLAB program being run to produce a measurement after a random reference length was inserted).

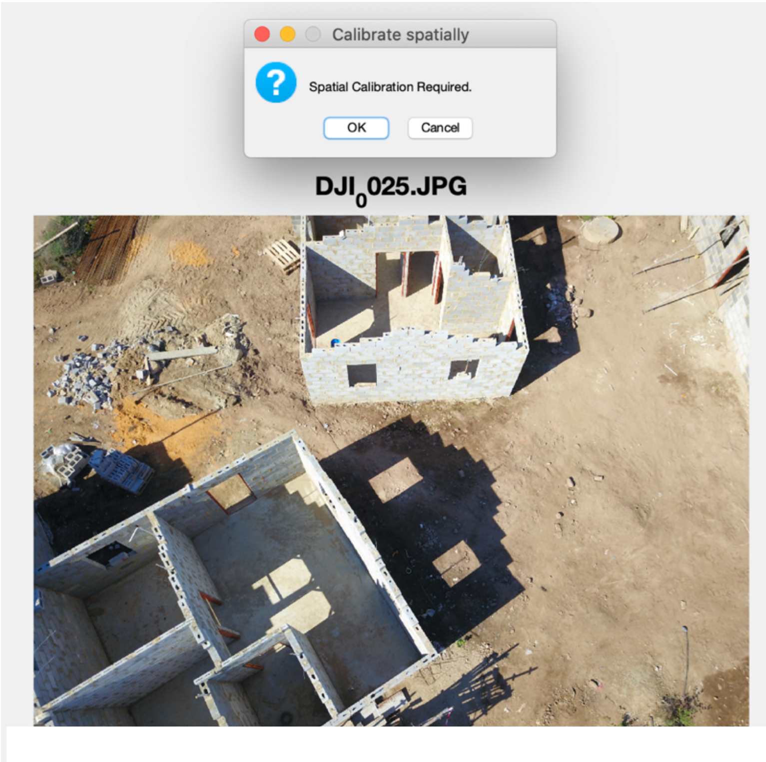


Figure 28. Graphical User Interface of MATLAB Requiring Calibration

Figure 29. Known Length Calibrating Image on MATLAB Software (Red

Figure 30. Length Being Measured on MATLAB Software (Green Line)

4.4.2.3. Comparing 2D analysis to Traditional

In addition to determining the accuracy of measurements taken from the 2D images, the time taken to extract these measurements was recorded. In doing so, it was possible to determine if the proposed methods would be practical and beneficial when compared to the traditional method. The time required to measure each of the buildings using the different methods (traditional, CCS QTO4 and MATLAB) can be seen in Table 3 and Table 4, for the SASS and HDDS units, respectively:

Table 3: Time Taken to Collect Data on SASS Units Using Different Methods.

Time Taken (in min.) to Collect Data SASS			
	Measurement Type		
Unit No	**Traditional**	**QTO**	**MATLAB**
10918	11	38	44
10922	14	39	46
10926	12	40	47
10927	11	41	39
10929	13	40	48
10930	11	38	46
10932	15	44	41
10933	10	41	43
10934	12	39	49
10935	15	42	42
12071	11	38	41
12126	10	43	48
12127	11	45	46
12148	13	36	43
12149	11	43	40
12157	14	44	44
Average	**12.1**	**40.7**	**44.2**

Table 4: Time Taken to Collect Data on HDDS Units Using Different Methods.

Time Taken (in min.) to Collect Data HDDS			
	Measurement Type		
Unit No	**Traditional**	**QTO**	**MATLAB**
BOQ1	35	80	83
BOQ2	38	74	86
BOQ3	34	85	86
BOQ4	37	74	86
BOQ5	40	76	87
BOQ6	41	85	88
BOQ7	34	74	80
BOQ8	37	75	89
Average	**37**	**77.9**	**85.6**

The time taken to collect data from 2D images does not include the time taken to capture the images on site, when considering this in addition to Table 3 and Table 4 it becomes evident that the time required to collect data using 2D drone images makes this method impractical.

4.4.3. 3-Dimensional Drone (3D) Image Analysis Software

A 3D model was investigated to determine whether dimensions can be detected and measured accurately in a shorter period of time than using the 2D model. Two software packages were considered for producing 3D models from drone images were considered namely, PIX4D and Agisoft Metashape. As previously discussed, image overlapping is important to provide good quality 3D models. Taking images with the required overlap can be done automatically through use of PIX4D's flight path generation capability.

This software allows the user to choose an object and customize a flight path around it together with the spacing of images that must be captured to achieve the required image overlapping (see Figure 31). However, in order to create a 3D model using this software requires payment of the monthly subscription fees. Therefore Agisoft Metashape (no fees) was used to develop the 3D model of units.

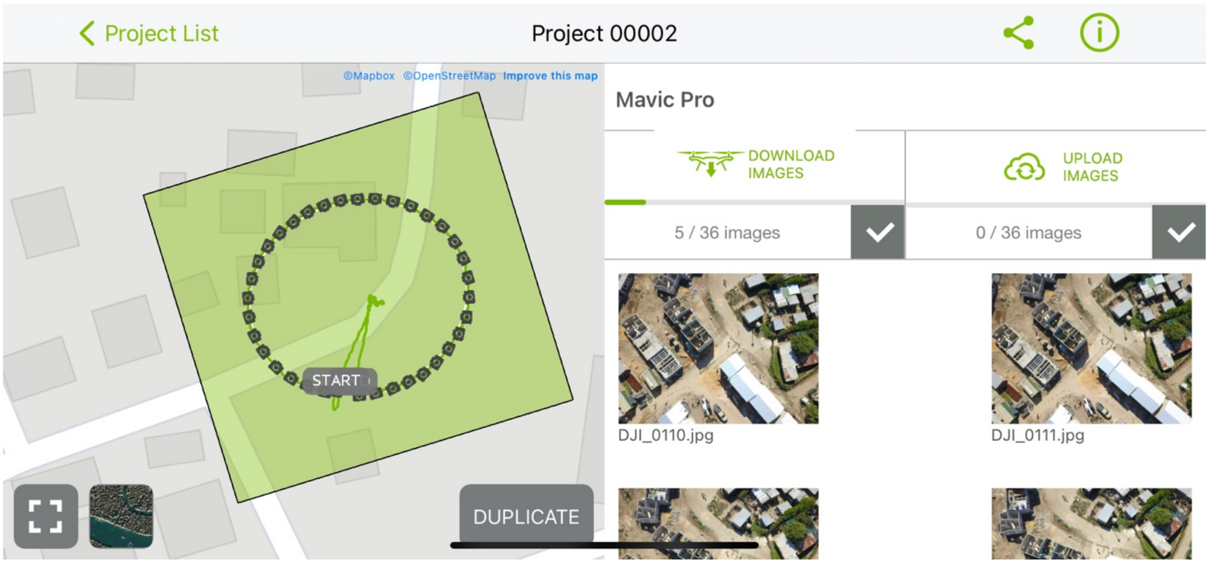


Figure 31. Automatic Flight Path and Image Capturing Using PIX4D Software

Figure 31. depicts a flight path that was flown on Project 2. In order to produce an accurate 3D model of a housing unit, the user should also take images at varying heights. This proved difficult to execute as both projects have a very dense building layout limiting the available flight space. Furthermore, the drone is required to fly sideways, (where there are no object avoidance sensors) while taking the images automatically. Therefore, it was decided that images would rather be taken manually to avoid the risk of the drone colliding with another building.

A total of 43 images were captured and imported into the Agisoft Metashape software. The process described in section 2.6.4.6. was followed systematically to produce a 3D model of a housing unit on

Project 2. During this process the user is faced with a decision on whether a high quality model should be produced that takes long to process, or whether the model should be produced quickly at lower quality. To determine the scale of variance between the two options, the settings were selected with the processing times associated as detailed in Table 5:

Table 5: Time Taken to Produce a 3D Model Using Agisoft Metashape.

Number of images = 43	**Option 1:** High Quality Long process time		**Option 2:** Low Quality Short Processing Time	
	Preference	**Processing Time**	**Preference**	**Processing Time**
Align Photos		26min 32sec		14min 45sec
Accuracy	High		Low	
Generic Preselection	Default		Default	
Key Point Limit	1000		500	
Tie Point Limit	4000		2000	
Apply Masks	Off		Off	
Guided Image Matching	On		Off	
Adaptive Camera Model Fitting	On		Off	
Build Dense Cloud		4hr 34min 12sec		56min 43sec
Quality	High		Low	
Depth Filtering	Aggressive		Mild	
Colour Points	On		On	
Point Confidence	Off		Off	
Build Mesh		1hr 45min 32sec		23min 11sec
Source Data	Dense Cloud		Tie Points	
Surface Type	Arbitrary		Height	
Quality/Face Count	High (240 000)		Low (26 000)	
Interpolation	On		Off	
Vertex Colours	On		On	
	TOTAL TIME	**6hr 46min 6sec**		**1hr 34min 39sec**

By comparing the high- and low quality 3D models produced (see Figure 32 - Figure 37) it is clear that there is a significant difference between the quality of models. Using the preferences associated with the low quality model produces a 3D model which is not useable for defect detection. However, developing a model of high quality which is useable, takes too long to classify this as a practical solution. Consequentially, this method was not further investigated.

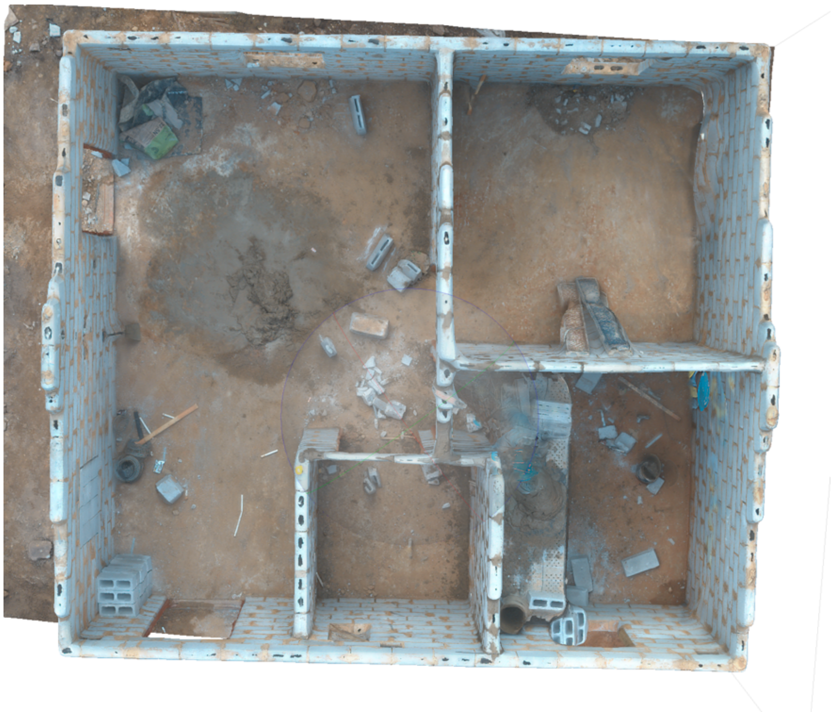


Figure 32. High Quality 3D Model of SASS Unit Generated with Agisoft Metashape (1)

Figure 33. Low Quality 3D Model of SASS Unit Generated with Agisoft Metashape (1)

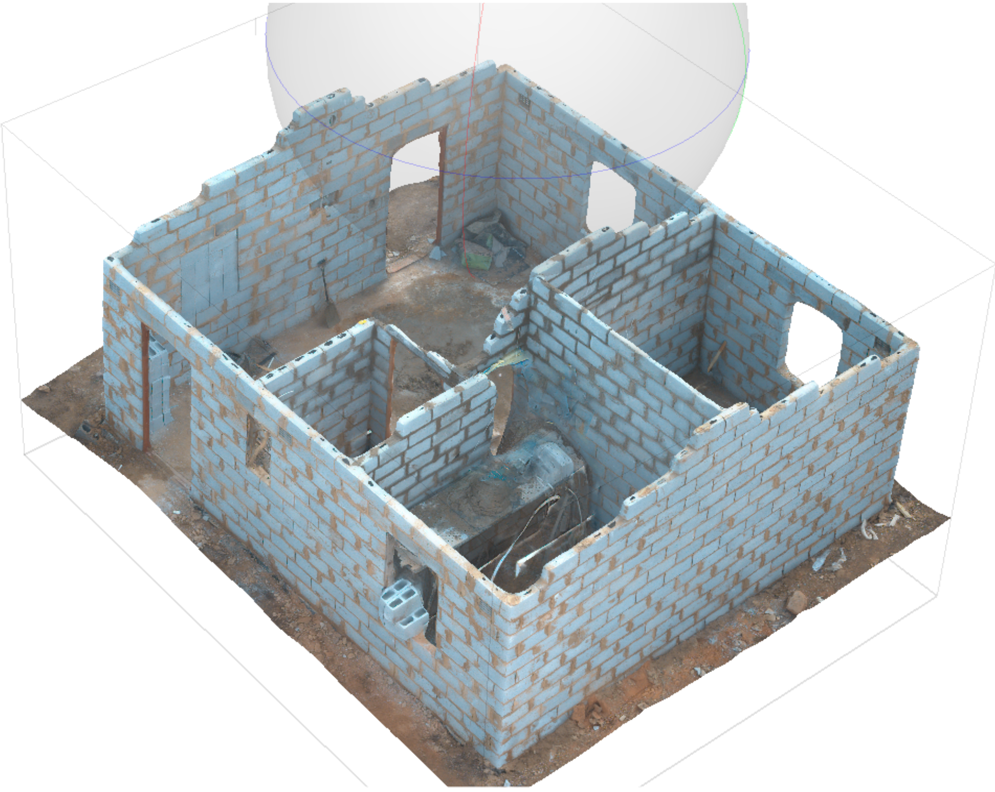


Figure 34. High Quality 3D Model of SASS Unit Generated with Agisoft Metashape (2).

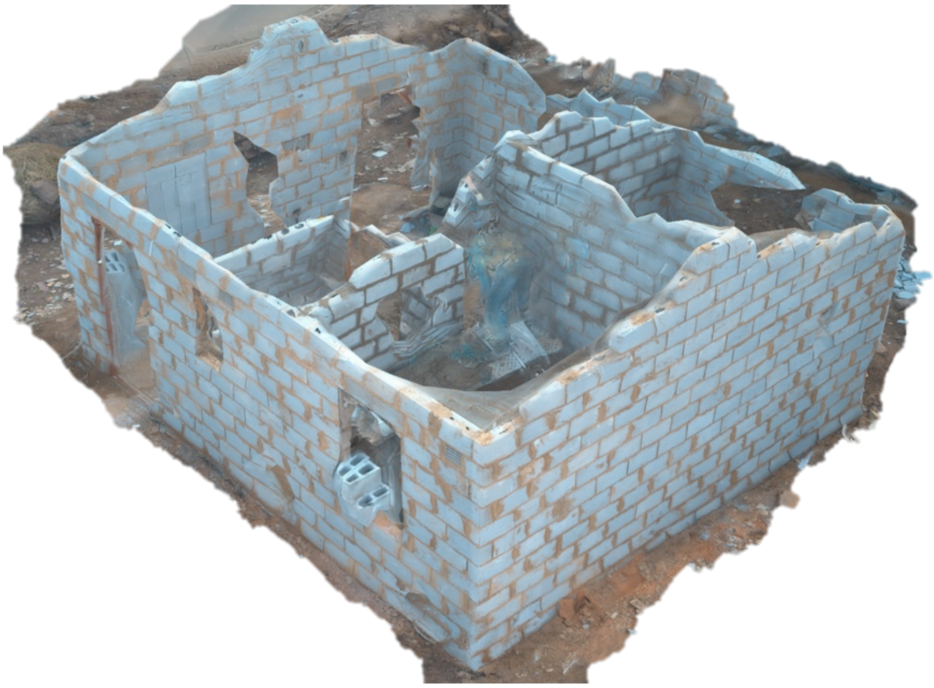


Figure 35. Low Quality 3D Model of SASS Unit Generated with Agisoft Metashape (2).

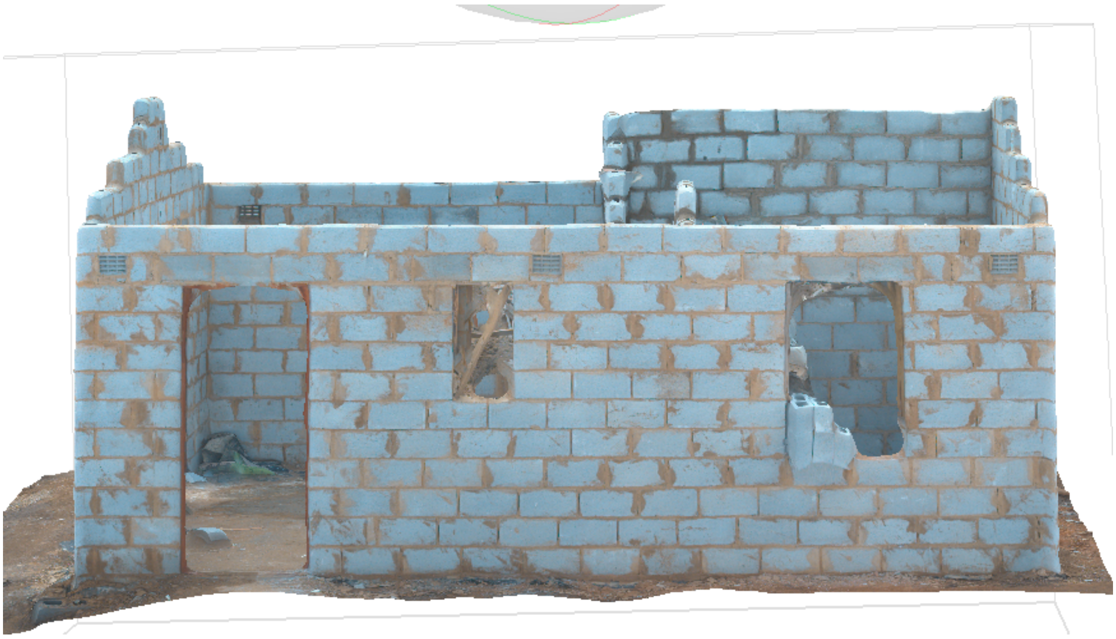


Figure 36. High Quality 3D Model of SASS Unit Generated with Agisoft Metashape (3).

Figure 37. Low Quality 3D Model of SASS Unit Generated with Agisoft Metashape (3).

4.5. Progress Monitoring as a Solution

Both the 2D and the 3D methods were classified as effective as they could be used to detect defects and thereby assist with improving quality. However, both of these methods were deemed impractical as they took longer to execute than simply using the traditional method. A final suggestion is to implement the drone for site monitoring use together with a dedicated Quality Manager (discussed further in chapter 6) .

The software previously mentioned can be implemented to create a flight path which can be flown periodically. The flight path chosen can be flown periodically and take images at certain points on site, thereby assisting the Quality Manager with effectively and practically monitoring the Works and the progress thereof. As an example, progress of HDDS (BQ01 to BQ08) can be seen in Figure 38 - Figure 45 (backgrounds have been removed to protect the identity of the location of the project).

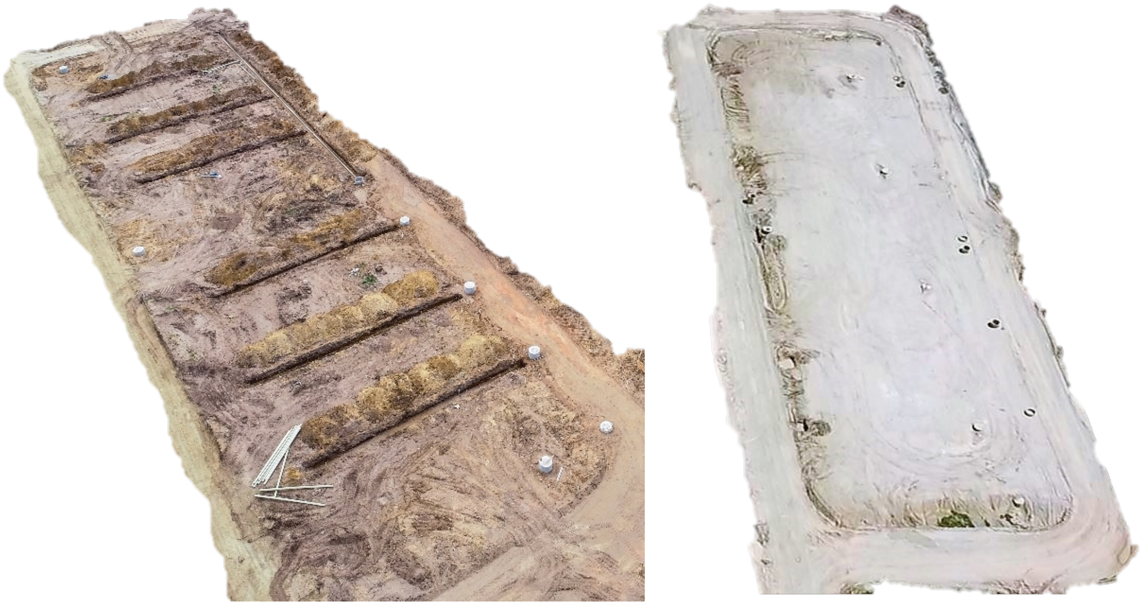


Figure 38. Services Being Installed on HDDS Project (Left) and Platform Completed Subsequently (Right) (Monitoring Image 1)

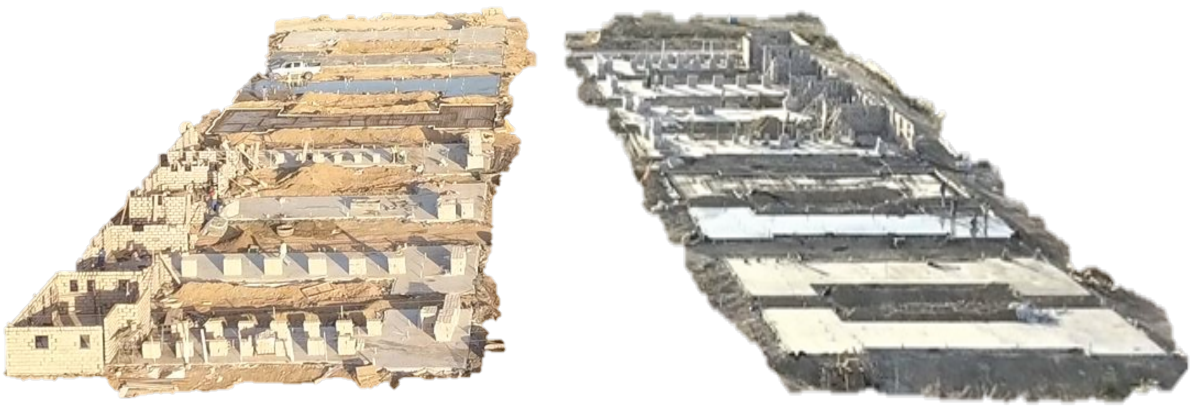


Figure 39. Raft Foundations being Completed and First Blockwork Commencing (Monitoring Image 2)

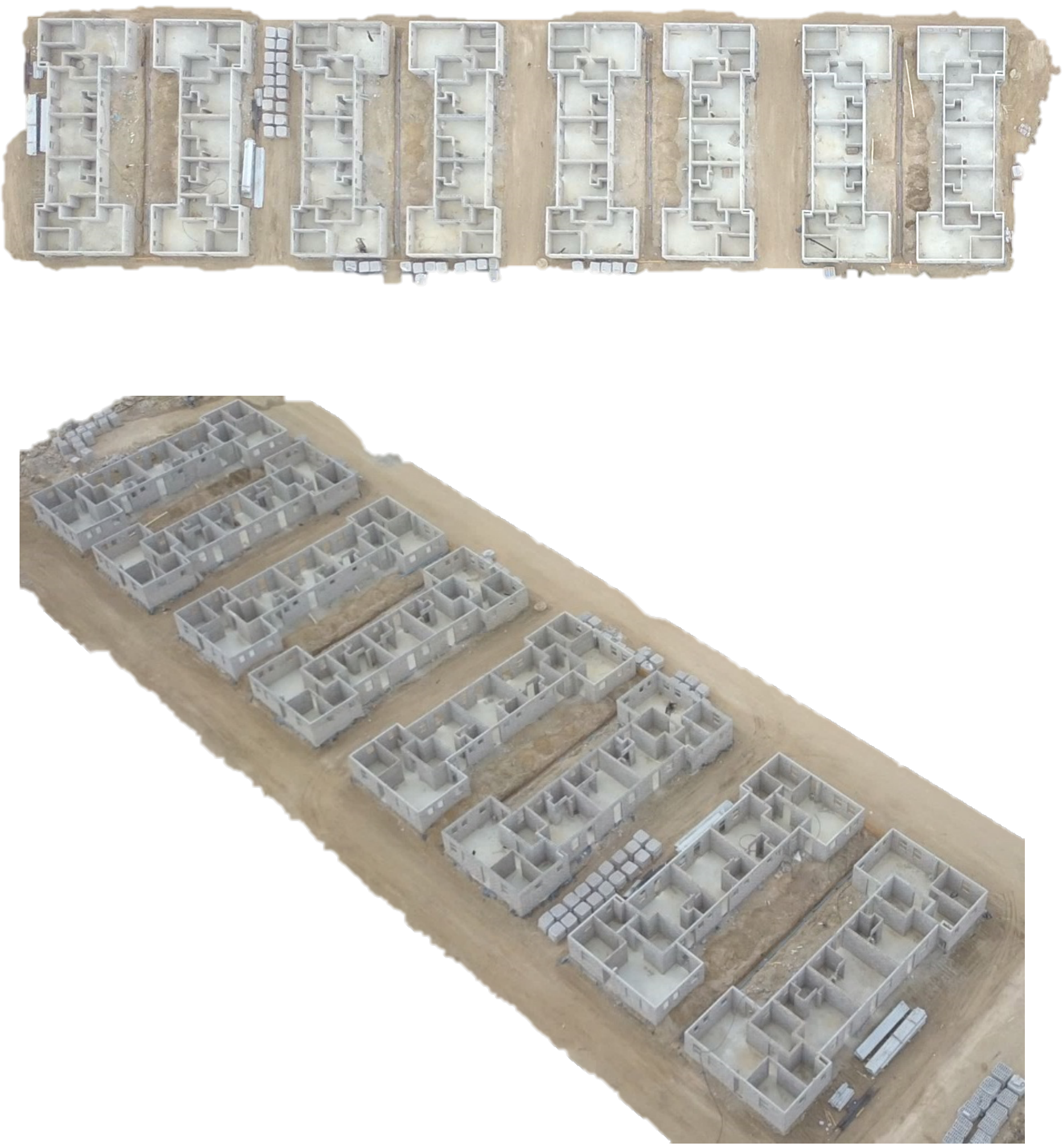


Figure 40. Ground Floor Blockwork Completed (Monitoring Image 3)

Figure 41. Hybrid Suspended Slabs Packed (Monitoring Image 4)

Figure 42. Hybrid Suspended Slabs Cast and First Floor Blockwork Commencing (Monitoring Image 5)

Figure 43. First Floor Blockwork Complete and Roof Construction Commencing (Monitoring Image 6)

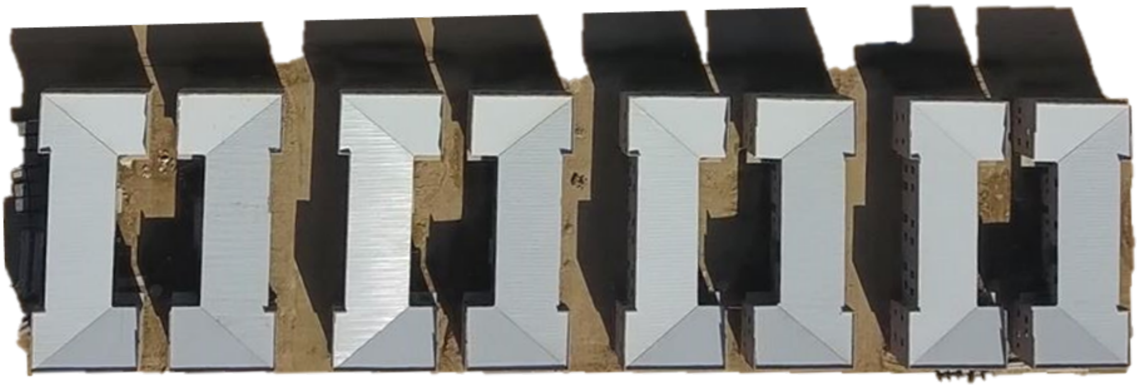


Figure 44. Roofs Completed

Figure 45. Building Works Completed
(Monitoring Image 8)

4.6. Chapter Synthesis

The time required to extract measurements from a 2D image makes this method impractical. The main reason is due to the human aspect which requires the user to accurately select the corner points which must be used for reference, and thereafter accurately select the points which need to measured.

Not only does this require a substantial amount of time, but it requires accuracy from the user, as an error of 1 pixel relates to an error of 0.9mm. If the corner points could be accurately measured in a shorter period of time without the need for significant human interaction, the method could become more practical. This could either be achieved through complex coding or more advanced drone technology. However, at present the 2D method was not seen as a practical solution when compared to the time required to inspect dimensional errors in housing units by using the traditional method.

Literature reported that site monitoring using drones is currently one of the widest applications of drone usage in the construction industry. This may change as the technology for drone-based measurement inspection (investigated in this study in 2D measurements) continually improves, however, current findings still favour the implementation of site monitoring with drones as a means to assist with improving quality control on affordable housing projects.

CHAPTER 5: RESULTS AND DISCUSSIONS

5.1. Chapter Overview

This chapter discusses the results obtained from the analysis of both traditional measurement data and the measurement data generated from drone images. Traditional measurement data and drone imaging were collected as raw data during the execution phase of this study and processed accordingly.

The relative error between the actual measurements collected on-site and the specified measurements as stipulated in the official building plan, was determined along with the corresponding variance across each unit, as well as between each unique measurement points across all the units. The relative error will be referred to as the percentage quality defects and the corresponding variance will be referred to variance between the extent of quality defects, where quality defects are defined as errors in wall length alone.

To compare the accuracy of drone-based measurement generation through QTO4 and MATLAB to the actual measurements collected by the traditional method, both the HDDS (first level) and SASS units were investigated. The accuracy and efficiency were investigated by comparing the relative error and time associated with data processing through each route. The variance between the relative error was also determine and discussed when comparing the drone-based data generation methods.

Both 2D and 3D analysis methods were investigated for the drone-based data generation, and outcomes are discussed briefly. The associated limitations are also presented for each analysis route, specifically focussing on the factors that informed the framework developed to improve quality monitoring and control in the next chapter.

5.2. Results and Discussions

5.2.1. Overview

This section discusses the results that were obtained from measurement data during the execution phase of the study. Raw data was collected in the form of on-site hand measurements (or traditional measurements) of each wall with a unique measurement ID. For each of the 8 HDDS units, both the ground level (60 walls) and first level walls (71 walls) were measured in accordance to their unique measurement ID. For each of the 16 SASS units 21 walls were measured according to their unique measurement ID. The raw data measurements that were collected and subsequently used in the data analyses, can be seen in Appendix C.

The traditional measurements were compared to the specified measurement value taking into account the allowable tolerance as specified by SANS 10155:1980. The measurements reporting outside of the specified tolerance range, either less than the minimum or more than the maximum allowable, was determined and collectively considered as the tolerance failure rate. The tolerance failure rate was compared for both the ground level, and the first level HDDS units, and the SASS units.

To compare the traditional method of data collection to collection by means of drone technology, a comparable dataset of measurements through drone imaging was generated. Drone images were taken of each HDDS and SASS unit measured during the traditional data collection phase with the exception of the ground level of the HDDS units. Different software options were investigated to generate wall measurements from the drone images and two main methods were ultimately selected: QTO4 and MATLAB. A complete measurement dataset was generated for all HDDS units (first level) and SASS units and compared to the traditional measurement obtained to assess the accuracy of the generated measurements.

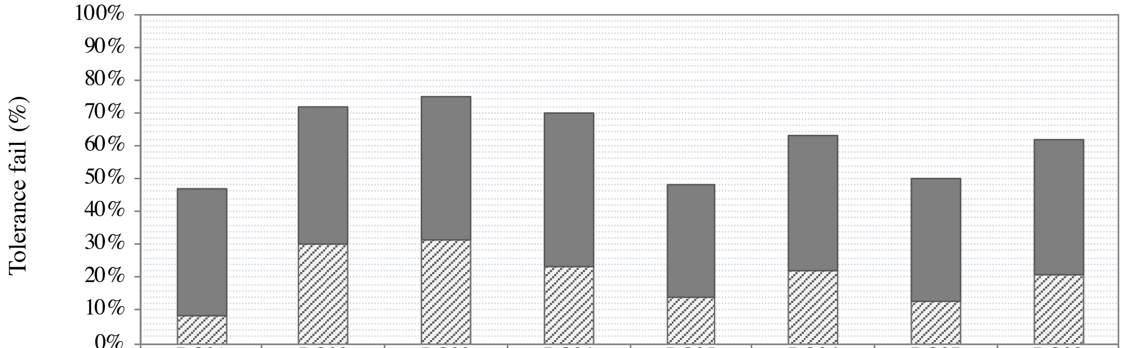
5.2.2. Traditional Measurements

The traditional measurements of both HDDS and SASS units were collected and compared to the required measurement specified on the official building plan. It was expected that the actual measurements would vary from the specified measurements and an allowable tolerance was defined in accordance to the standards as set out by SANS 10155:1980 (2000). By comparing the actual measurements to the specifications and defined tolerance, a conclusion could be drawn on the success rate of measurements within allowable tolerance.

The relative difference between the actual measurements and the specified measurement was calculated for each measurement ID and the variance was determined across each unit. Furthermore, the variance between each of the different measurement points was also determined. The processed data presented in this section can be seen in tabular form in Appendix D.

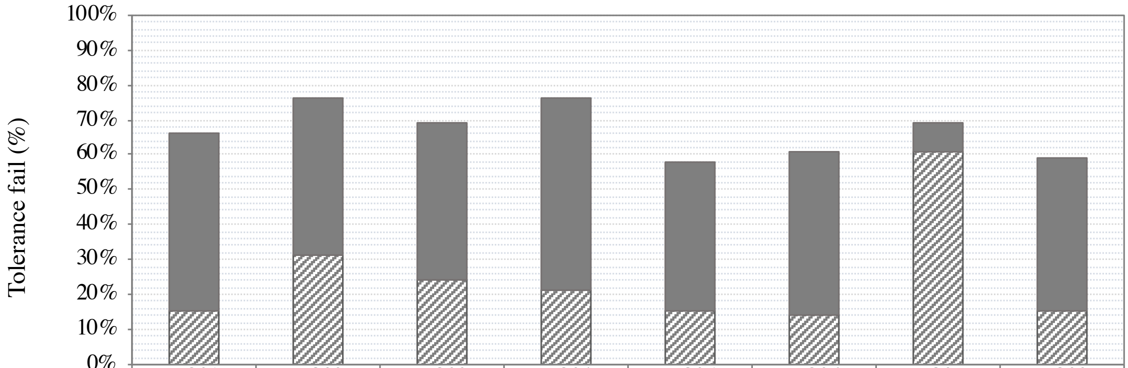
5.2.2.1. HDDS units

The HDDS units consisted of both the Ground Level and the First Level measurements. The actual measurements collected as traditional data was compared to the build specifications and corresponding allowable tolerance. Measurements that reported below the minimum (more than 15mm smaller than specification) or above the maximum (more than 15mm larger than specification) allowable tolerance collectively contributed to the total tolerance failure percentage across each unit and between each unique measurement point or wall across all units. A visual representation of the tolerance failure rate for both the Ground Level, and the First Level, can be seen in Figure 46 and Figure 47, respectively:



	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08
Above maximum	38%	42%	44%	47%	35%	41%	38%	41%
Below minimum	9%	30%	31%	23%	14%	22%	13%	21%

Figure 46: HDDS (Ground Level) measurements reporting below the minimum and above the maximum allowable tolerance.



	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08
Above maximum	51%	45%	45%	55%	42%	46%	8%	44%
Below minimum	15%	31%	24%	21%	15%	14%	61%	15%

Figure 47: HDDS (First Level) measurements reporting below the minimum and above the maximum allowable tolerance.

From Figure 46 and Figure 47 and a visual inspection of the trend across units it is evident that the amount of first level errors are more than ground level errors, and where measurements report a greater percentage of errors on the ground level, an increased number of error also occurs on the first level relative to the other units is observed. Therefore, the errors on the ground level affects the extent of the errors on the first level.

To further compare the source of error between the ground level and the first level, the average error due to measurements reporting below the minimum, and those reporting above the maximum, was determined and compared. In addition to the respective average tolerance failure rates, the associated standard deviation was also determined and is presented in Table 6:

Table 6: Average tolerance failure rate for HDDS Ground Level vs First Level measurements.

Tolerance fail (error)	HDDS (Ground Level)		HDDS (First Level)	
	Below	Above	Below	Above
Average	20%	41%	42%	25%
Standard deviation	8%	4%	14%	16%

From Table 6, it is observed that the error on the ground level was influenced more by measurements reporting above the specification (41%), as opposed to measurements reporting below the specification (20%). In contrast, the error on the first level was more impacted by measurements reporting below the specification (42%), as opposed to measurements reporting above the specification (25%).

The average error from all 8 units was also considered and are presented in Table 7 for both the ground level, and the first level.

Table 7: Total tolerance failure percentages for Ground Level and First Level HDDS measurements.

Unit	HDDS (Ground Level)	HDDS (First Level)
BQ01	47%	66%
BQ02	72%	76%
BQ03	75%	69%
BQ04	70%	76%
BQ05	48%	58%
BQ06	63%	61%
BQ07	50%	69%
BQ08	62%	59%
Average	**61%**	**67%**
Standard deviation	**11%**	**7%**

From Table 7, it can be observed that the average error for the first level is greater than that of the ground level. The first level measurements report a 67% error compared to a 61% error on the ground level. This was expected since the quality issues on the ground level would indirectly affect the quality on the first level.

The measurements for each of the walls, represented by a unique measurement ID number, were compared across the 8 units to determine the probability of an error occurring for the specified measurement ID. If the probability of an error occurring was the same for multiple measurements, they were grouped together to provide the overall percentage of measurements (or walls) in the dataset that were associated with this probability of error. For the ground level, Table 8 represents the probability of error for each unique measurement ID and the percentage measurements associated with each error probability:

Table 8: HDDS (Ground Level) error probability as a function of unique measurement ID.

Probability of Error	Measurement ID	Total Measurements	Percentage Measurements
100%	4, 7, 9, 43	4	7%
88%	12, 21, 22, 60	4	7%
75%	8, 10, 19, 30, 32, 35, 37, 38, 40, 44, 46, 48, 53, 55, 56, 58	16	27%
63%	6, 14, 16, 24, 25, 27, 31, 41, 45, 51	10	17%
50%	3, 5, 11, 13, 15, 18, 20, 26, 33, 47, 50, 52, 54, 57, 59	15	25%
38%	1, 2, 23, 36, 39, 42	6	10%
25%	28, 29, 34	3	5%
13%	17, 49	2	3%

Evidently, approximately 82% of walls measured on the ground level had a 50% and higher probability of being out of tolerance.

For the first level, Table 9 represents the probability of error occurring for each unique measurement ID and the percentage measurements associated with probability of error:

Table 9: HDDS (First Level) error probability as a function of unique measurement ID.

Probability of error	Measurement ID	Total Measurements	Percentage Measurements
100%	5, 6, 10, 26, 28, 32, 42, 45, 46, 50, 54, 58, 65, 67, 68	15	21.1%
88%	2, 11, 16, 17, 23, 25, 44, 52, 63	9	12.7%
75%	1, 4, 13, 15, 21, 22, 29, 37, 38, 39, 59, 61, 69, 71	14	19.7%
63%	3, 18, 19, 30, 33, 34, 35, 36, 43, 48, 49, 64	12	16.9%
50%	12, 40, 47, 56, 57, 62, 66	7	9.9%
38%	8, 20, 27, 41, 51, 53	6	8.5%
25%	31	1	1.4%
13%	7, 9, 24, 60	4	5.6%
0%	14, 55, 70	3	4.2%

From Table 9 approximately 80% of walls measured on the first level had a 50% and higher probability of being out of tolerance.

To assess the variation in relative error between the measurements across all the units, a box and whisker plot was generated for both the ground level and the first level data. The relative error between the actual measurement collected on-site and the specified measurement value was calculated (see Appendix D) and used as the basis of the comparison. The box and whisker plot generated for the ground level measurements is presented in Figure 48:

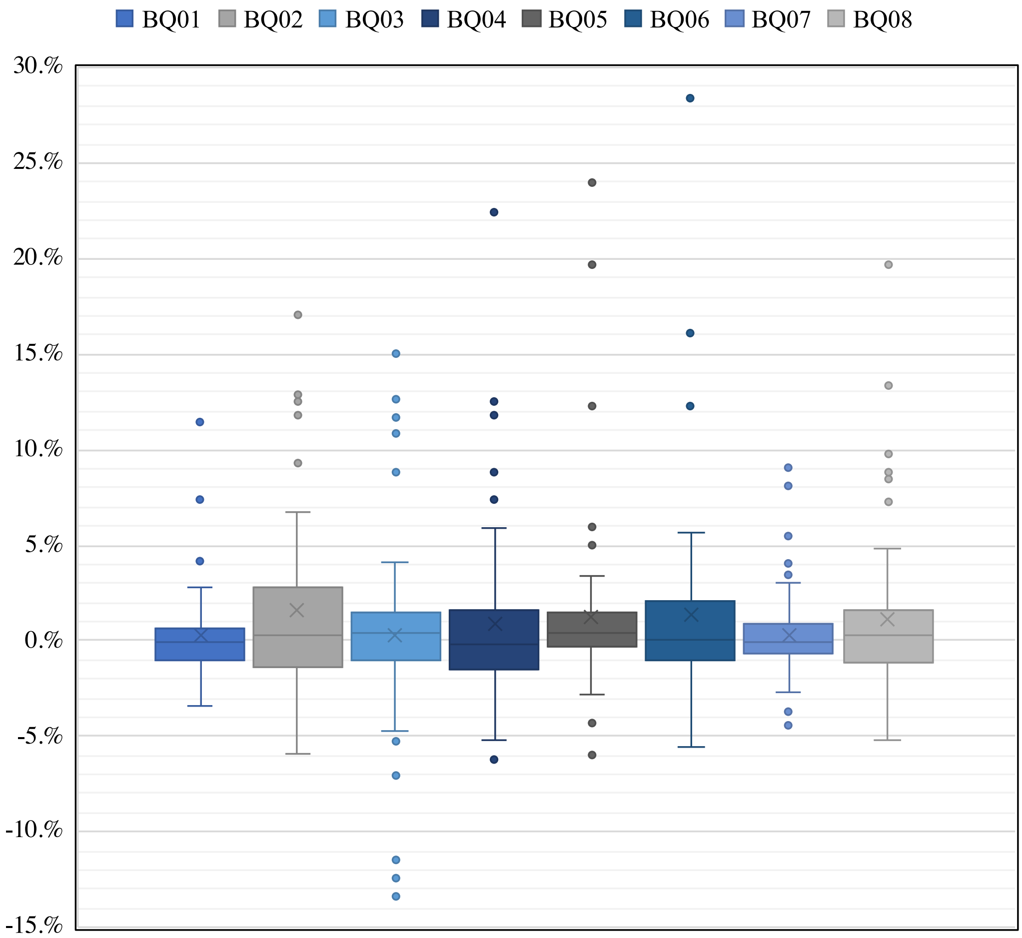


Figure 48: Box and whisker plot representing the relative error in measurements between 8 HDDS units (Ground level).

The following observations were made from Figure 48:

- The average relative error between the actual measurements and the specified measurements remained fairly consistent across all the units, reporting error variances within the range of 0 ± 1%. This concluded that the measurement data, i.e., the extent of quality defects, was comparable between each of the unit.
- The interquartile range (IQR) of the relative error for each of the units reported between 0 ± 2.5%; i.e., concluding that 50% of the measurements, or quality defects, had an associated relative error of no more than 2.5%.

- The IQR for BQ02 was the broadest, indicating that this unit had the largest concentration of quality defects in terms of wall lengths.
- The IQR for BQ01 and BQ07 was more compressed, indicating the lowest concentration of quality defects in terms of wall lengths.
- The outliers for all the units indicate that the relative error data determined consisted predominantly of positive differences, owing to the fact that most measurements reported higher than the specified measurement value. The data presented in Table 6 corroborates this conclusion.

The box and whisker plot generated for the relative error variance of the HDDS first level measurements is presented in Figure 49:

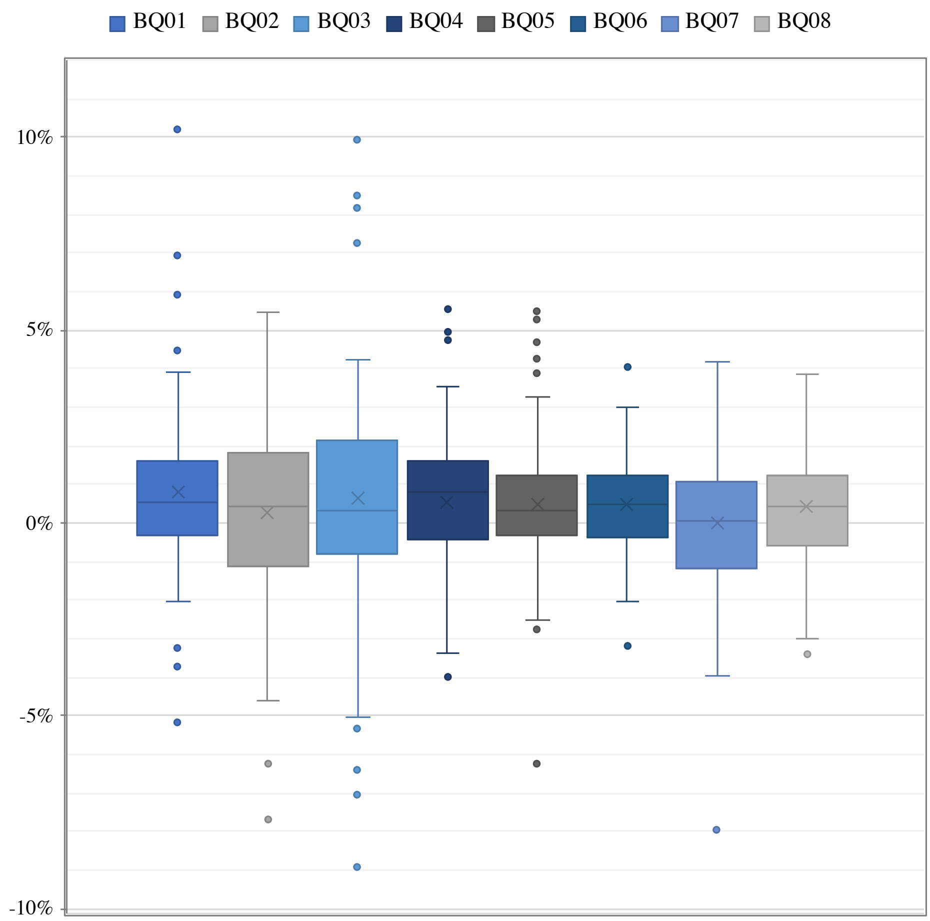


Figure 49: Box and whisker diagram representing the relative error in measurements between 8 HDDS units (First level).

The following observations were made from Figure 49:

- The average relative error between the actual measurements and the specified measurements remained fairly consistent across all the units, reporting error variances within the range of 0 ±

1%. This concluded that the measurement data, i.e., the extent of quality defects, was comparable between each of the unit.

- The interquartile range (IQR) of the relative error for each of the units reported between 0 ± 2.5%; i.e., concluding that 50% of the measurements, or quality defects, had an associated relative error of no more than 2.5%.
- The IQR for BQ02 and BQ03 was the broadest, indicating that these units had the largest concentration of quality defects in terms of wall lengths.
- The IQR for BQ05 and BQ06 was more compressed, indicating the lowest concentration of quality defects in terms of wall lengths.

The variation between each measurement point error across the 8 HDDS units was determined and can be seen in the following figures for both the ground level (Figure 50), and the first level (Figure 51):

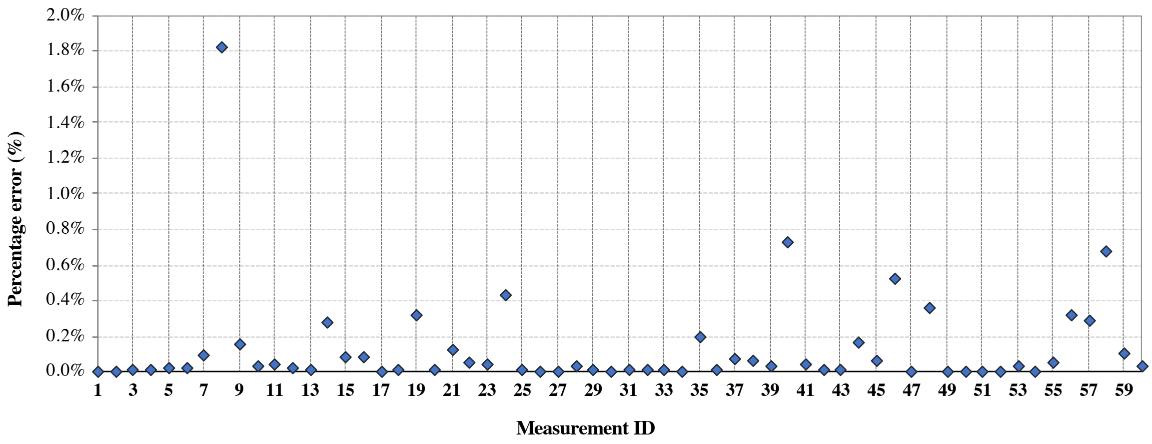


Figure 50: Variation in relative error between 60 measurement points of each of the 8 HDDS units (Ground level).

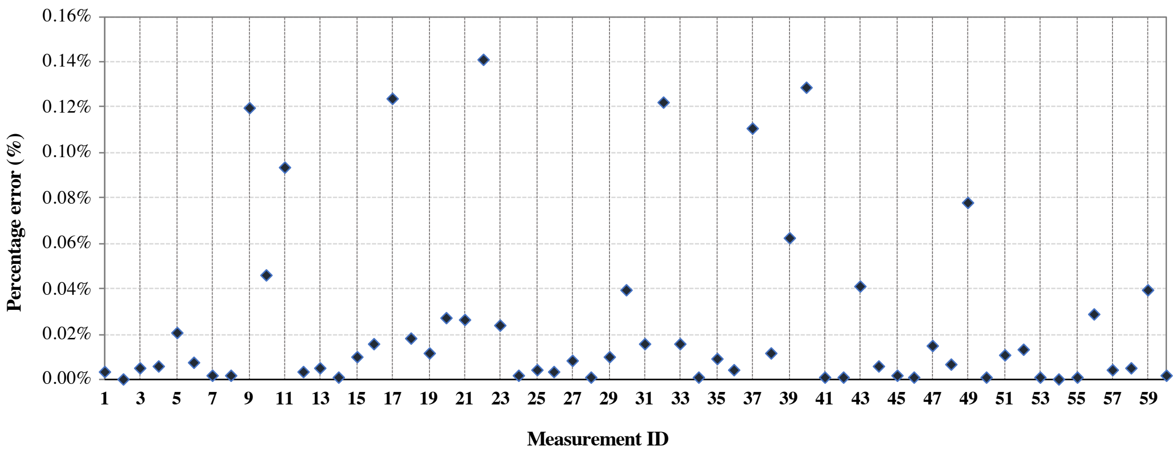


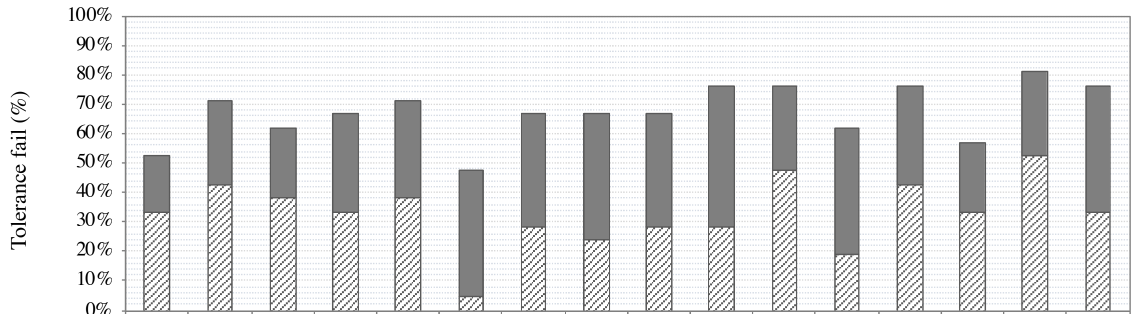
Figure 51: Variation in relative error between 60 measurement points of each of the 8 HDDS units (First Level).

From Figure 50 and Figure 51 it is clear that the variance between each measurement point is generally greater when considering the first level.

- The ground level variance between the measurements report between 0 and 2.0%.
- The first level variance between the measurements report between 0 and 0.16%.

5.2.2.2. SASS units

The SASS units consisted only of ground level measurements. The actual measurements collected as traditional data was compared to the build specifications and corresponding allowable tolerance. Measurements that reported below the minimum or above the maximum allowable tolerance collectively contributed to the total tolerance failure percentage across each unit and between each unique measurement point or wall across all units. A visual representation of the probability of error across each unit can be observed in Figure 52:



	10932	10933	10934	10935	10930	10929	10927	10926	10922	10918	12127	12126	12148	12157	12149	12071
Above maximum	19%	29%	24%	33%	33%	43%	38%	43%	38%	48%	29%	43%	33%	24%	29%	43%
Below minimum	33%	43%	38%	33%	38%	5%	29%	24%	29%	29%	48%	19%	43%	33%	52%	33%

Figure 52: SASSS measurements reporting below the minimum and above the maximum allowable tolerance.

A visual inspection of the trend across the units (Figure 52) indicate that the tolerance failure ranges between 50 – 80%. To compare the source of percentage of errors occurring in terms of measurements reporting below the minimum, and those reporting above the maximum, the average percentage of errors occurring for each was determined and compared. In addition to the respective average error percentage, the associated standard deviation was also determined and is presented in Table 10:

Table 10: Total tolerance failure rate for SASS measurements.

Unit	Error percentage		
	Below	Above	Total
10932	33%	19%	52%
10933	43%	29%	71%
10934	38%	24%	62%
10935	33%	33%	67%
10930	38%	33%	71%
10929	5%	43%	48%
10927	29%	38%	67%
10926	24%	43%	67%
10922	29%	38%	67%
10918	29%	48%	76%
12127	48%	29%	76%
12126	19%	43%	62%
12148	43%	33%	76%
12157	33%	24%	57%
12149	52%	29%	81%
12071	33%	43%	76%
Average	**33%**	**34%**	**67%**
Standard deviation	**11%**	**8%**	**9%**

From Table 10, it was determined that the errors occurring below the minimum tolerance (33%) was similar to the errors occurring above the maximum tolerance (34%).

The same approach followed for the HDDS units was followed for SASS units and, as such, the measurements for each of the walls, represented by a unique measurement ID number, were compared across the 16 units to determine the probability of an error occurring for the specified measurement ID. If the probability of an error occurring was the same for multiple measurements, they were grouped together to provide the overall percentage of measurements (or walls) in the dataset that were associated with to this probability of error. For the ground level, Table 11 represents the probability of error for each unique measurement ID and the percentage measurements associated with each error probability:

Table 11: SASS tolerance failure rate as a function of unique measurement ID.

Tolerance failure rate	Measurement ID	Total measurements	Measurements at failure rate
100%	2, 4	2	9.5%
88%	6, 14, 15	3	14.3%
75%	1, 13	2	9.5%
69%	8, 10, 20	3	14.3%
63%	11, 16, 18	3	14.3%
56%	5, 12, 17, 19, 21	5	23.8%
44%	7, 9	2	9.5%
38%	3	1	4.8%
0%		0	0.0%

Evidently, approximately 78.6% of walls measured on the ground level had a 50% and higher probability of being out of tolerance.

The box and whisker plot generated for the 16 SASS units' measurements is presented in Figure 53:

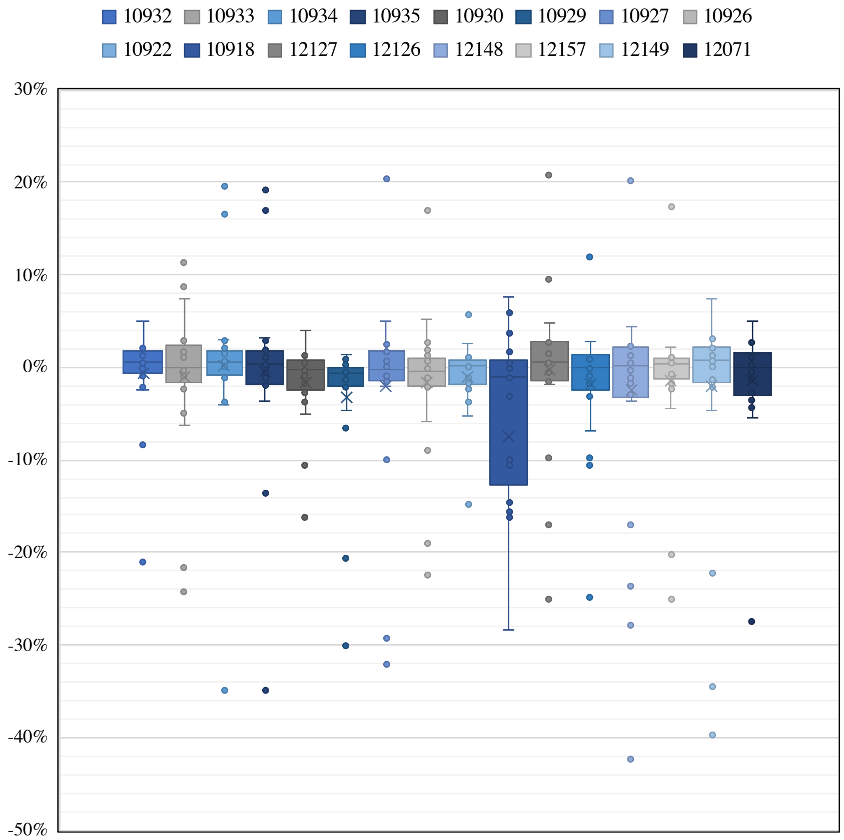


Figure 53: Box and whisker diagram representing the relative error in measurements between 16 SASS units.

The following observations were made from Figure 53:

- The average relative error between the actual measurements and the specified measurements remained fairly consistent across all the units, reporting error variances within the range of 0 ± 1%. This concluded that the measurement data, i.e., the extent of quality defects, was comparable between each of the unit.
- The interquartile range (IQR) of the relative error for each of the units (with the exception of unit 10918) reported between 0 ± 2.5%; i.e., concluding that 50% of the measurements, or quality defects, had an associated relative error of no more than 2.5%.
- The IQR for unit 10918 was the broadest, indicating that this unit had the largest concentration of quality defects in terms of wall lengths.
- The IQR for 10929 and 12157 was more compressed, indicating the lowest concentration of quality defects in terms of wall lengths.

For the sake of brevity, these descriptions are not included for the box and whiskers diagrams which will follow. Instead, only the general trends are discussed.

The variation between each measurement point error across the 16 SASS units was determined and can be seen in the Figure 54:

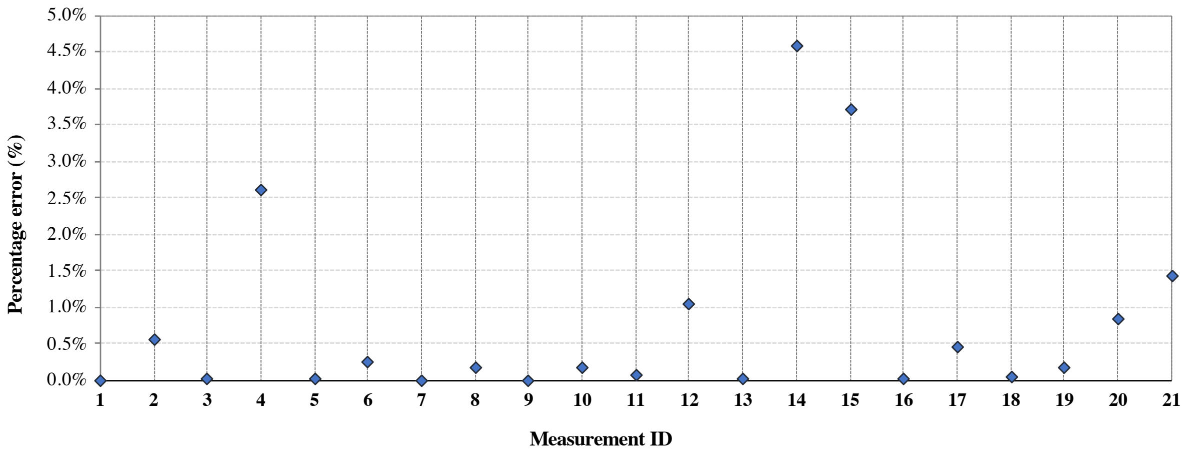


Figure 54: Variation in relative error between 21 measurement points of each of the 16 SASS units).

5.2.3. Drone measurements and 2D Analysis Methods

The measurements obtained through drone technology, of both HDDS and SASS units, were generated by processing drone images in QTO4 and MATLAB to produce length measurements as output. To this end, two datasets were generated for both the HDDS and SASS units and compared to the actual measurements collected as traditional measurements on-site. It was expected that the drone generated measurements would vary from the actual measurements and the relative error between the generated data and the actual data was used as the basis for comparison. This was done for both QTO4 and

MATLAB to conclude whether monitoring of quality, defined as wall lengths, is more effective than monitoring by means of traditional measurements. The accuracy of QTO4 and MATLAB was also compared on the basis of calculated relative error and processing time.

The relative difference between the generated measurements and the actual measurements was calculated for each measurement ID and the variance in relative error was determined across each unit. Furthermore, the variance between each of the different measurement points was also determined. The processed data presented in this section can be seen in tabular form in Appendix D.

5.2.3.1. HDDS Units

To determine whether MATLAB or QTO4 can be employed to measure the same walls accurately from a drone imagine compared to the traditional measurement method, measurements for the first level of each HDDS unit was generated through both MATLAB and QTO4 respectively. The relative error was calculated between the generated data and the traditional data, and the corresponding variance was calculated for each data set.

To assess the variation in relative error between the measurements across all the units, a box and whisker plot was generated for the HDDS measurements generated through QTO4 and MATLAB as seen inFigure 55 and Figure 56, respectively:

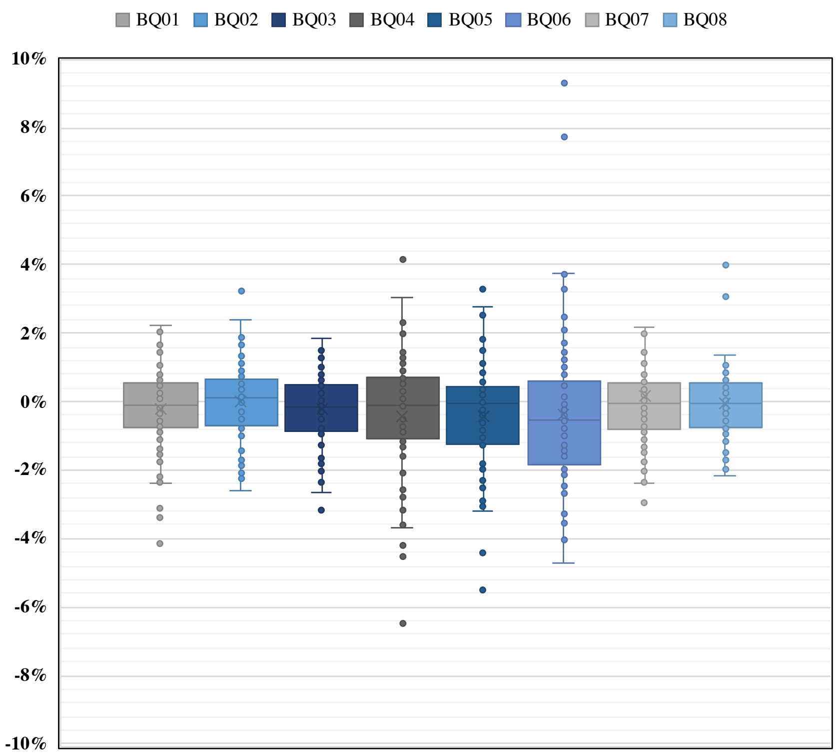


Figure 55: Box and whisker diagram representing the relative error measurements generated by QTO for 8 HDDS units.

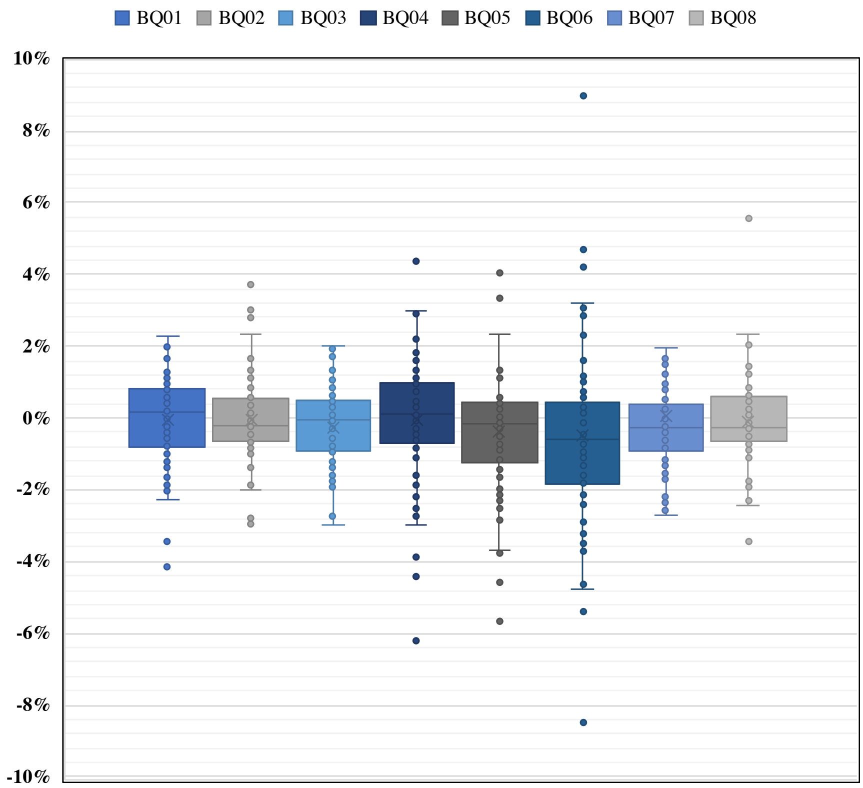


Figure 56: Box and whisker diagram representing the relative error measurements generated by MATLAB for 8 HDDS units.

The average variance in measurements collected for both software types was then calculated and presented as a box and whiskers diagram in Figure 57. From Figure 57 it can be seen that the variance of measurements collected by QTO and MATLAB was relatively similar results for the HDDS units.

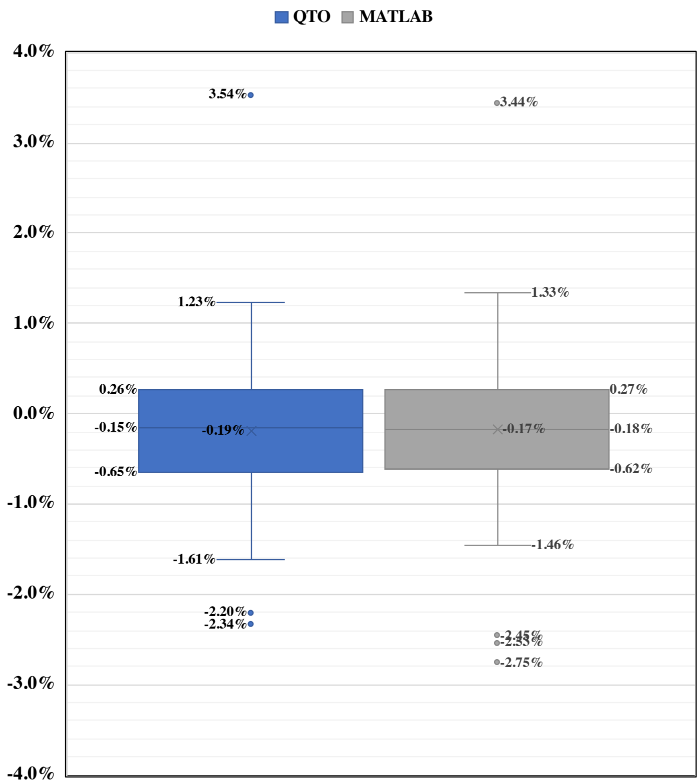


Figure 57: Box and whisker diagram representing the variance in measurements generated by QTO vs. MATLAB for 8 HDDS units.

The low variance between actual values meant that average difference between the actual dimension on-site and the measurement being generated was consistent and that the measurements taken from the drone could be considered if they were accurate enough. To determine the accuracy of the measurements generated from both MATLAB and QTO, the average absolute difference between the actual measurement and the measurements generated were determined (see Appendix D) and summarized in Table 12.

Table 12. Average Absolute Difference of Drone Measurements Compared to Actual Measurements (HDDS)

	Average Absolute Difference (in mm)	
Unit	**QTO4**	**MATLAB**
BQ01	21.7	22.8
BQ02	20.1	21.9
BQ03	18.9	19.3
BQ04	27.4	28.4
BQ05	25.1	26.4
BQ06	36.0	39.7
BQ07	31.1	32.9
BQ08	16.2	19.0
AVERAGE	24.5	26.3

From Table 12 it was found that the average accuracy of measurements taken from QTO4 and MATLAB on the HDDS units was 24.5 mm and 26.3 mm, respectively.

5.2.3.2. SASS Units

To determine whether MATLAB or QTO4 can be employed to measure the same walls accurately from a drone imagine compared to the traditional measurement method, measurements of each SASS unit was generated through both MATLAB and QTO4 respectively. The relative error was calculated between the generated data and the actual traditional data, and the corresponding variance was calculated for each data set.

To assess the variation in relative error between the measurements across all the units, a box and whisker plot was generated for the SASS measurements generated through QTO4 and MATLAB as seen in Figure 58 and Figure 59, respectively:

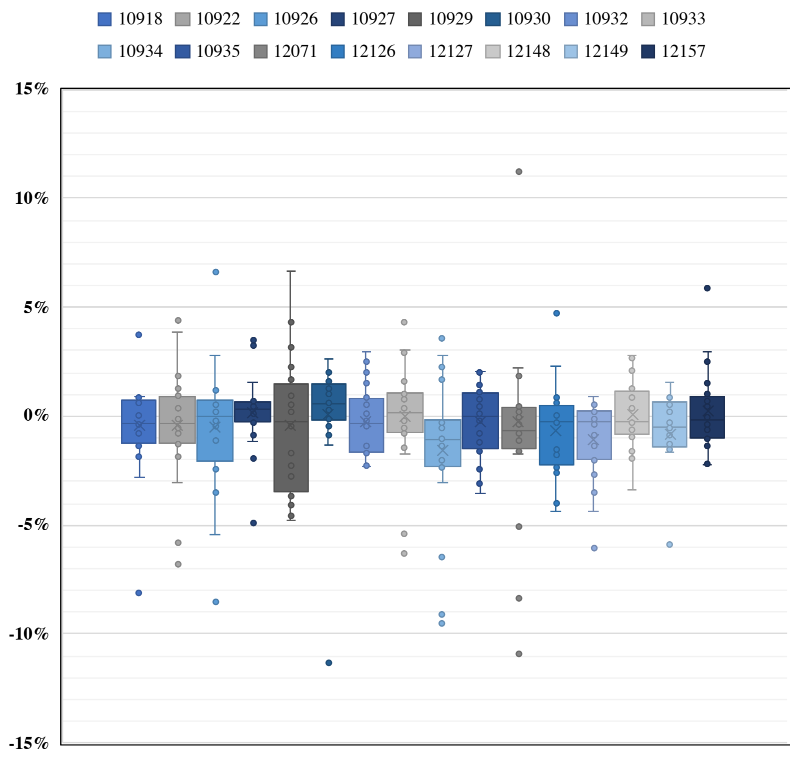


Figure 58: Box and whisker diagram representing the relative error measurements generated by QTO for 16 SASS units.

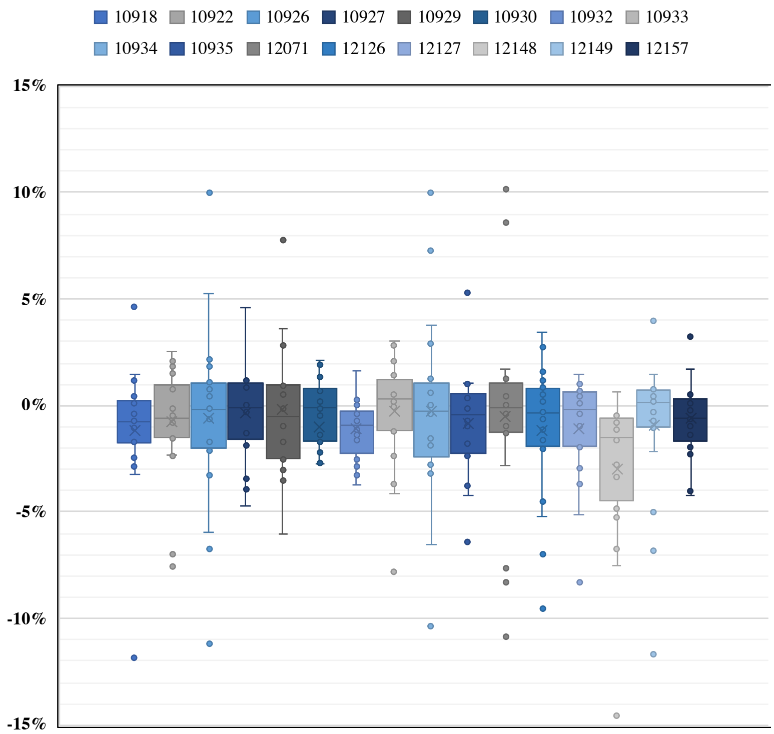


Figure 59: Box and whisker diagram representing the relative error measurements generated by MATLAB for 16 SASS units.

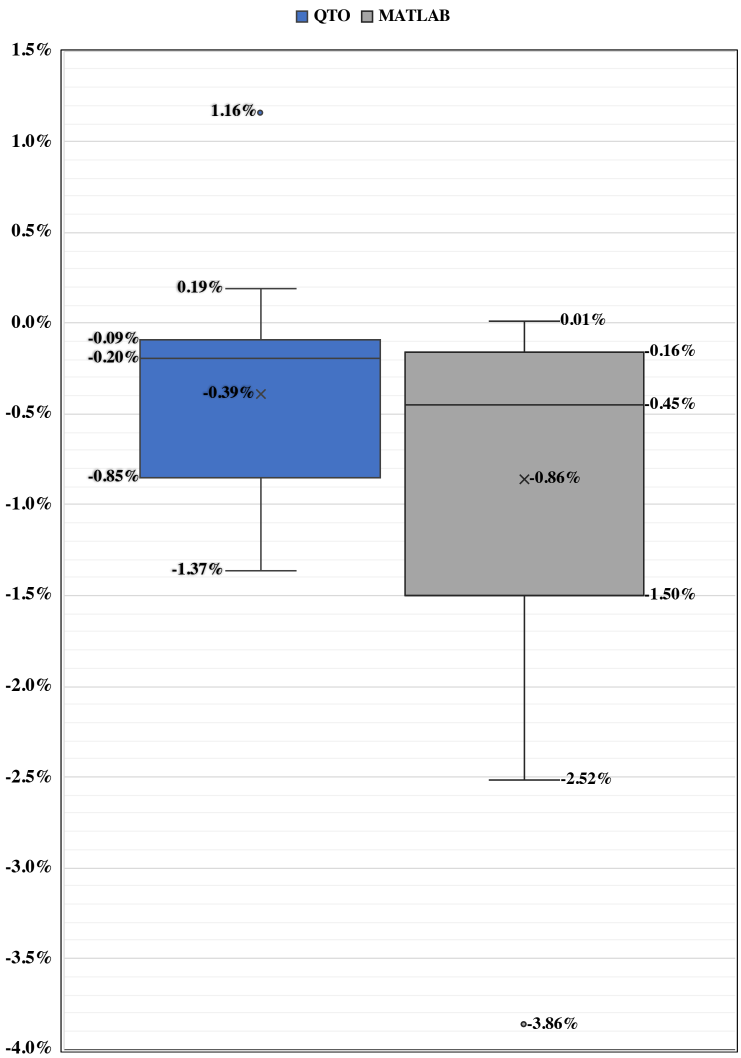


Figure 60: Box and whisker diagram representing the variance in measurements generated by QTO vs. MATLAB for 16 SASS units.

The low variance between actual values meant that average difference between the actual dimension on-site and the measurement being generated was consistent and that the measurements taken from the drone could be considered if they were accurate enough when compared to the actual measurements taken on site. To determine the accuracy of the measurements generated from both MATLAB and QTO, the average absolute difference between the actual measurement and the measurements generated were determined (see Appendix D) and summarized in Table 13

Table 13. Average Absolute Difference of Drone Measurements Compared to Actual Measurements (SASS)

	Average Absolute Difference (in mm)	
Unit	**QTO4**	**MATLAB**
10918	20.1	27.3
10922	21.7	23.2
10926	23.5	31.6
10927	15.1	18.7
10929	31.2	31.0
10930	20.6	23.6
10932	20.7	20.4
10933	21.6	20.9
10934	31.0	29.4
10935	18.0	20.9
12071	29.0	29.1
12126	17.1	25.1
12127	15.9	20.4
12148	15.3	35.2
12149	19.0	20.0
12157	16.3	18.1
AVERAGE	21.0	24.7

From Table 13 it was found that the average accuracy of measurements taken from QTO4 and MATLAB on the SASS units was 21 mm and 24.7 mm, respectively.

5.2.4. Syntheses from Results Obtained

Comparing the traditional measurements of the HDDS to the specified dimensions it was found that the ground level and first level reported a 61% and 67% of error, respectively. This was expected since the quality issues on the ground level would indirectly affect the quality on the first level. Additionally, when investigating which walls most likely occurred in tolerance failure, it was found that 81% of walls have a 50% and higher probability of being out of tolerance.

Comparing the traditional measurements of the SASS to the specified dimensions it was found that there was 67% error. Additionally, when investigating which walls most likely occurred in tolerance failure, it was found that 78.6% of walls have a 50% and higher probability of being out of tolerance.

QTO4 and MATLAB measurements generated were compared to the actual measurements taken on-site. From this it was found that on average 50% of the measurements had an associated relative error of no more than 2.5%. The small amount of variance between measurements meant that the measurements being generated were consistent (i.e. the average difference between the generated measurement and the actual measurement was consistent). However, the average accuracy of drone measurements compared to actual measurements was 22.8 mm and 25.5 mm for QTO and MATLAB, respectively. Measurements using these pieces of software are directly related to the accuracy of the calibration and thereafter the accuracy of points being chosen on the image.

This measurement method is limited by human error that occurs when images aren't calibrated correctly. Problems then arise when the known length is not calibrated correctly, as this causes all other lengths to be generated incorrectly. In some instances the images had to be recalibrated after noticing that there were large discrepancies between the actual measurements taken on site, and the measurements which were being generated through the software.

Although these methods seemed to be innovative and relatively effective with regards to accuracy, they cannot be considered[i] as practical. The drone would be more effective if implemented as a progress monitoring and documentation device on site, but less so for the purpose of quality control through measurement generation and comparison to specifications.

CHAPTER 6: FRAMEWORK FOR THE USE OF DRONE TECHNOLOGY IN CONSTRUCTION

Although the study found that the implementation of drones for the inspection of dimensional aspects of quality was not practical, it is still recommended that a drone be implemented on an affordable housing project to assist with QC through visual- and progress management. The advantages of using a drone to assist with site monitoring during the construction phase have been made evident and this chapter will address how this recommendation can be implemented practically.

From the literature it was found that the construction industry is still hesitant to adopt emerging technologies to assist with quality management. This was also experienced during the completion of this study, as none of the Contractor's employees had used a drone to assist with construction works before the study commenced. However, as the study progressed and the capabilities of a drone were realized, the use of a drone became more familiar and sought after by all parties.

The capabilities of using a drone on a construction site surpassed the investigations conducted in this study and some other significant contributions made through use of a drone during this study were:

- Images initially taken for the purpose of this study were used for progress reports
- A video taken of the site was used to corroborate a delay claim.
- The Employer's Agent requested that drone images be attached to all progress reports.
- Progress videos and images were sent to the Client which increased stakeholder satisfaction.
- Inspections of the roofs were done by means of drone to ensure that all mortar from plaster works had been cleaned by the responsible subcontractor.
- Installation of solar geysers was monitored.
- Roof truss inspections were conducted without need for harnesses or unsafe inspections.

The efficiency of inspections and daily progress monitoring was increased through the use of pre-programmed flight paths. Instead of having to walk the entire site (approximately 1km on the HDDS site), the drone could be launched from the site office each morning and fly a designated path without the need of a user to fly the drone. Once the flight path had been completed the drone landed itself and the video and/or images taken were quickly analysed, either directly on a mobile device or on a computer, to obtain an update of the progress and the site dynamics. All these images are stored on the Contractor's OneDrive and information can be used at any time to assist with Contractual issues.

In order to simplify the process of implementing a drone on a construction site, this chapter describes a proposed framework that could be used to assist with the implementation of a drone on an affordable housing project.

6.1. Pre-Construction

The implementation of a drone is a process which should be administered with proper planning. Therefore, this process should begin before construction commences to ensure an effortless integration when construction commences.

The flow diagram below (Figure 61) shows the steps that must be followed before construction commences

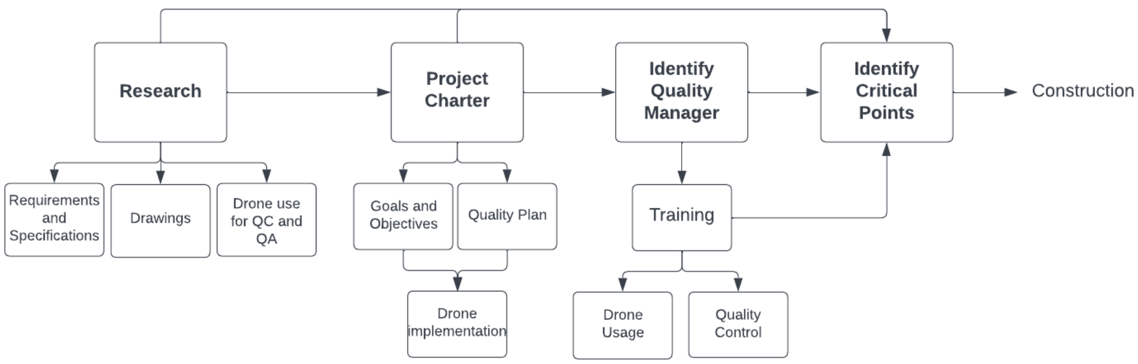


Figure 61. Pre-construction flow diagram for Implementing Drones to Assist with QC

6.1.1. Research

Upon committing to complete the Works stipulated in the Contract, all parties are to agree that they will fulfil their responsibilities to produce the required product (ISO, 2015). Therefore, it is important to do research before the construction works commence to ensure that all parties have a clear understanding of:

1. The requirements and specifications.
2. The construction drawings and all additional requirements that may from those stated at tender stage.
3. How a drone can be implemented to assist with QC and QA

6.1.2. Project Charter

This is an effective way to summarize the requirements of the project after the research has been conducted. A standard project charter document could be implemented, however, it is important to list the goals and objectives of the project to determine how a drone can assist with achieving this.

The implementation of an effective Quality Plan (QP) assists with increasing the quality, therefore, the project charter should clearly outline the QP and make specific mention to the use of a drone which will assist with improving QA through QC. This should be project specific and can make mention of any of the applications of drone use mentioned above and throughout the thesis.

6.1.3. Dedicated Quality Manager

The data analysed in chapter 4 found that a large number of defects were being missed although quality checks and supervision were in place. Supervision employed on these projects clearly indicates the need for the employment of a party who is dedicated solely to quality management. This can be justified by findings in section 2.5. that state that the largest effort is required during the construction phase. Therefore, there should be an increased effort afforded to QC during the construction phase.

Employing such a party will be to the benefit of the Contractor, as this party will assist with early defect detection and will in turn lessen the costs of rework. However, as stated in the literature review and found by conducting this study, appropriate training on quality management and the capability of drones within the construction industry will also be advantageous.

6.1.4. Identify all Critical Areas.

The use of a drone can assist in a multitude of ways. The data obtained in this research found that blockwork is indeed an area for concern. Therefore, it is important to determine which areas will be inspected and at what intervals they will be inspected. By making subcontractors and labourers aware of inspections hold points it will be possible to continuously administer QC at these critical areas.

6.2. During Construction:

Ensuing the formation of the QP which also identifies the Quality Manager and his/her responsibilities, the framework continues to the implementation of the drone during construction works. As discussed in section 2.5, a collaborative and continuous effort should be made by all parties involved to improve Quality Control (QC). Therefore, parties should be informed of the proposed QC strategy through means of on-site progress monitoring using a drone.

The strategy that follows can be seen in the flow diagram in Figure 62.

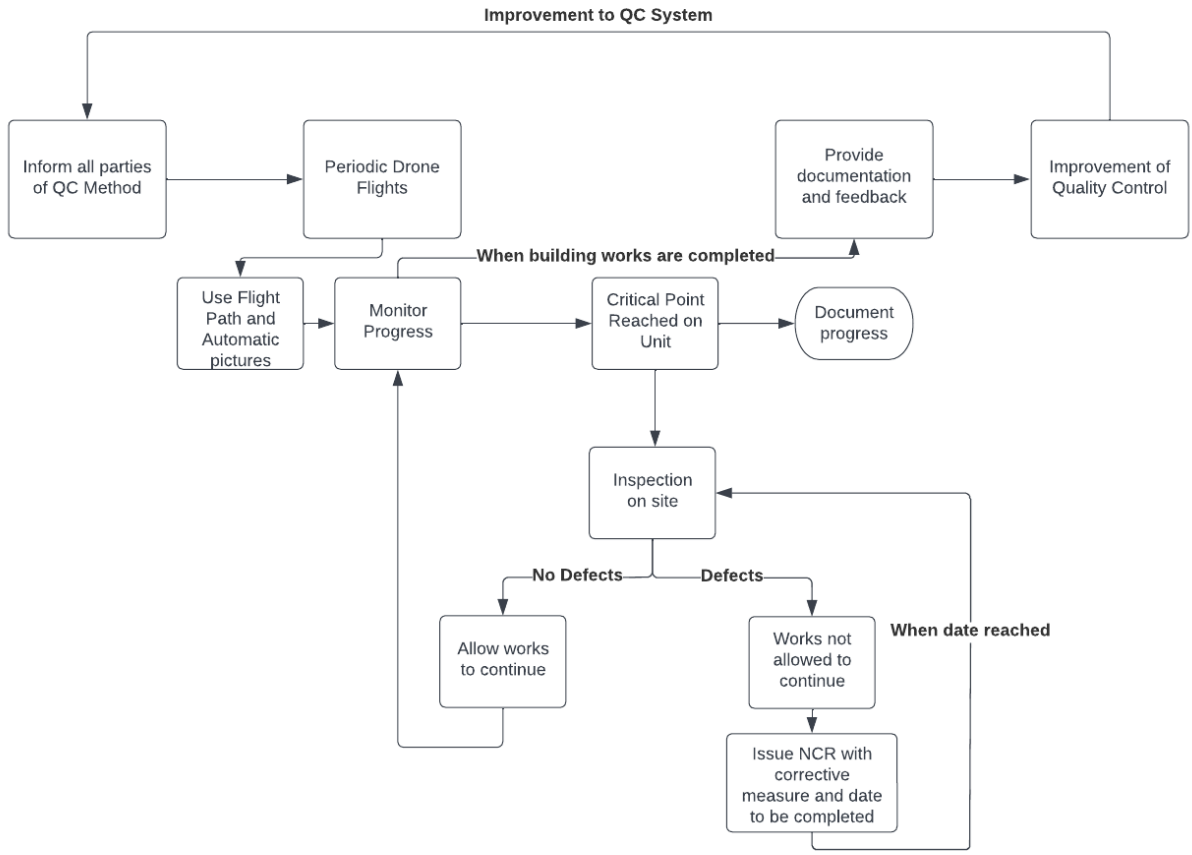


Figure 62. During Construction Flow Diagram for Implementing Drones to Assist with QC

6.2.1. Periodic Drone Flights

The Quality Manager should develop a schedule which can be followed to inspect the progress of the site. Masonry blocks were focussed on for the purpose of this study and, if this were to be considered then periodic drone flights could be conducted on a weekly basis.

This can be executed by making use of the drone software mentioned in section 4.4.3 or other software that allows the user to automate a drone flight. The flight path chosen can take images of the critical areas (inspection hold points) identified and thereby keep the Quality Manager informed of the progress on site.

The Quality Manager can then do an in depth inspection of a unit when it reaches a critical point to increase the probability of early defect detection. If a defect is detected, the Quality Manager can issue an Non-Conformance Report (NCR) to the party responsible and stipulate which corrective measures should be taken to rectify the issue by which date. In order to document the defect, the Quality Manager refers to the date the image was taken at a critical point, providing him/her with photographic evidence of the incidence to corroborate the NCR.

6.2.2. Documentation and Improvement

Once a unit has been completed the Quality Manager can provide the stakeholders with feedback on each unit's NCRs issued and time taken to complete. The key to a successful management system, as discussed in section 2.3, lies in continuous improvement. Therefore, the Quality Manager must take advantage of the opportunity to provide, and receive, feedback regarding the newly implemented QC strategy.

In conclusion, the framework provided is a recommendation which has been developed by completing this study and by observing the possibilities which become available when the use of this technology is embraced.

CHAPTER 7: SUMMARY AND CONCLUSIONS

7.1. Summary

Following years of corrective action and implementation of policies in an attempt to eradicate the affordable housing backlog that permeated through from the apartheid era into the new democratic South Africa, the backlog continuously increases. In addition to time- and budget constraints, issues such as low quality of housing units place further strain on progression towards overcoming the housing backlog.

Defects resulting from low quality work and ineffective quality monitoring during the construction phase of affordable housing units, have significantly impacted the residents and more recently, the stakeholders of these projects.

The aim of this study was to determine how a drone can be used to improve the dimensional aspects during quality control on affordable housing projects.

This study found 2D and 3D methods through which drones could be used as a tool to monitor the dimensional aspects of quality within the affordable housing sector, as both methods could accurately identify dimensional quality concerns. However, it was determined that neither of these methods are currently practical due to the time required from the user to accurately implement this method. This could change once technology advances to a point where the corners of a building could accurately be identified without the need for significant human interaction. General progress- and site monitoring through the use of a drone is proposed and a framework is put forward through which a drone can practically be implemented in construction.

7.2. Conclusions

The requirement for quantitative production within a short timeframe presents a significant limitation in terms of continual quality control throughout the construction process. In an effort to find a solution towards continual process and quality monitoring, without compromising on time and cost, the application of drone technology to monitor progress and certain quality aspects on-site in real-time was investigated in this study. The objectives of the study were achieved through the processes described in the following paragraphs.

Firstly, quality concerns were identified in affordable housing projects. This entailed the on-site collection of wall dimension measurements of 8 HDDS and 16 SASS units by the traditional method of tape measurement by hand. By comparing 336 measurements from the SASS units and 1 048 measurements from the HDDS units to the specified dimensions, it was determined that 67% measurements fall outside of the allowable tolerance range (built either short of the minimum, or over the maximum tolerance) for the SASS units, and 61% and 67% for the ground level, and first level of the HDDS units, respectively. Therefore, poor masonry quality was identified for further investigation.

The systems development cycle was then employed to assist with the development process of implementing a technological approach to current quality control methods. The process set out in the systems development cycle was followed and drone footage was successfully collected for each unit considered during the traditional data collection phase. The drone images were processed using QTO4 and MATLAB as 2D analysis software, through which the wall measurements were generated and compared to the actual corresponding actual measurement collected on-site. The measurements obtained from QTO4 and MATLAB had low variance and generated results within reasonable accuracy (absolute average accuracy of 22.8 mm for QTO4 and 25.5 mm for MATLAB), however, not to the required standard for application within the industry at this time. A 3D analysis method was investigated in an attempt to increase the accuracy of the generated measurements, however, the processing time required to generate a 3D model of the units was not regarded as practical (6hr 36min to generate a model of a SASS unit, compared to 12min for traditional measurements taken by tape measure). It should be noted that both the 2D and 3D analysis software was limited to free or demo versions currently available for use to the public. This limitation may be overcome if more advanced software is utilized, however for the purpose of this study, and within the context of affordable housing projects, increased costs incurred by more advanced software is not a viable consideration.

A framework which integrates the use of drones and other quality control methods to identify quality defects, increase quality monitoring, assurance and control, decrease project schedule- and cost overruns and increase stakeholder satisfaction was developed and presented. The framework describes how a drone can be used by a Quality Manager who is solely responsible for QC on affordable housing projects.

The aim of this study was successfully achieved in determining how a drone can be used to improve quality control on affordable housing projects. Albeit not exclusively through quality control monitoring but through continuous progress monitoring and visual management. This was ultimately achieved by firstly identifying common quality concerns in affordable housing projects and exploring the quality control methods currently used, along with their associated limitations. Once the quality control concerns and the methods to address these concerns were known, the system development cycle was implemented to assist in developing the process of investigating how drones can be integrated into quality monitoring and control to conclusively build on the traditional methods. Through the investigative approach developed on the basis of the system development cycle, the framework for drone integration in monitoring and improving quality within the limits of affordable housing was successfully developed.

As technology advances, the current limitations associated with drone-based quality control will be resolved, allowing for many opportunities of improvement in the future.

7.3. Future Research Recommendations

7.3.1. Alternative Software options

It is recommended that the use and practicality of more expensive software options be investigated. The implementation of additional technologies such as LiDAR should be researched together with the development of a program that can automatically detect the corners of walls and calculate the length of specific walls.

The research should further investigate other methods which can be implemented to improve the practicality of inspections done on site using modern technologies.

7.3.2. Implementation of a Quality Manager Integrated with Use of a Drone

The proposed framework suggests the use of a quality manager on a project who is solely responsible for quality control. It could be of benefit if this is researched on affordable housing projects with the aim of determining the effectiveness of such a solution.

The research should investigate how the quality manager can be integrated into the project and the Contract (see Figure 63 for an example).

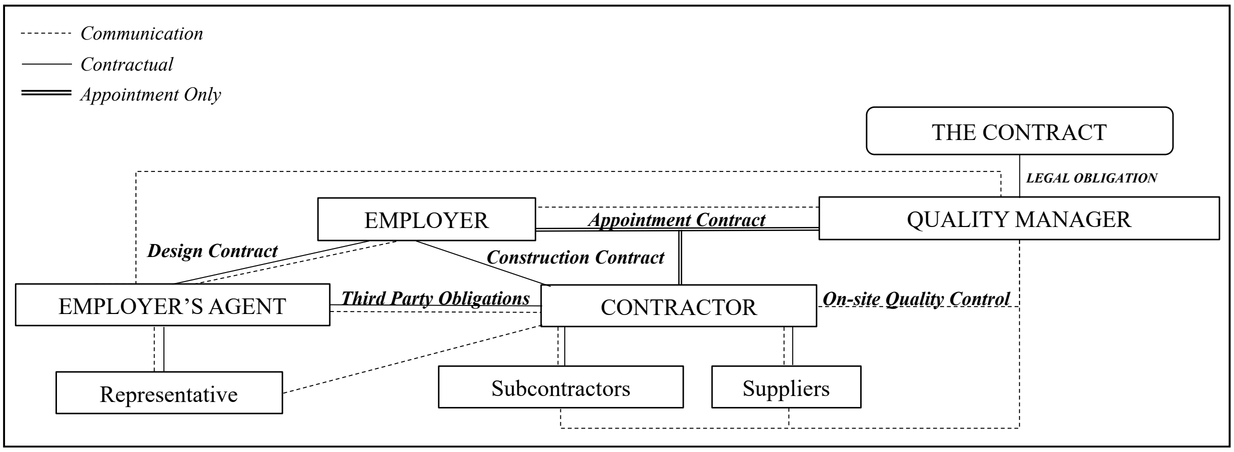


Figure 63. Example of Quality Manager Implementation in Project

The research should determine whether the occurrence of defects decreases and can determine the savings that can accrue throughout the project through the implementation of such a party.

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APPENDIX A – SANS 10155:1980 EXTRACT

Specifications

The following table details the permissible deviations as defined by SANS and was used as the basis to which deviations within the collected data was compared:

Table 14. Permissible Deviations (PD) in Masonry Work (Adapted from SANS 10155: 1980 Accuracy in Buildings p29).

Description	PD (mm)	
	Grade	
	II	I
Position on plan		
PD of fair-faced specified side of wall from design postion	± 15	± 10
Length		
≤ 5m	± 15	± 10
> 5 ≤ 10m	± 20	± 15
> 10m	± 25	± 20
Height		
≤ 3m: Brickwork	± 10	± 5
≤ 3m: Blockwork	± 15	± 10
> 3 ≤ 6m	± 20	± 15
> 6m	± 25	± 20
Wall Thickness	± 15	± 10
Level of Bed Joints		
Length ≤ 5m	± 10	± 5
> 5 ≤ 10m	± 15	± 10
>10 ≤ 20m	± 20	± 15
add for every 5m > 20m	± 5	± 5
Straightness		
In any 5m (Not cumulative): Brickwork	15	10
In any 5m (Not cumulative): Blockwork	10	5
Verticality		
In any 8 course Brickwork	± 10	± 5
In any 3m	± 15	± 10
Finished Surfaces		
PD of any point from a 2m straight edge placed in any direction on the wall	6	3

APPENDIX B – ETHICS APPROVAL

UNIVERSITEIT STELLENBOSCH UNIVERSITY

NOTICE OF PROVISIONAL ETHICS APPROVAL BY DESC/FESC

REC: Social, Behavioural and Education Research (SBER) - Initial Application Form

Date: 15/09/2022

Project ID: 25902

Project title: Improving the quality in affordable housing using drones

Dear Mr PG Ruthven

Kindly note that your research ethics application has been reviewed by the Department/Faculty Ethics Screening Committee (DESC/FESC): Faculty of Engineering and has subsequently been classified as a **low risk** project.

This means that you have provisional ethics approval to start with recruitment and data collection activities.

Your DESC/FESC approved application has been sent to the Social, Behavioural and Education Research Ethics Committee (REC: SBE) at Stellenbosch University for ratification. It is important that you note the following regarding the ratification process:

1) The REC: SBE may add a few additional stipulations/conditions before final approval is granted, but essentially a **low risk** approval from the DESC/FESC means that you may start with your data collection activities, provided you've received the necessary **permission(s)** from any other participating gatekeeper(s)/organisation(s)/institution(s) (where it may apply).

2) You can expect to receive a formal letter of ethics clearance from the Research Ethics Committee (REC) at Stellenbosch University within 40 days. Please feel free to follow up with the REC: SBE office (applyethics@sun.ac.za) if you have not received a formal letter confirming ethics clearance after 40 days.

Congratulations on the successful completion of your ethics application!

Ms T Ficker

tanya@sun.ac.za

DESC/FESC coordinator: Faculty of Engineering

Page 1 of 1

Figure 64. Ethics Clearance from the DESC

APPENDIX C – RAW DATA

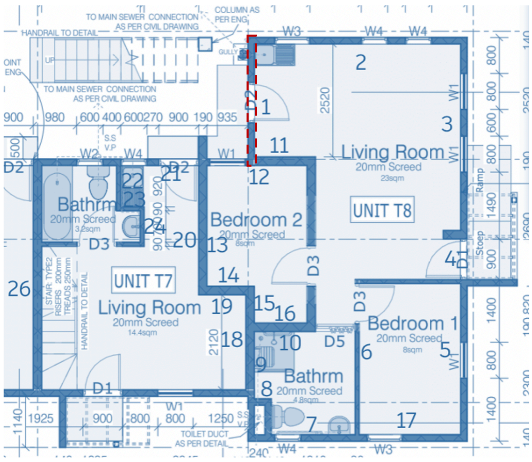
The measurement data collected for this study consisted of length (in meters) measurements of walls. These measurements are obtained through the traditional method of hand measurements and is referred to as such throughout. As mentioned, HDDS and SASS units were investigated to provide a broader range of insights, i.e.

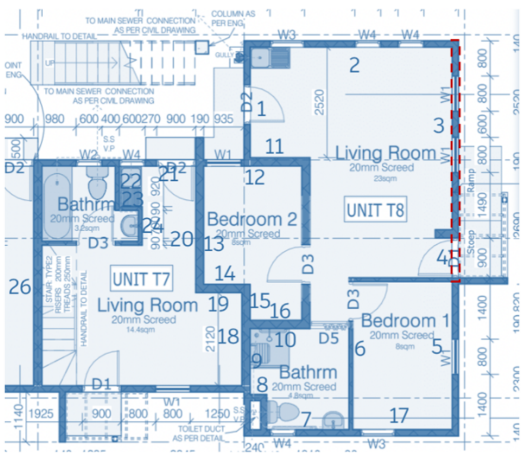
1. High density (units built in proximity) vs. single standalone units to assess the effect of proximity on the quality deviations.
2. Double story vs. single story units to assess the effect of building on different floors.

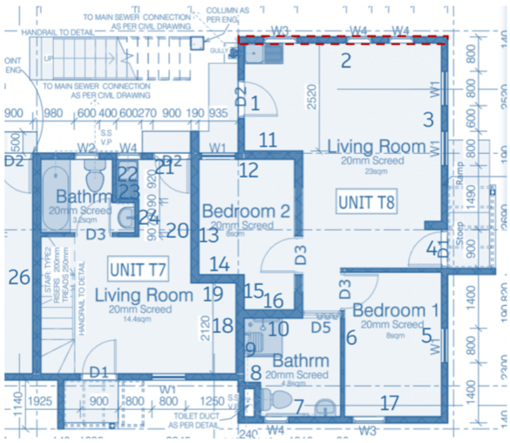
This appendix provides the raw data measurements collected for 8 different HDDS units and 16 different SASS units.

Measurement points:

To compare measurements from each unit, appropriate measurement points were identified and assigned with a unique measurement ID. The following figures show examples of how the various measurement IDs were assigned:







Traditional measurements: HDDS units

Table 15: Raw data measured for HDDS Ground Floor (Units BQ01 - BQ08).

Measurement ID	Specification	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08
1	**2520**	2507	2510	2498	2510	2542	2495	2505	2510
2	**4685**	4688	4675	4702	4715	4683	4683	4698	4711
3	**4210**	4214	4122	4184	4120	4220	4196	4215	4120
4	**900**	862	847	870	870	881	853	864	870
5	**3370**	3358	3430	3357	3465	3335	3358	3359	3465
6	**3370**	3355	3420	3321	3460	3345	3364	3355	3460
7	**1910**	1890	1995	1892	2010	1992	1997	1888	2010
8	**380**	393	335	400	295	305	272	394	305
9	**1500**	1480	1471	1311	1480	1410	1419	1478	1480
10	**1400**	1422	1348	1419	1420	1386	1401	1420	1420
11	**1390**	1391	1329	1384	1418	1387	1410	1394	1411
12	**2270**	2290	2203	2236	2250	2255	2199	2289	2250
13	**2690**	2705	2713	2758	2750	2679	2703	2701	2750
14	**1075**	1068	1104	1040	980	1074	943	1065	980
15	**820**	830	765	809	795	823	825	838	795
16	**1200**	1229	1126	1207	1212	1183	1202	1228	1219
17	**2305**	2291	2292	2281	2310	2294	2294	2295	2310
18	**2120**	2060	2073	2103	2115	2113	2115	2103	2110
19	**1075**	1067	1094	1048	941	1062	941	1048	970
20	**2880**	2893	2976	2894	2922	2889	2922	2851	2890
21	**1770**	1747	1818	1718	1879	1761	1829	1717	1850
22	**1700**	1718	1667	1741	1631	1701	1665	1745	1672
23	**920**	905	945	882	907	906	907	888	905
24	**600**	531	525	547	615	589	615	546	520

Measurement ID	Specification	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08
25	**880**	881	893	903	898	899	898	901	875
26	**4235**	4231	4180	4256	4235	4229	4261	4190	4220
27	**5000**	5012	5049	5053	5021	5013	5029	5040	5000
28	**2035**	2022	1975	2022	2047	2033	1944	2030	2045
29	**2110**	2115	2166	2115	2121	2119	2138	2116	2123
30	**1800**	1819	1836	1819	1825	1796	1812	1829	1820
31	**3200**	3226	3204	3226	3148	3142	3203	3204	3155
32	**3200**	3178	3231	3157	3225	3228	3209	3223	3204
33	**4635**	4639	4627	4563	4575	4626	4535	4629	4560
34	**2120**	2093	2119	2093	2117	2110	2105	2120	2110
35	**1075**	1068	1097	949	1011	1038	1018	1070	997
36	**2880**	2915	2879	2870	2883	2915	2834	2888	2880
37	**1770**	1733	1874	1735	1801	1733	1783	1775	1790
38	**1700**	1738	1620	1741	1665	1747	1691	1698	1679
39	**920**	905	921	893	936	905	902	921	935
40	**600**	556	498	642	606	526	633	567	607
41	**880**	903	890	939	890	901	928	896	890
42	**2270**	2291	2275	2261	2261	2255	2246	2259	2218
43	**2690**	2738	2642	2706	2715	2719	2719	2719	2710
44	**1075**	1062	1096	959	1032	1043	1014	1067	994
45	**820**	836	830	798	788	823	783	823	793
46	**1195**	1220	1041	1355	1231	1180	1227	1180	1230
47	**3510**	3565	3503	3504	3524	3534	3487	3534	3525
48	**1390**	1416	1257	1562	1431	1382	1423	1382	1420
49	**2520**	2511	2481	2518	2521	2525	2528	2525	2515
50	**4685**	4705	4667	4690	4708	4695	4698	4695	4701
51	**4210**	4200	4208	4181	4278	4230	4263	4230	4225
52	**2305**	2295	2274	2308	2289	2326	2297	2326	2290
53	**3460**	3470	3478	3459	3391	3422	3480	3422	3295
54	**2305**	2310	2274	2274	2290	2272	2307	2272	2290
55	**3370**	3375	3360	3528	3351	3352	3291	3352	3250
56	**1390**	1413	1260	1550	1411	1390	1440	1395	1410
57	**1500**	1390	1490	1274	1500	1425	1460	1515	1492
58	**380**	390	331	372	335	289	319	349	348
59	**900**	908	893	927	833	873	869	897	895
60	**1910**	1905	1979	1962	1950	2024	1976	1995	1980

Table 16: Raw data measured for HDDS First Floor (Units BQ01 - BQ08)

Measurement no	Specification	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08
1	3230	3210	3165	3206	3194	3234	3210	3215	3205
2	4965	4944	4939	4945	4943	4948	4935	4954	4944
3	2710	2670	2660	2712	2674	2709	2670	2696	2686
4	3540	3580	3628	3564	3591	3532	3580	3582	3560
5	1695	1662	1602	1653	1639	1602	1662	1653	1643
6	2930	2955	3011	3025	2997	3011	2955	2992	2982
7	3130	3115	3130	3153	3133	3130	3115	3138	3128
8	3040	3045	3015	3021	3027	3015	3045	3038	3028
9	900	895	885	980	920	885	895	917	907
10	1035	1015	991	946	984	991	1015	1005	995
11	2050	2023	2178	2042	2081	2178	2019	2091	2081
12	2930	2941	2985	2960	2962	2926	2941	2958	2948
13	2650	2642	2605	2592	2613	2600	2642	2629	2619
14	3040	3041	3060	3033	3045	3054	3041	3053	3043
15	3685	3679	3610	3571	3620	3615	3679	3645	3635
16	1695	1699	1628	1658	1662	1643	1660	1678	1668
17	1810	1831	1775	1630	1746	1795	1831	1782	1772
18	1835	1835	1803	1757	1799	1815	1835	1820	1810
19	2650	2661	2612	2580	2618	2611	2661	2636	2600
20	2700	2630	2778	2706	2705	2700	2720	2761	2715
21	3640	3640	3700	3833	3725	3655	3681	3689	3698
22	1375	1235	1385	1275	1299	1330	1346	1382	1331
23	1325	1374	1350	1410	1378	1361	1344	1361	1365
24	2650	2632	2660	2653	2649	2659	2646	2666	2654
25	2350	2306	2305	2347	2320	2329	2318	2302	2325
26	3745	3705	3635	3697	3679	3699	3679	3671	3691
27	2350	2282	2345	2350	2326	2336	2333	2344	2336
28	3670	3730	3710	3710	3717	3697	3692	3719	3708
29	1895	1885	1835	1886	1869	1873	1859	1841	1870
30	1895	1810	1916	1910	1879	1863	1889	1931	1889
31	1230	1270	1228	1240	1246	1258	1227	1230	1244
32	1095	1030	1040	1150	1074	1037	1062	1049	1070
33	3345	3305	3345	3222	3291	3341	3320	3355	3318
34	2350	2328	2335	2320	2328	2329	2330	2345	2336
35	3345	3300	3376	3290	3322	3330	3340	3381	3338
36	2350	2305	2340	2335	2327	2310	2332	2351	2334
37	2250	2275	2293	2066	2212	2276	2244	2293	2241

Measurement no	Specification	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08
38	2700	2678	2755	2730	2721	2680	2718	2756	2720
39	3240	3247	3220	3000	3156	3250	3198	3217	3193
40	1330	1238	1378	1341	1319	1268	1335	1369	1325
41	3670	3655	3653	3665	3658	3667	3653	3633	3659
42	1895	1872	1855	1856	1861	1861	1863	1851	1867
43	1225	1202	1175	1235	1204	1245	1194	1178	1210
44	1095	1052	1070	1071	1065	1081	1069	1061	1073
45	3745	3781	3815	3800	3799	3809	3779	3779	3791
46	2350	2308	2325	2311	2315	2321	2323	2322	2324
47	3745	3760	3785	3800	3782	3754	3763	3761	3650
48	2350	2320	2315	2355	2330	2366	2324	2311	2336
49	1330	1346	1432	1345	1375	1344	1372	1436	1375
50	4635	4675	4700	4697	4691	4678	4668	4709	4684
51	2700	2671	2755	2705	2711	2708	2715	2760	2718
52	2710	2718	2685	2608	2671	2678	2681	2687	2682
53	4965	4955	4935	4976	4956	4957	4945	4923	4954
54	3230	3208	3205	3210	3208	3212	3207	3200	3212
55	3130	3123	3140	3120	3128	3128	3125	3141	3132
56	3020	2928	3065	3105	3033	3030	3032	3067	3037
57	3540	3510	3570	3585	3555	3552	3548	3572	3556
58	1695	1640	1630	1669	1647	1656	1650	1641	1656
59	2650	2787	2625	2652	2688	2680	2647	2622	2671
60	1835	1836	1825	1810	1824	1826	1821	1831	1828
61	1790	1810	1850	1805	1822	1835	1813	1855	1825
62	900	904	867	934	902	901	882	866	897
63	1035	1031	980	947	986	995	993	995	998
64	2140	2111	2155	2080	2116	2120	2130	2161	2129
65	2650	2608	2615	2610	2611	2618	2618	2614	2620
66	3040	3010	3040	3004	3018	3022	3025	3047	3028
67	3685	3760	3600	3606	3656	3650	3640	3649	3658
68	1895	1829	1982	2028	1947	1936	1934	1970	1943
69	3040	3008	3030	2993	3011	3010	3020	3028	3020
70	2930	2930	2935	2928	2931	2930	2925	2930	2932
71	2050	1994	2060	1966	2007	2061	2032	2071	2033

SASS Units

Table 17: Raw data measured for SASS (Units 1 - 7)

Measurement ID	Specification	10932	10933	10934	10935	10930	10929	10927
1	2815	2800	2820	2790	2785	2878	2816	2742
2	2940	2910	2890	2850	2843	2909	2958	2965
3	875	860	895	870	869	883	882	860
4	620	750	770	645	642	721	748	802
5	1940	1900	1920	1913	1910	1910	1929	1879
6	2320	2280	2150	2270	2274	2227	2334	2204
7	2815	2800	2760	2800	2802	2777	2818	2832
8	2800	2780	2720	2820	2848	2774	2801	2783
9	1940	1980	1950	1925	1976	1934	1956	1969
10	2940	2790	2850	2855	2853	2916	2950	2961
11	3450	3380	3460	3425	3437	3426	3399	3459
12	860	840	860	860	857	903	850	852
13	3960	3965	4000	3945	3949	3940	4010	3942
14	600	590	730	810	809	616	607	793
15	600	650	600	500	498	663	780	478
16	1890	1890	1895	1910	1913	1895	1978	1905
17	800	800	730	643	646	810	817	785
18	1800	1800	1780	1795	1810	1831	1835	1979
19	800	820	850	830	908	807	793	817
20	1000	1010	1050	1010	1018	1038	998	1015
21	800	790	710	800	797	800	853	800

Table 18: Raw data measured for SASS (Units 8 - 16)

Measurement ID	**Specification**	10926	10922	10918	12127	12126	12148	12157	12071
1	2815	2842	2797	2798	2800	2789	2787	2782	2786
2	2940	3112	3009	3772	2855	2990	3045	3011	3099
3	875	864	853	866	857	862	855	863	852
4	620	738	712	1074	726	662	726	746	790
5	1940	1928	1972	1935	1928	1932	1954	1922	1950
6	2320	2345	2291	2695	2284	2319	2288	2290	2284
7	2815	2820	2800	2794	2799	2780	2801	2800	2797
8	2800	2782	2758	3235	2811	2797	2738	2785	2793
9	1940	1982	1928	1931	1963	1938	1947	1931	1931
10	2940	2929	2910	3371	2993	2962	2934	2954	2980

Measurement ID	**Specification**	10926	10922	10918	12127	12126	12148	12157	12071
11	3450	3518	3439	3794	3350	3453	3427	3424	3454
12	860	843	859	795	818	1073	1063	898	847
13	3960	3983	4001	3967	4020	3850	3853	3943	3982
14	600	569	631	564	659	659	392	496	621
15	600	654	599	664	543	619	854	750	584
16	1890	1903	1959	1942	1898	1909	1945	1923	1953
17	800	778	754	771	775	789	814	802	822
18	1800	1809	1831	1822	1811	1816	1820	1805	1825
19	800	798	807	808	778	789	765	782	776
20	1000	831	1018	984	792	1106	799	1002	1044
21	800	980	806	825	1000	705	1023	806	760

The measurements below compare the actual measurements to the specification to determine whether or not the measurements adhered to the specifications set out by SANS 10155:2000. The following applies:

- Green measurements < 15mm and not within specification.
- Red measurements > 15mm and not within specification.
- Other are within specification.

BQ01 Ground Level (Measured at top)			
Measurement no	Specification	Actual	Difference
1	2520	2507	-13
2	4685	4688	3
3	4210	4214	4
4	900	862	-38
5	3370	3358	-12
6	3370	3355	-15
7	1910	1890	-20
8	380	393	13
9	1500	1480	-20
10	1400	1422	22
11	1390	1391	1
12	2270	2290	20
13	2690	2705	15
14	1075	1068	-7
15	820	830	10
16	1200	1229	29
17	2305	2291	-14
18	2120	2060	-60
19	1075	1067	-8
20	2880	2893	13
21	1770	1747	-23
22	1700	1718	18
23	920	905	-15
24	600	531	-69
25	880	881	1
26	4235	4231	-4
27	5000	5012	12
28	2035	2022	-13
29	2110	2115	5
30	1800	1819	19
31	3200	3226	26
32	3200	3178	-22
33	4635	4639	4
34	2120	2093	-27
35	1075	1068	-7
36	2880	2915	35
37	1770	1733	-37
38	1700	1738	38
39	920	905	-15
40	600	556	-44
41	880	903	23
42	2270	2291	21
43	2690	2738	48
44	1075	1062	-13
45	820	836	16
46	1195	1220	25
47	3510	3565	55
48	1390	1416	26
49	2520	2511	-9
50	4685	4705	20
51	4210	4200	-10
52	2305	2295	-10
53	3460	3470	10
54	2305	2310	5
55	3370	3375	5
56	1390	1413	23
57	1500	1390	-110
58	380	390	10
59	900	908	8
60	1910	1905	-5

BQ01 First Level (Measured at top)			
Measurement no	Specification	Actual	Difference
1	3230	3210	-20
2	4965	4944	-21
3	2710	2670	-40
4	3540	3580	40
5	1695	1662	-33
6	2930	2955	25
7	3130	3115	-15
8	3040	3045	5
9	900	895	-5
10	1035	1015	-20
11	2050	2023	-27
12	2930	2941	11
13	2650	2642	-8
14	3040	3041	1
15	3685	3679	-6
16	1695	1699	4
17	1810	1831	21
18	1835	1835	0
19	2650	2661	11
20	2700	2630	-70
21	3640	3640	0
22	1375	1235	-140
23	1325	1374	49
24	2650	2632	-18
25	2350	2306	-44
26	3745	3705	-40
27	2350	2282	-68
28	3670	3730	60
29	1895	1885	-10
30	1895	1810	-85
31	1230	1270	40
32	1095	1030	-65
33	3345	3305	-40
34	2350	2328	-22
35	3345	3300	-45
36	2350	2305	-45
37	2250	2275	25
38	2700	2678	-22
39	3240	3247	7
40	1330	1238	-92
41	3670	3655	-15
42	1895	1872	-23
43	1225	1202	-23
44	1095	1052	-43
45	3745	3781	36
46	2350	2308	-42
47	3745	3760	15
48	2350	2320	-30
49	1330	1346	16
50	4635	4675	40
51	2700	2671	-29
52	2710	2718	8
53	4965	4955	-10
54	3230	3208	-22
55	3130	3123	-7
56	3020	2928	-92
57	3540	3510	-30
58	1695	1640	-55
59	2650	2787	137
60	1835	1836	1
61	1790	1810	20
62	900	904	4
63	1035	1031	-4
64	2140	2111	-29
65	2650	2608	-42
66	3040	3010	-30
67	3685	3760	75
68	1895	1829	-66
69	3040	3008	-32
70	2930	2930	0
71	2050	1994	-56

Figure 65. BQO1 Measurement Data

BQ02 Ground Level			
Measurement no	Specification	Actual	Difference
1	2520	2510	-10
2	4685	4675	-10
3	4210	4122	-88
4	900	847	-53
5	3370	3430	60
6	3370	3420	50
7	1910	1995	85
8	380	335	-45
9	1500	1471	-29
10	1400	1348	-52
11	1390	1329	-61
12	2270	2203	-67
13	2690	2713	23
14	1075	1104	29
15	820	765	-55
16	1200	1126	-74
17	2305	2292	-13
18	2120	2073	-47
19	1075	1094	19
20	2880	2976	96
21	1770	1818	48
22	1700	1667	-33
23	920	945	25
24	600	525	-75
25	880	893	13
26	4235	4180	-55
27	5000	5049	49
28	2035	1975	-60
29	2110	2166	56
30	1800	1836	36
31	3200	3204	4
32	3200	3231	31
33	4635	4627	-8
34	2120	2119	-1
35	1075	1097	22
36	2880	2879	-1
37	1770	1874	104
38	1700	1620	-80
39	920	921	1
40	600	498	-102
41	880	890	10
42	2270	2275	5
43	2690	2642	-48
44	1075	1096	21
45	820	830	10
46	1195	1041	-154
47	3510	3503	-7
48	1390	1257	-133
49	2520	2481	-39
50	4685	4667	-18
51	4210	4208	-2
52	2305	2274	-31
53	3460	3478	18
54	2305	2274	-31
55	3370	3360	-10
56	1390	1260	-130
57	1500	1490	-10
58	380	331	-49
59	900	893	-7
60	1910	1979	69

BQ02 First Level (Measured at top)			
Measurement no	Specification	Actual	Difference
1	3230	3165	-65
2	4965	4939	-26
3	2710	2660	-50
4	3540	3628	88
5	1695	1602	-93
6	2930	3011	81
7	3130	3130	0
8	3040	3015	-25
9	900	885	-15
10	1035	991	-44
11	2050	2178	128
12	2930	2985	55
13	2650	2605	-45
14	3040	3060	20
15	3685	3610	-75
16	1695	1628	-67
17	1810	1775	-35
18	1835	1803	-32
19	2650	2612	-38
20	2700	2778	78
21	3640	3700	60
22	1375	1385	10
23	1325	1350	25
24	2650	2660	10
25	2350	2305	-45
26	3745	3635	-110
27	2350	2345	-5
28	3670	3710	40
29	1895	1835	-60
30	1895	1916	21
31	1230	1228	-2
32	1095	1040	-55
33	3345	3345	0
34	2350	2335	-15
35	3345	3376	31
36	2350	2340	-10
37	2250	2293	43
38	2700	2755	55
39	3240	3220	-20
40	1330	1378	48
41	3670	3653	-17
42	1895	1855	-40
43	1225	1175	-50
44	1095	1070	-25
45	3745	3815	70
46	2350	2325	-25
47	3745	3785	40
48	2350	2315	-35
49	1330	1432	102
50	4635	4700	65
51	2700	2755	55
52	2710	2685	-25
53	4965	4935	-30
54	3230	3205	-25
55	3130	3140	10
56	3020	3065	45
57	3540	3570	30
58	1695	1630	-65
59	2650	2625	-25
60	1835	1825	-10
61	1790	1850	60
62	900	867	-33
63	1035	980	-55
64	2140	2155	15
65	2650	2615	-35
66	3040	3040	0
67	3685	3600	-85
68	1895	1982	87
69	3040	3030	-10
70	2930	2935	5
71	2050	2060	10

Figure 66. BQ02 Measurement Data

BQ03 Ground Level			
Measurement no	Specification	Actual	Difference
1	2520	2498	-22
2	4685	4702	17
3	4210	4184	-26
4	900	870	-30
5	3370	3357	-13
6	3370	3321	-49
7	1910	1892	-18
8	380	400	20
9	1500	1311	-189
10	1400	1419	19
11	1390	1384	-6
12	2270	2236	-34
13	2690	2758	68
14	1075	1040	-35
15	820	809	-11
16	1200	1207	7
17	2305	2281	-24
18	2120	2103	-17
19	1075	1048	-27
20	2880	2894	14
21	1770	1718	-52
22	1700	1741	41
23	920	882	-38
24	600	547	-53
25	880	903	23
26	4235	4256	21
27	5000	5053	53
28	2035	2022	-13
29	2110	2115	5
30	1800	1819	19
31	3200	3226	26
32	3200	3157	-43
33	4635	4563	-72
34	2120	2093	-27
35	1075	949	-126
36	2880	2870	-10
37	1770	1735	-35
38	1700	1741	41
39	920	893	-27
40	600	642	42
41	880	939	59
42	2270	2261	-9
43	2690	2706	16
44	1075	959	-116
45	820	798	-22
46	1195	1355	160
47	3510	3504	-6
48	1390	1562	172
49	2520	2518	-2
50	4685	4690	5
51	4210	4181	-29
52	2305	2308	3
53	3460	3459	-1
54	2305	2274	-31
55	3370	3528	158
56	1390	1550	160
57	1500	1274	-226
58	380	372	-8
59	900	927	27
60	1910	1962	52

BQ03 First Level (Measured at top)			
Measurement no	Specification	Actual	Difference
1	3230	3206	-24
2	4965	4945	-20
3	2710	2712	2
4	3540	3564	24
5	1695	1653	-42
6	2930	3025	95
7	3130	3153	23
8	3040	3021	-19
9	900	980	80
10	1035	946	-89
11	2050	2042	-8
12	2930	2960	30
13	2650	2592	-58
14	3040	3033	-7
15	3685	3571	-114
16	1695	1658	-37
17	1810	1630	-180
18	1835	1757	-78
19	2650	2580	-70
20	2700	2706	6
21	3640	3833	193
22	1375	1275	-100
23	1325	1410	85
24	2650	2653	3
25	2350	2347	-3
26	3745	3697	-48
27	2350	2350	0
28	3670	3710	40
29	1895	1886	-9
30	1895	1910	15
31	1230	1240	10
32	1095	1150	55
33	3345	3222	-123
34	2350	2320	-30
35	3345	3290	-55
36	2350	2335	-15
37	2250	2066	-184
38	2700	2730	30
39	3240	3000	-240
40	1330	1341	11
41	3670	3665	-5
42	1895	1856	-39
43	1225	1235	10
44	1095	1071	-24
45	3745	3800	55
46	2350	2311	-39
47	3745	3800	55
48	2350	2355	5
49	1330	1345	15
50	4635	4697	62
51	2700	2705	5
52	2710	2608	-102
53	4965	4976	11
54	3230	3210	-20
55	3130	3120	-10
56	3020	3105	85
57	3540	3585	45
58	1695	1669	-26
59	2650	2652	2
60	1835	1810	-25
61	1790	1805	15
62	900	934	34
63	1035	947	-88
64	2140	2080	-60
65	2650	2610	-40
66	3040	3004	-36
67	3685	3606	-79
68	1895	2028	133
69	3040	2993	-47
70	2930	2928	-2
71	2050	1966	-84

Figure 67. BQ03 Measurement Data

BQ04 Ground Level			
Measurement no	Specification	Actual	Difference
1	2520	2510	-10
2	4685	4715	30
3	4210	4120	-90
4	900	870	-30
5	3370	3465	95
6	3370	3460	90
7	1910	2010	100
8	380	295	-85
9	1500	1480	-20
10	1400	1420	20
11	1390	1418	28
12	2270	2250	-20
13	2690	2750	60
14	1075	980	-95
15	820	795	-25
16	1200	1212	12
17	2305	2310	5
18	2120	2115	-5
19	1075	941	-134
20	2880	2922	42
21	1770	1879	109
22	1700	1631	-69
23	920	907	-13
24	600	615	15
25	880	898	18
26	4235	4235	0
27	5000	5021	21
28	2035	2047	12
29	2110	2121	11
30	1800	1825	25
31	3200	3148	-52
32	3200	3225	25
33	4635	4575	-60
34	2120	2117	-3
35	1075	1011	-64
36	2880	2883	3
37	1770	1801	31
38	1700	1665	-35
39	920	936	16
40	600	606	6
41	880	890	10
42	2270	2261	-9
43	2690	2715	25
44	1075	1032	-43
45	820	788	-32
46	1195	1231	36
47	3510	3524	14
48	1390	1431	41
49	2520	2521	1
50	4685	4708	23
51	4210	4278	68
52	2305	2289	-16
53	3460	3391	-69
54	2305	2290	-15
55	3370	3351	-19
56	1390	1411	21
57	1500	1500	0
58	380	335	-45
59	900	833	-67
60	1910	1950	40

BQ04 First Level			
Measurement no	Specification	Actual	Difference
1	3230	3194	-36
2	4965	4943	-22
3	2710	2674	-36
4	3540	3591	51
5	1695	1639	-56
6	2930	2997	67
7	3130	3133	3
8	3040	3027	-13
9	900	920	20
10	1035	984	-51
11	2050	2081	31
12	2930	2962	32
13	2650	2613	-37
14	3040	3045	5
15	3685	3620	-65
16	1695	1662	-33
17	1810	1746	-64
18	1835	1799	-36
19	2650	2618	-32
20	2700	2705	5
21	3640	3725	85
22	1375	1299	-76
23	1325	1378	53
24	2650	2649	-1
25	2350	2320	-30
26	3745	3679	-66
27	2350	2326	-24
28	3670	3717	47
29	1895	1869	-26
30	1895	1879	-16
31	1230	1246	16
32	1095	1074	-21
33	3345	3291	-54
34	2350	2328	-22
35	3345	3322	-23
36	2350	2327	-23
37	2250	2212	-38
38	2700	2721	21
39	3240	3156	-84
40	1330	1319	-11
41	3670	3658	-12
42	1895	1861	-34
43	1225	1204	-21
44	1095	1065	-30
45	3745	3799	54
46	2350	2315	-35
47	3745	3782	37
48	2350	2330	-20
49	1330	1375	45
50	4635	4691	56
51	2700	2711	11
52	2710	2671	-39
53	4965	4956	-9
54	3230	3208	-22
55	3130	3128	-2
56	3020	3033	13
57	3540	3555	15
58	1695	1647	-48
59	2650	2688	38
60	1835	1824	-11
61	1790	1822	32
62	900	902	2
63	1035	986	-49
64	2140	2116	-24
65	2650	2611	-39
66	3040	3018	-22
67	3685	3656	-29
68	1895	1947	52
69	3040	3011	-29
70	2930	2931	1
71	2050	2007	-43

Figure 68. BQ04 Measurement Data

BQ05 Ground Level			
Measurement no	Specification	Actual	Difference
1	2520	2542	22
2	4685	4683	-2
3	4210	4220	10
4	900	881	-19
5	3370	3335	-35
6	3370	3345	-25
7	1910	1992	82
8	380	305	-75
9	1500	1410	-90
10	1400	1386	-14
11	1390	1387	-3
12	2270	2255	-15
13	2690	2679	-11
14	1075	1074	-1
15	820	823	3
16	1200	1183	-17
17	2305	2294	-11
18	2120	2113	-7
19	1075	1062	-13
20	2880	2889	9
21	1770	1761	-9
22	1700	1701	1
23	920	906	-14
24	600	589	-11
25	880	899	19
26	4235	4229	-6
27	5000	5013	13
28	2035	2033	-2
29	2110	2119	9
30	1800	1796	-4
31	3200	3142	-58
32	3200	3228	28
33	4635	4626	-9
34	2120	2110	-10
35	1075	1038	-37
36	2880	2915	35
37	1770	1733	-37
38	1700	1747	47
39	920	905	-15
40	600	526	-74
41	880	901	21
42	2270	2255	-15
43	2690	2719	29
44	1075	1043	-32
45	820	823	3
46	1195	1180	-15
47	3510	3534	24
48	1390	1382	-8
49	2520	2525	5
50	4685	4695	10
51	4210	4230	20
52	2305	2326	21
53	3460	3422	-38
54	2305	2272	-33
55	3370	3352	-18
56	1390	1390	0
57	1500	1425	-75
58	380	289	-91
59	900	873	-27
60	1910	2024	114

BQ05 First Level			
Measurement no	Specification	Actual	Difference
1	3230	3234	4
2	4965	4948	-17
3	2710	2709	-1
4	3540	3532	-8
5	1695	1602	-93
6	2930	3011	81
7	3130	3130	0
8	3040	3015	-25
9	900	885	-15
10	1035	991	-44
11	2050	2178	128
12	2930	2926	-4
13	2650	2600	-50
14	3040	3054	14
15	3685	3615	-70
16	1695	1643	-52
17	1810	1795	-15
18	1835	1815	-20
19	2650	2611	-39
20	2700	2700	0
21	3640	3655	15
22	1375	1330	-45
23	1325	1361	36
24	2650	2659	9
25	2350	2329	-21
26	3745	3699	-46
27	2350	2336	-14
28	3670	3697	27
29	1895	1873	-22
30	1895	1863	-32
31	1230	1258	28
32	1095	1037	-58
33	3345	3341	-4
34	2350	2329	-21
35	3345	3330	-15
36	2350	2310	-40
37	2250	2276	26
38	2700	2680	-20
39	3240	3250	10
40	1330	1268	-62
41	3670	3667	-3
42	1895	1861	-34
43	1225	1245	20
44	1095	1081	-14
45	3745	3809	64
46	2350	2321	-29
47	3745	3754	9
48	2350	2366	16
49	1330	1344	14
50	4635	4678	43
51	2700	2708	8
52	2710	2678	-32
53	4965	4957	-8
54	3230	3212	-18
55	3130	3128	-2
56	3020	3030	10
57	3540	3552	12
58	1695	1656	-39
59	2650	2680	30
60	1835	1826	-9
61	1790	1835	45
62	900	901	1
63	1035	995	-40
64	2140	2120	-20
65	2650	2618	-32
66	3040	3022	-18
67	3685	3650	-35
68	1895	1936	41
69	3040	3010	-30
70	2930	2930	0
71	2050	2061	11

Figure 69. BQ05 Measurement Data

BQ06 Ground Level

Measurement no	Specification	Actual	Difference
1	2520	2495	-25
2	4685	4683	-2
3	4210	4196	-14
4	900	853	-47
5	3370	3358	-12
6	3370	3364	-6
7	1910	1997	87
8	380	272	-108
9	1500	1419	-81
10	1400	1401	1
11	1390	1410	20
12	2270	2199	-71
13	2690	2703	13
14	1075	943	-132
15	820	825	5
16	1200	1202	2
17	2305	2294	-11
18	2120	2115	-5
19	1075	941	-134
20	2880	2922	42
21	1770	1829	59
22	1700	1665	-35
23	920	907	-13
24	600	615	15
25	880	898	18
26	4235	4261	26
27	5000	5029	29
28	2035	1944	-91
29	2110	2138	28
30	1800	1812	12
31	3200	3203	3
32	3200	3209	9
33	4635	4535	-100
34	2120	2105	-15
35	1075	1018	-57
36	2880	2834	-46
37	1770	1783	13
38	1700	1691	-9
39	920	902	-18
40	600	633	33
41	880	928	48
42	2270	2246	-24
43	2690	2719	29
44	1075	1014	-61
45	820	783	-37
46	1195	1227	32
47	3510	3487	-23
48	1390	1423	33
49	2520	2528	8
50	4685	4698	13
51	4210	4263	53
52	2305	2297	-8
53	3460	3480	20
54	2305	2307	2
55	3370	3291	-79
56	1390	1440	50
57	1500	1460	-40
58	380	319	-61
59	900	869	-31
60	1910	1976	66

BQ06 First Level

leasurement I	Specification	Actual	Difference
1	3230	3210	-20
2	4965	4935	-30
3	2710	2670	-40
4	3540	3580	40
5	1695	1662	-33
6	2930	2955	25
7	3130	3115	-15
8	3040	3045	5
9	900	895	-5
10	1035	1015	-20
11	2050	2019	-31
12	2930	2941	11
13	2650	2642	-8
14	3040	3041	1
15	3685	3679	-6
16	1695	1660	-35
17	1810	1831	21
18	1835	1835	0
19	2650	2661	11
20	2700	2720	20
21	3640	3681	41
22	1375	1346	-29
23	1325	1344	19
24	2650	2646	-4
25	2350	2318	-32
26	3745	3679	-66
27	2350	2333	-17
28	3670	3692	22
29	1895	1859	-36
30	1895	1889	-6
31	1230	1227	-3
32	1095	1062	-33
33	3345	3320	-25
34	2350	2330	-20
35	3345	3340	-5
36	2350	2332	-18
37	2250	2244	-6
38	2700	2718	18
39	3240	3198	-42
40	1330	1335	5
41	3670	3653	-17
42	1895	1863	-32
43	1225	1194	-31
44	1095	1069	-26
45	3745	3779	34
46	2350	2323	-27
47	3745	3763	18
48	2350	2324	-26
49	1330	1372	42
50	4635	4668	33
51	2700	2715	15
52	2710	2681	-29
53	4965	4945	-20
54	3230	3207	-23
55	3130	3125	-5
56	3020	3032	12
57	3540	3548	8
58	1695	1650	-45
59	2650	2647	-3
60	1835	1821	-14
61	1790	1813	23
62	900	882	-18
63	1035	993	-42
64	2140	2130	-10
65	2650	2618	-32
66	3040	3025	-15
67	3685	3640	-45
68	1895	1934	39
69	3040	3020	-20
70	2930	2925	-5
71	2050	2032	-18

Figure 70. BQ06 Measurement Data

BQ07 Ground Level

Measurement no	Specification	Actual	Difference
1	2520	2505	-15
2	4685	4698	13
3	4210	4215	5
4	900	864	-36
5	3370	3359	-11
6	3370	3355	-15
7	1910	1888	-22
8	380	394	14
9	1500	1478	-22
10	1400	1420	20
11	1390	1394	4
12	2270	2289	19
13	2690	2701	11
14	1075	1065	-10
15	820	838	18
16	1200	1228	28
17	2305	2295	-10
18	2120	2103	-17
19	1075	1048	-27
20	2880	2851	-29
21	1770	1717	-53
22	1700	1745	45
23	920	888	-32
24	600	546	-54
25	880	901	21
26	4235	4190	-45
27	5000	5040	40
28	2035	2030	-5
29	2110	2116	6
30	1800	1829	29
31	3200	3204	4
32	3200	3223	23
33	4635	4629	-6
34	2120	2120	0
35	1075	1070	-5
36	2880	2888	8
37	1770	1775	5
38	1700	1698	-2
39	920	921	1
40	600	567	-33
41	880	896	16
42	2270	2259	-11
43	2690	2719	29
44	1075	1067	-8
45	820	823	3
46	1195	1180	-15
47	3510	3534	24
48	1390	1382	-8
49	2520	2525	5
50	4685	4695	10
51	4210	4230	20
52	2305	2326	21
53	3460	3422	-38
54	2305	2272	-33
55	3370	3352	-18
56	1390	1395	5
57	1500	1515	15
58	380	349	-31
59	900	897	-3
60	1910	1995	85

BQ07 First Level

Measurement no	Specification	Actual	Difference
1	3230	3215	-15
2	4965	4954	-11
3	2710	2696	-14
4	3540	3582	42
5	1695	1653	-42
6	2930	2992	62
7	3130	3138	8
8	3040	3038	-2
9	900	917	17
10	1035	1005	-30
11	2050	2091	41
12	2930	2958	28
13	2650	2629	-21
14	3040	3053	13
15	3685	3645	-40
16	1695	1678	-17
17	1810	1782	-28
18	1835	1820	-15
19	2650	2636	-14
20	2700	2761	61
21	3640	3689	49
22	1375	1382	7
23	1325	1361	36
24	2650	2666	16
25	2350	2302	-48
26	3745	3671	-74
27	2350	2344	-6
28	3670	3719	49
29	1895	1841	-54
30	1895	1931	36
31	1230	1230	0
32	1095	1049	-46
33	3345	3355	10
34	2350	2345	-5
35	3345	3381	36
36	2350	2351	1
37	2250	2293	43
38	2700	2756	56
39	3240	3217	-23
40	1330	1369	39
41	3670	3633	-37
42	1895	1851	-44
43	1225	1178	-47
44	1095	1061	-34
45	3745	3779	34
46	2350	2322	-28
47	3745	3761	16
48	2350	2311	-39
49	1330	1436	106
50	4635	4709	74
51	2700	2760	60
52	2710	2687	-23
53	4965	4923	-42
54	3230	3200	-30
55	3130	3141	11
56	3020	3067	47
57	3540	3572	32
58	1695	1641	-54
59	2650	2622	-28
60	1835	1831	-4
61	1790	1855	65
62	900	866	-34
63	1035	995	-40
64	2140	2161	21
65	2650	2614	-36
66	3040	3047	7
67	3685	3649	-36
68	1895	1970	75
69	3040	3028	-12
70	2930	2930	0
71	2050	2071	21

Figure 71. BQ07 Measurement Data

BQ08 Ground Level

Measurement no	Specification	Actual	Difference
1	2520	2510	-10
2	4685	4711	26
3	4210	4120	-90
4	900	870	-30
5	3370	3465	95
6	3370	3460	90
7	1910	2010	100
8	380	305	-75
9	1500	1480	-20
10	1400	1420	20
11	1390	1411	21
12	2270	2250	-20
13	2690	2750	60
14	1075	980	-95
15	820	795	-25
16	1200	1219	19
17	2305	2310	5
18	2120	2110	-10
19	1075	970	-105
20	2880	2890	10
21	1770	1850	80
22	1700	1672	-28
23	920	905	-15
24	600	520	-80
25	880	875	-5
26	4235	4220	-15
27	5000	5000	0
28	2035	2045	10
29	2110	2123	13
30	1800	1820	20
31	3200	3155	-45
32	3200	3204	4
33	4635	4560	-75
34	2120	2110	-10
35	1075	997	-78
36	2880	2880	0
37	1770	1790	20
38	1700	1679	-21
39	920	935	15
40	600	607	7
41	880	890	10
42	2270	2218	-52
43	2690	2710	20
44	1075	994	-81
45	820	793	-27
46	1195	1230	35
47	3510	3525	15
48	1390	1420	30
49	2520	2515	-5
50	4685	4701	16
51	4210	4225	15
52	2305	2290	-15
53	3460	3295	-165
54	2305	2290	-15
55	3370	3250	-120
56	1390	1410	20
57	1500	1492	-8
58	380	348	-32
59	900	895	-5
60	1910	1980	70

BQ08 First Level

Measurement no	Specification	Actual	Difference
1	3230	3205	-25
2	4965	4944	-21
3	2710	2686	-24
4	3540	3560	20
5	1695	1643	-52
6	2930	2982	52
7	3130	3128	-2
8	3040	3028	-12
9	900	907	7
10	1035	995	-40
11	2050	2081	31
12	2930	2948	18
13	2650	2619	-31
14	3040	3043	3
15	3685	3635	-50
16	1695	1668	-27
17	1810	1772	-38
18	1835	1810	-25
19	2650	2600	-50
20	2700	2715	15
21	3640	3698	58
22	1375	1331	-44
23	1325	1365	40
24	2650	2654	4
25	2350	2325	-25
26	3745	3691	-54
27	2350	2336	-14
28	3670	3708	38
29	1895	1870	-25
30	1895	1889	-6
31	1230	1244	14
32	1095	1070	-25
33	3345	3318	-27
34	2350	2336	-14
35	3345	3338	-7
36	2350	2334	-16
37	2250	2241	-9
38	2700	2720	20
39	3240	3193	-47
40	1330	1325	-5
41	3670	3659	-11
42	1895	1867	-28
43	1225	1210	-15
44	1095	1073	-22
45	3745	3791	46
46	2350	2324	-26
47	3745	3650	-95
48	2350	2336	-14
49	1330	1375	45
50	4635	4684	49
51	2700	2718	18
52	2710	2682	-28
53	4965	4954	-11
54	3230	3212	-18
55	3130	3132	2
56	3020	3037	17
57	3540	3556	16
58	1695	1656	-39
59	2650	2671	21
60	1835	1828	-7
61	1790	1825	35
62	900	897	-3
63	1035	998	-37
64	2140	2129	-11
65	2650	2620	-30
66	3040	3028	-12
67	3685	3658	-27
68	1895	1943	48
69	3040	3020	-20
70	2930	2932	2
71	2050	2033	-17

Figure 72. BQ08 Measurement Data

10918			
Measurement no	Theoretical	Actual	Difference
1	2815	2798	-17
2	2940	3772	832
3	875	866	-9
4	620	1074	454
5	1890	1935	45
6	2320	2695	375
7	2815	2794	-21
8	2800	3235	435
9	1940	1931	-9
10	2940	3371	431
11	3450	3794	344
12	860	795	-65
13	3960	3967	7
14	600	564	-36
15	600	664	64
16	1890	1942	52
17	800	771	-29
18	1800	1822	22
19	800	808	8
20	1000	984	-16
21	800	825	25

10922			
Measurement no	Theoretical	Actual	Difference
1	2815	2797	18
2	2940	3009	-69
3	875	853	22
4	620	712	-92
5	1890	1972	-82
6	2320	2291	29
7	2815	2800	15
8	2800	2758	42
9	1940	1928	12
10	2940	2910	30
11	3450	3439	11
12	860	859	1
13	3960	4001	-41
14	600	631	-31
15	600	599	1
16	1890	1959	-69
17	800	754	46
18	1800	1831	-31
19	800	807	-7
20	1000	1018	-18
21	800	806	6

10926			
Measurement no	Theoretical	Actual	Difference
1	2815	2842	27
2	2940	3112	172
3	875	864	-11
4	620	738	118
5	1890	1928	38
6	2320	2345	25
7	2815	2820	5
8	2800	2782	-18
9	1940	1982	42
10	2940	2929	-11
11	3450	3518	68
12	860	843	-17
13	3960	3983	23
14	600	569	-31
15	600	654	54
16	1890	1903	13
17	800	778	-22
18	1800	1809	9
19	800	798	-2
20	1000	831	-169
21	800	980	180

10927			
Measurement no	Theoretical	Actual	Difference
1	2815	2742	-73
2	2940	2965	25
3	875	860	-15
4	620	802	182
5	1890	1879	-11
6	2320	2204	-116
7	2815	2832	17
8	2800	2783	-17
9	1940	1969	29
10	2940	2961	21
11	3450	3459	9
12	860	852	-8
13	3960	3942	-18
14	600	793	193
15	600	478	-122
16	1890	1905	15
17	800	785	-15
18	1800	1979	179
19	800	817	17
20	1000	1015	15
21	800	800	0

Figure 73. 10918, 10922, 10926 and 10927 Measurement Data

10929			
Measurement no	Theoretical	Actual	Difference
1	2815	2816	-1
2	2940	2958	-18
3	875	882	-7
4	620	748	-128
5	1890	1929	-39
6	2320	2334	-14
7	2815	2818	-3
8	2800	2801	-1
9	1940	1956	-16
10	2940	2950	-10
11	3450	3399	51
12	860	850	10
13	3960	4010	-50
14	600	607	-7
15	600	780	-180
16	1890	1978	-88
17	800	817	-17
18	1800	1835	-35
19	800	793	7
20	1000	998	2
21	800	853	53

10930			
Measurement no	Theoretical	Actual	Difference
1	2815	2878	63
2	2940	2909	-31
3	875	883	8
4	620	721	101
5	1890	1910	20
6	2320	2227	-93
7	2815	2777	-38
8	2800	2774	-26
9	1940	1934	-6
10	2940	2916	-24
11	3450	3426	-24
12	860	903	43
13	3960	3940	-20
14	600	616	16
15	600	663	63
16	1890	1895	5
17	800	810	10
18	1800	1831	31
19	800	807	7
20	1000	1038	38
21	800	800	0

10932			
Measurement no	Specification	Actual	Difference
1	2815	2800	-15
2	2940	2910	-30
3	875	860	-15
4	620	750	130
5	1890	1900	10
6	2320	2280	-40
7	2815	2800	-15
8	2800	2780	-20
9	1940	1980	40
10	2800	2790	-10
11	3450	3380	-70
12	860	840	-20
13	3960	3965	5
14	600	590	-10
15	600	650	50
16	1890	1890	0
17	800	800	0
18	1800	1800	0
19	800	820	20
20	1000	1010	10
21	800	790	-10

10933			
Measurement no	Theoretical	Actual	Difference
1	2815	2820	5
2	2940	2890	-50
3	875	895	20
4	620	770	150
5	1890	1920	30
6	2320	2150	-170
7	2815	2760	-55
8	2800	2720	-80
9	1940	1950	10
10	2800	2850	50
11	3450	3460	10
12	860	860	0
13	3960	4000	40
14	600	730	130
15	600	600	0
16	1890	1895	5
17	800	730	-70
18	1800	1780	-20
19	800	850	50
20	1000	1050	50
21	800	710	-90

Figure 74. 10929, 10930, 10932 and 10933 Measurement Data

10934

Measurement no	Theoretical	Actual	Difference
1	2815	2790	-25
2	2940	2850	-90
3	875	870	-5
4	620	645	25
5	1890	1913	23
6	2320	2270	-50
7	2815	2800	-15
8	2800	2820	20
9	1940	1925	-15
10	2800	2855	55
11	3450	3425	-25
12	860	860	0
13	3960	3945	-15
14	600	810	210
15	600	500	-100
16	1890	1910	20
17	800	643	-157
18	1800	1795	-5
19	800	830	30
20	1000	1010	10
21	800	800	0

10935

Measurement no	Theoretical	Actual	Difference
1	2815	2785	-30
2	2940	2843	-97
3	875	869	-6
4	620	642	22
5	1890	1910	20
6	2320	2274	-46
7	2815	2802	-13
8	2800	2848	48
9	1940	1976	36
10	2800	2853	53
11	3450	3437	-13
12	860	857	-3
13	3960	3949	-11
14	600	809	209
15	600	498	-102
16	1890	1913	23
17	800	646	-154
18	1800	1810	10
19	800	908	108
20	1000	1018	18
21	800	797	-3

12071

Measurement no	Theoretical	Actual	Difference
1	2815	2786	29
2	2940	3099	-159
3	875	852	23
4	620	790	-170
5	1890	1950	-60
6	2320	2284	36
7	2815	2797	18
8	2800	2663	137
9	1940	1931	9
10	2800	2850	-50
11	3450	3576	-126
12	860	847	13
13	3960	4082	-122
14	600	621	-21
15	600	584	16
16	1890	1953	-63
17	800	822	-22
18	1800	1825	-25
19	800	776	24
20	1000	1044	-44
21	800	760	40

12126

Measurement no	Theoretical	Actual	Difference
1	2815	2789	26
2	2940	2990	-50
3	875	862	13
4	620	662	-42
5	1890	1932	-42
6	2320	2319	1
7	2815	2780	35
8	2800	2667	133
9	1940	1938	2
10	2800	2832	-32
11	3450	3628	-178
12	860	1073	-213
13	3960	3850	110
14	600	659	-59
15	600	619	-19
16	1890	1909	-19
17	800	789	11
18	1800	1816	-16
19	800	789	11
20	1000	1106	-106
21	800	705	95

Figure 75. 10934, 10935, 12071 and 12126 Measurement Data

12127			
Measurement no	Theoretical	Actual	Difference
1	2815	2800	15
2	2940	2855	85
3	875	857	18
4	620	726	-106
5	1890	1928	-38
6	2320	2284	36
7	2815	2799	16
8	2800	2681	119
9	1940	1963	-23
10	2800	2863	-63
11	3450	3480	-30
12	860	818	42
13	3960	4120	-160
14	600	659	-59
15	600	543	57
16	1890	1898	-8
17	800	775	25
18	1800	1811	-11
19	800	778	22
20	1000	792	208
21	800	1000	-200

12148			
Measurement no	Theoretical	Actual	Difference
1	2815	2787	28
2	2940	3045	-105
3	875	855	20
4	620	726	-106
5	1890	1954	-64
6	2320	2288	32
7	2815	2801	14
8	2800	2738	62
9	1940	1947	-7
10	2940	2934	6
11	3450	3427	23
12	860	1063	-203
13	3960	3853	107
14	600	392	208
15	600	854	-254
16	1890	1945	-55
17	800	814	-14
18	1800	1820	-20
19	800	765	35
20	1000	799	201
21	800	1023	-223

12149			
Measurement no	Theoretical	Actual	Difference
1	2815	2786	29
2	2940	3076	-136
3	875	853	22
4	620	834	-214
5	1890	1924	-34
6	2320	2265	55
7	2815	2804	11
8	2800	2633	167
9	1940	1964	-24
10	2800	2810	-10
11	3450	3525	-75
12	860	1051	-191
13	3960	3877	83
14	600	384	216
15	600	838	-238
16	1890	1831	59
17	800	795	5
18	1800	1783	17
19	800	796	4
20	1000	1021	-21
21	800	741	59

12157			
Measurement no	Theoretical	Actual	Difference
1	2815	2782	33
2	2940	3011	-71
3	875	863	12
4	620	746	-126
5	1890	1922	-32
6	2320	2290	30
7	2815	2800	15
8	2800	2655	145
9	1940	1931	9
10	2800	2824	-24
11	3450	3544	-94
12	860	898	-38
13	3960	4018	-58
14	600	496	104
15	600	750	-150
16	1890	1923	-33
17	800	802	-2
18	1800	1805	-5
19	800	782	18
20	1000	1002	-2
21	800	806	-6

Figure 76. 12127, 12148, 12149 and 12157 Measurement Data

APPENDIX D – PROCESSED DATA

This appendix presents processed data for both HDDS and SASS units. Traditional measurements and measurements generated from drone imaging is presented and compared. The processed data is in the form of relative error between the following measurements:

- Traditional measurements vs. building specifications
- Drone measurements: QTO generated measurements vs. traditional measurements
- Drone measurements: MATLAB generated measurements vs. traditional measurements

The variance between units for each measurement is presented, as well as the variance between the measurements of each unit for both the HDDS and SASS units.

<u>HDDS Units</u>

The tables below represent the relative error between the building specification and the traditional measurements obtained for the HDDS units:

Table 19: Processed traditional data measured for HDDS Ground Floor (Units BQ01 - BQ08) – Percentage error.

Measurement ID	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08	Variance
1	0.52%	0.40%	0.87%	0.40%	-0.87%	0.99%	0.60%	0.40%	0.003%
2	-0.06%	0.21%	-0.36%	-0.64%	0.04%	0.04%	-0.28%	-0.55%	0.001%
3	-0.10%	2.09%	0.62%	2.14%	-0.24%	0.33%	-0.12%	2.14%	0.012%
4	4.22%	5.89%	3.33%	3.33%	2.11%	5.22%	4.00%	3.33%	0.014%
5	0.36%	-1.78%	0.39%	-2.82%	1.04%	0.36%	0.33%	-2.82%	0.025%
6	0.45%	-1.48%	1.45%	-2.67%	0.74%	0.18%	0.45%	-2.67%	0.026%
7	1.05%	-4.45%	0.94%	-5.24%	-4.29%	-4.55%	1.15%	-5.24%	0.091%
8	-3.42%	11.84%	-5.26%	22.37%	19.74%	28.42%	-3.68%	19.74%	1.820%
9	1.33%	1.93%	12.60%	1.33%	6.00%	5.40%	1.47%	1.33%	0.160%
10	-1.57%	3.71%	-1.36%	-1.43%	1.00%	-0.07%	-1.43%	-1.43%	0.035%
11	-0.07%	4.39%	0.43%	-2.01%	0.22%	-1.44%	-0.29%	-1.51%	0.040%
12	-0.88%	2.95%	1.50%	0.88%	0.66%	3.13%	-0.84%	0.88%	0.022%
13	-0.56%	-0.86%	-2.53%	-2.23%	0.41%	-0.48%	-0.41%	-2.23%	0.012%
14	0.65%	-2.70%	3.26%	8.84%	0.09%	12.28%	0.93%	8.84%	0.281%
15	-1.22%	6.71%	1.34%	3.05%	-0.37%	-0.61%	-2.20%	3.05%	0.086%
16	-2.42%	6.17%	-0.58%	-1.00%	1.42%	-0.17%	-2.33%	-1.58%	0.079%
17	0.61%	0.56%	1.04%	-0.22%	0.48%	0.48%	0.43%	-0.22%	0.002%
18	2.83%	2.22%	0.80%	0.24%	0.33%	0.24%	0.80%	0.47%	0.010%
19	0.74%	-1.77%	2.51%	12.47%	1.21%	12.47%	2.51%	9.77%	0.321%

Measurement ID	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08	Variance
20	-0.45%	-3.33%	-0.49%	-1.46%	-0.31%	-1.46%	1.01%	-0.35%	0.016%
21	1.30%	-2.71%	2.94%	-6.16%	0.51%	-3.33%	2.99%	-4.52%	0.123%
22	-1.06%	1.94%	-2.41%	4.06%	-0.06%	2.06%	-2.65%	1.65%	0.057%
23	1.63%	-2.72%	4.13%	1.41%	1.52%	1.41%	3.48%	1.63%	0.041%
24	11.50%	12.50%	8.83%	-2.50%	1.83%	-2.50%	9.00%	13.33%	0.433%
25	-0.11%	-1.48%	-2.61%	-2.05%	-2.16%	-2.05%	-2.39%	0.57%	0.013%
26	0.09%	1.30%	-0.50%	0.00%	0.14%	-0.61%	1.06%	0.35%	0.005%
27	-0.24%	-0.98%	-1.06%	-0.42%	-0.26%	-0.58%	-0.80%	0.00%	0.001%
28	0.64%	2.95%	0.64%	-0.59%	0.10%	4.47%	0.25%	-0.49%	0.032%
29	-0.24%	-2.65%	-0.24%	-0.52%	-0.43%	-1.33%	-0.28%	-0.62%	0.007%
30	-1.06%	-2.00%	-1.06%	-1.39%	0.22%	-0.67%	-1.61%	-1.11%	0.004%
31	-0.81%	-0.13%	-0.81%	1.63%	1.81%	-0.09%	-0.13%	1.41%	0.012%
32	0.69%	-0.97%	1.34%	-0.78%	-0.88%	-0.28%	-0.72%	-0.13%	0.007%
33	-0.09%	0.17%	1.55%	1.29%	0.19%	2.16%	0.13%	1.62%	0.008%
34	1.27%	0.05%	1.27%	0.14%	0.47%	0.71%	0.00%	0.47%	0.003%
35	0.65%	-2.05%	11.72%	5.95%	3.44%	5.30%	0.47%	7.26%	0.195%
36	-1.22%	0.03%	0.35%	-0.10%	-1.22%	1.60%	-0.28%	0.00%	0.008%
37	2.09%	-5.88%	1.98%	-1.75%	2.09%	-0.73%	-0.28%	-1.13%	0.072%
38	-2.24%	4.71%	-2.41%	2.06%	-2.76%	0.53%	0.12%	1.24%	0.066%
39	1.63%	-0.11%	2.93%	-1.74%	1.63%	1.96%	-0.11%	-1.63%	0.030%
40	7.33%	17.00%	-7.00%	-1.00%	12.33%	-5.50%	5.50%	-1.17%	0.732%
41	-2.61%	-1.14%	-6.70%	-1.14%	-2.39%	-5.45%	-1.82%	-1.14%	0.045%
42	-0.93%	-0.22%	0.40%	0.40%	0.66%	1.06%	0.48%	2.29%	0.009%
43	-1.78%	1.78%	-0.59%	-0.93%	-1.08%	-1.08%	-1.08%	-0.74%	0.011%
44	1.21%	-1.95%	10.79%	4.00%	2.98%	5.67%	0.74%	7.53%	0.166%
45	-1.95%	-1.22%	2.68%	3.90%	-0.37%	4.51%	-0.37%	3.29%	0.065%
46	-2.09%	12.89%	-13.39%	-3.01%	1.26%	-2.68%	1.26%	-2.93%	0.526%
47	-1.57%	0.20%	0.17%	-0.40%	-0.68%	0.66%	-0.68%	-0.43%	0.005%
48	-1.87%	9.57%	-12.37%	-2.95%	0.58%	-2.37%	0.58%	-2.16%	0.361%
49	0.36%	1.55%	0.08%	-0.04%	-0.20%	-0.32%	-0.20%	0.20%	0.004%
50	-0.43%	0.38%	-0.11%	-0.49%	-0.21%	-0.28%	-0.21%	-0.34%	0.001%
51	0.24%	0.05%	0.69%	-1.62%	-0.48%	-1.26%	-0.48%	-0.36%	0.006%
52	0.43%	1.34%	-0.13%	0.69%	-0.91%	0.35%	-0.91%	0.65%	0.006%
53	-0.29%	-0.52%	0.03%	1.99%	1.10%	-0.58%	1.10%	4.77%	0.032%
54	-0.22%	1.34%	1.34%	0.65%	1.43%	-0.09%	1.43%	0.65%	0.005%
55	-0.15%	0.30%	-4.69%	0.56%	0.53%	2.34%	0.53%	3.56%	0.057%
56	-1.65%	9.35%	-11.51%	-1.51%	0.00%	-3.60%	-0.36%	-1.44%	0.323%
57	7.33%	0.67%	15.07%	0.00%	5.00%	2.67%	-1.00%	0.53%	0.286%

Measurement ID	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08	Variance
58	-2.63%	12.89%	2.11%	11.84%	23.95%	16.05%	8.16%	8.42%	0.672%
59	-0.89%	0.78%	-3.00%	7.44%	3.00%	3.44%	0.33%	0.56%	0.100%
60	0.26%	-3.61%	-2.72%	-2.09%	-5.97%	-3.46%	-4.45%	-3.66%	0.033%
Variance	0.06%	0.22%	0.25%	0.20%	0.21%	0.28%	0.05%	0.18%	

{Box and whisker in results and discussion; generated from the data in the tables below}

Table 20: Processed traditional data measured for HDDS First Floor (Units BQ01 - BQ08) – Percentage error.

Measurement ID	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08	Variance
1	0.62%	2.01%	0.74%	1.11%	-0.12%	0.62%	0.46%	0.77%	0.004%
2	0.42%	0.52%	0.40%	0.44%	0.34%	0.60%	0.22%	0.42%	0.000%
3	1.48%	1.85%	-0.07%	1.33%	0.04%	1.48%	0.52%	0.89%	0.005%
4	-1.13%	-2.49%	-0.68%	-1.44%	0.23%	-1.13%	-1.19%	-0.56%	0.006%
5	1.95%	5.49%	2.48%	3.30%	5.49%	1.95%	2.48%	3.07%	0.021%
6	-0.85%	-2.76%	-3.24%	-2.29%	-2.76%	-0.85%	-2.12%	-1.77%	0.008%
7	0.48%	0.00%	-0.73%	-0.10%	0.00%	0.48%	-0.26%	0.06%	0.002%
8	-0.16%	0.82%	0.63%	0.43%	0.82%	-0.16%	0.07%	0.39%	0.002%
9	0.56%	1.67%	-8.89%	-2.22%	1.67%	0.56%	-1.89%	-0.78%	0.119%
10	1.93%	4.25%	8.60%	4.93%	4.25%	1.93%	2.90%	3.86%	0.046%
11	1.32%	-6.24%	0.39%	-1.51%	-6.24%	1.51%	-2.00%	-1.51%	0.093%
12	-0.38%	-1.88%	-1.02%	-1.09%	0.14%	-0.38%	-0.96%	-0.61%	0.004%
13	0.30%	1.70%	2.19%	1.40%	1.89%	0.30%	0.79%	1.17%	0.005%
14	-0.03%	-0.66%	0.23%	-0.16%	-0.46%	-0.03%	-0.43%	-0.10%	0.001%
15	0.16%	2.04%	3.09%	1.76%	1.90%	0.16%	1.09%	1.36%	0.010%
16	-0.24%	3.95%	2.18%	1.95%	3.07%	2.06%	1.00%	1.59%	0.016%
17	-1.16%	1.93%	9.94%	3.54%	0.83%	-1.16%	1.55%	2.10%	0.124%
18	0.00%	1.74%	4.25%	1.96%	1.09%	0.00%	0.82%	1.36%	0.018%
19	-0.42%	1.43%	2.64%	1.21%	1.47%	-0.42%	0.53%	1.89%	0.012%
20	2.59%	-2.89%	-0.22%	-0.19%	0.00%	-0.74%	-2.26%	-0.56%	0.027%
21	0.00%	-1.65%	-5.30%	-2.34%	-0.41%	-1.13%	-1.35%	-1.59%	0.026%
22	10.18%	-0.73%	7.27%	5.53%	3.27%	2.11%	-0.51%	3.20%	0.140%
23	-3.70%	-1.89%	-6.42%	-4.00%	-2.72%	-1.43%	-2.72%	-3.02%	0.024%
24	0.68%	-0.38%	-0.11%	0.04%	-0.34%	0.15%	-0.60%	-0.15%	0.002%
25	1.87%	1.91%	0.13%	1.28%	0.89%	1.36%	2.04%	1.06%	0.004%
26	1.07%	2.94%	1.28%	1.76%	1.23%	1.76%	1.98%	1.44%	0.004%
27	2.89%	0.21%	0.00%	1.02%	0.60%	0.72%	0.26%	0.60%	0.008%

Measurement ID	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08	Variance
28	-1.63%	-1.09%	-1.09%	-1.28%	-0.74%	-0.60%	-1.34%	-1.04%	0.001%
29	0.53%	3.17%	0.47%	1.37%	1.16%	1.90%	2.85%	1.32%	0.010%
30	4.49%	-1.11%	-0.79%	0.84%	1.69%	0.32%	-1.90%	0.32%	0.039%
31	-3.25%	0.16%	-0.81%	-1.30%	-2.28%	0.24%	0.00%	-1.14%	0.015%
32	5.94%	5.02%	-5.02%	1.92%	5.30%	3.01%	4.20%	2.28%	0.122%
33	1.20%	0.00%	3.68%	1.61%	0.12%	0.75%	-0.30%	0.81%	0.016%
34	0.94%	0.64%	1.28%	0.94%	0.89%	0.85%	0.21%	0.60%	0.001%
35	1.35%	-0.93%	1.64%	0.69%	0.45%	0.15%	-1.08%	0.21%	0.009%
36	1.91%	0.43%	0.64%	0.98%	1.70%	0.77%	-0.04%	0.68%	0.004%
37	-1.11%	-1.91%	8.18%	1.69%	-1.16%	0.27%	-1.91%	0.40%	0.111%
38	0.81%	-2.04%	-1.11%	-0.78%	0.74%	-0.67%	-2.07%	-0.74%	0.012%
39	-0.22%	0.62%	7.41%	2.59%	-0.31%	1.30%	0.71%	1.45%	0.062%
40	6.92%	-3.61%	-0.83%	0.83%	4.66%	-0.38%	-2.93%	0.38%	0.128%
41	0.41%	0.46%	0.14%	0.33%	0.08%	0.46%	1.01%	0.30%	0.001%
42	1.21%	2.11%	2.06%	1.79%	1.79%	1.69%	2.32%	1.48%	0.001%
43	1.88%	4.08%	-0.82%	1.71%	-1.63%	2.53%	3.84%	1.22%	0.041%
44	3.93%	2.28%	2.19%	2.74%	1.28%	2.37%	3.11%	2.01%	0.006%
45	-0.96%	-1.87%	-1.47%	-1.44%	-1.71%	-0.91%	-0.91%	-1.23%	0.001%
46	1.79%	1.06%	1.66%	1.49%	1.23%	1.15%	1.19%	1.11%	0.001%
47	-0.40%	-1.07%	-1.47%	-0.99%	-0.24%	-0.48%	-0.43%	2.54%	0.015%
48	1.28%	1.49%	-0.21%	0.85%	-0.68%	1.11%	1.66%	0.60%	0.007%
49	-1.20%	-7.67%	-1.13%	-3.38%	-1.05%	-3.16%	-7.97%	-3.38%	0.078%
50	-0.86%	-1.40%	-1.34%	-1.21%	-0.93%	-0.71%	-1.60%	-1.06%	0.001%
51	1.07%	-2.04%	-0.19%	-0.41%	-0.30%	-0.56%	-2.22%	-0.67%	0.011%
52	-0.30%	0.92%	3.76%	1.44%	1.18%	1.07%	0.85%	1.03%	0.013%
53	0.20%	0.60%	-0.22%	0.18%	0.16%	0.40%	0.85%	0.22%	0.001%
54	0.68%	0.77%	0.62%	0.68%	0.56%	0.71%	0.93%	0.56%	0.000%
55	0.22%	-0.32%	0.32%	0.06%	0.06%	0.16%	-0.35%	-0.06%	0.001%
56	3.05%	-1.49%	-2.81%	-0.43%	-0.33%	-0.40%	-1.56%	-0.56%	0.029%
57	0.85%	-0.85%	-1.27%	-0.42%	-0.34%	-0.23%	-0.90%	-0.45%	0.004%
58	3.24%	3.83%	1.53%	2.83%	2.30%	2.65%	3.19%	2.30%	0.005%
59	-5.17%	0.94%	-0.08%	-1.43%	-1.13%	0.11%	1.06%	-0.79%	0.039%
60	-0.05%	0.54%	1.36%	0.60%	0.49%	0.76%	0.22%	0.38%	0.002%
61	-1.12%	-3.35%	-0.84%	-1.79%	-2.51%	-1.28%	-3.63%	-1.96%	0.011%
62	-0.44%	3.67%	-3.78%	-0.22%	-0.11%	2.00%	3.78%	0.33%	0.061%
63	0.39%	5.31%	8.50%	4.73%	3.86%	4.06%	3.86%	3.57%	0.050%
64	1.36%	-0.70%	2.80%	1.12%	0.93%	0.47%	-0.98%	0.51%	0.014%
65	1.58%	1.32%	1.51%	1.47%	1.21%	1.21%	1.36%	1.13%	0.000%

Measurement ID	BQ01	BQ02	BQ03	BQ04	BQ05	BQ06	BQ07	BQ08	Variance
66	0.99%	0.00%	1.18%	0.72%	0.59%	0.49%	-0.23%	0.39%	0.002%
67	-2.04%	2.31%	2.14%	0.79%	0.95%	1.22%	0.98%	0.73%	0.018%
68	3.48%	-4.59%	-7.02%	-2.74%	-2.16%	-2.06%	-3.96%	-2.53%	0.090%
69	1.05%	0.33%	1.55%	0.95%	0.99%	0.66%	0.39%	0.66%	0.002%
70	0.00%	-0.17%	0.07%	-0.03%	0.00%	0.17%	0.00%	-0.07%	0.000%
71	2.73%	-0.49%	4.10%	2.10%	-0.54%	0.88%	-1.02%	0.83%	0.032%
Variance	0.05%	0.06%	0.11%	0.03%	0.04%	0.01%	0.04%	0.02%	

Since the percentage error and variance between the measured error was determined to be lower for the First Level, traditional measurements of the first level were used as the basis forward.

To determine whether MATLAB or QTO can be employed to measure the same walls from a drone imagine, the traditional measurements of the first level was used to compare to the measurements generated by the software being investigated.

The following measurements were generated through MATLAB and QTO respectively. The first measurement was selected as the input length to calibrate the analysis (termed “reference”)

{Box and whisker diagram of variation between the QTO measurements of each unit, as well as the MATLAB measurements for each unit discussed in main text, refer to the table below for data reference}

Table 21: QTO and MATLAB generated data for HDDS (BQ01) with calculated relative error.

HDDS Unit	BQ01				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	3210	REFERENCE	REFERENCE		
2	4944	4978	4984	-0.69%	-0.81%
3	2670	2650	2653	0.75%	0.64%
4	3580	3591	3588	-0.31%	-0.22%
5	1662	1689	1678	-1.62%	-0.96%
6	2955	2982	2980	-0.91%	-0.85%
7	3115	3129	3133	-0.45%	-0.58%
8	3045	3053	3042	-0.26%	0.10%
9	895	899	891	-0.45%	0.45%
10	1015	1039	1028	-2.36%	-1.28%
11	2023	2057	2051	-1.68%	-1.38%
12	2941	2971	2969	-1.02%	-0.95%

HDDS Unit	BQ01				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
13	2642	2640	2635	0.08%	0.26%
14	3041	3057	3052	-0.53%	-0.36%
15	3679	3699	3671	-0.54%	0.22%
16	1699	1700	1692	-0.06%	0.41%
17	1831	1863	1868	-1.75%	-2.02%
18	1835	1879	1869	-2.40%	-1.85%
19	2661	2651	2648	0.38%	0.49%
20	2630	2627	2624	0.11%	0.23%
21	3640	3690	3691	-1.37%	-1.40%
22	1235	1225	1219	0.81%	1.30%
23	1374	1363	1357	0.80%	1.24%
24	2632	2650	2655	-0.68%	-0.87%
25	2306	2307	2302	-0.04%	0.17%
26	3705	3733	3733	-0.76%	-0.76%
27	2282	2276	2268	0.26%	0.61%
28	3730	3731	3729	-0.03%	0.03%
29	1885	1872	1864	0.69%	1.11%
30	1810	1797	1801	0.72%	0.50%
31	1270	1242	1241	2.20%	2.28%
32	1030	1015	1015	1.46%	1.46%
33	3305	3300	3299	0.15%	0.18%
34	2328	2301	2300	1.16%	1.20%
35	3300	3289	3292	0.33%	0.24%
36	2305	2303	2305	0.09%	0.00%
37	2275	2237	2237	1.67%	1.67%
38	2678	2624	2622	2.02%	2.09%
39	3247	3180	3179	2.06%	2.09%
40	1238	1231	1224	0.57%	1.13%
41	3655	3603	3582	1.42%	2.00%
42	1872	1860	1849	0.64%	1.23%
43	1202	1192	1191	0.83%	0.92%
44	1052	1055	1040	-0.29%	1.14%
45	3781	3787	3794	-0.16%	-0.34%
46	2308	2296	2302	0.52%	0.26%
47	3760	3746	3740	0.37%	0.53%
48	2320	2333	2337	-0.56%	-0.73%
49	1346	1332	1333	1.04%	0.97%
50	4675	4683	4688	-0.17%	-0.28%

HDDS Unit	BQ01				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
51	2671	2693	2697	-0.82%	-0.97%
52	2718	2831	2831	-4.16%	-4.16%
53	4955	4927	4932	0.57%	0.46%
54	3208	3233	3225	-0.78%	-0.53%
55	3123	3110	3103	0.42%	0.64%
56	2928	2920	2923	0.27%	0.17%
57	3510	3494	3489	0.46%	0.60%
58	1640	1676	1667	-2.20%	-1.65%
59	2787	2882	2881	-3.41%	-3.37%
60	1836	1842	1843	-0.33%	-0.38%
61	1810	1849	1851	-2.15%	-2.27%
62	904	894	897	1.11%	0.77%
63	1031	1031	1020	0.00%	1.07%
64	2111	2177	2184	-3.13%	-3.46%
65	2608	2601	2591	0.27%	0.65%
66	3010	3057	3048	-1.56%	-1.26%
67	3760	3771	3767	-0.29%	-0.19%
68	1829	1837	1839	-0.44%	-0.55%
69	3008	3042	3045	-1.13%	-1.23%
70	2930	2952	2942	-0.75%	-0.41%
71	1994	1999	1972	-0.25%	1.10%
Variance				0.02%	0.02%

Table 22: QTO and MATLAB generated data for HDDS (BQ02) with calculated relative error.

HDDS Unit	BQ02				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	3165	REFERENCE	REFERENCE		
2	4939	4974	4958	-0.71%	-0.38%
3	2660	2670	2674	-0.38%	-0.53%
4	3628	3621	3623	0.19%	0.14%
5	1602	1629	1646	-1.69%	-2.75%
6	3011	3073	3067	-2.06%	-1.86%
7	3130	3156	3174	-0.83%	-1.41%
8	3015	3010	3020	0.17%	-0.17%
9	885	905	889	-2.26%	-0.45%
10	991	982	987	0.91%	0.40%

HDDS Unit	BQ02				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
11	2178	2175	2186	0.14%	-0.37%
12	2985	3010	3004	-0.84%	-0.64%
13	2605	2603	2624	0.08%	-0.73%
14	3060	3059	3073	0.03%	-0.42%
15	3610	3567	3557	1.19%	1.47%
16	1628	1622	1634	0.37%	-0.37%
17	1775	1765	1772	0.56%	0.17%
18	1803	1803	1773	0.00%	1.66%
19	2612	2592	2586	0.77%	1.00%
20	2778	2760	2767	0.65%	0.40%
21	3700	3710	3715	-0.27%	-0.41%
22	1385	1367	1346	1.30%	2.82%
23	1350	1348	1352	0.15%	-0.15%
24	2660	2660	2660	0.00%	0.00%
25	2305	2230	2219	3.25%	3.73%
26	3635	3618	3599	0.47%	0.99%
27	2345	2351	2352	-0.26%	-0.30%
28	3710	3681	3678	0.78%	0.86%
29	1835	1853	1847	-0.98%	-0.65%
30	1916	1870	1858	2.40%	3.03%
31	1228	1221	1230	0.57%	-0.16%
32	1040	1026	1042	1.35%	-0.19%
33	3345	3283	3286	1.85%	1.76%
34	2335	2323	2343	0.51%	-0.34%
35	3376	3361	3357	0.44%	0.56%
36	2340	2340	2346	0.00%	-0.26%
37	2293	2255	2239	1.66%	2.35%
38	2755	2753	2773	0.07%	-0.65%
39	3220	3175	3188	1.40%	0.99%
40	1378	1359	1379	1.38%	-0.07%
41	3653	3648	3645	0.14%	0.22%
42	1855	1872	1887	-0.92%	-1.73%
43	1175	1196	1210	-1.79%	-2.98%
44	1070	1087	1072	-1.59%	-0.19%
45	3815	3805	3802	0.26%	0.34%
46	2325	2330	2312	-0.22%	0.56%
47	3785	3771	3777	0.37%	0.21%
48	2315	2292	2313	0.99%	0.09%

HDDS Unit	BQ02				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
49	1432	1425	1435	0.49%	-0.21%
50	4700	4720	4707	-0.43%	-0.15%
51	2755	2745	2724	0.36%	1.13%
52	2685	2695	2704	-0.37%	-0.71%
53	4935	4970	4967	-0.71%	-0.65%
54	3205	3230	3247	-0.78%	-1.31%
55	3140	3162	3148	-0.70%	-0.25%
56	3065	3115	3108	-1.63%	-1.40%
57	3570	3575	3562	-0.14%	0.22%
58	1630	1659	1663	-1.78%	-2.02%
59	2625	2616	2612	0.34%	0.50%
60	1825	1823	1843	0.11%	-0.99%
61	1850	1885	1884	-1.89%	-1.84%
62	867	850	855	1.96%	1.38%
63	980	998	988	-1.84%	-0.82%
64	2155	2164	2177	-0.42%	-1.02%
65	2615	2582	2586	1.26%	1.11%
66	3040	3083	3063	-1.41%	-0.76%
67	3600	3559	3552	1.14%	1.33%
68	1982	2033	2037	-2.57%	-2.77%
69	3030	3046	3036	-0.53%	-0.20%
70	2935	2963	2952	-0.95%	-0.58%
71	2060	2045	2025	0.73%	1.70%
Variance				0.01%	0.02%

Table 23: QTO and MATLAB generated data for HDDS (BQ03) with calculated relative error.

HDDS Unit	BQ03				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	3206	REFERENCE	REFERENCE		
2	4945	4980	4992	-0.71%	-0.95%
3	2712	2707	2709	0.18%	0.11%
4	3564	3566	3563	-0.06%	0.03%
5	1653	1680	1685	-1.63%	-1.94%
6	3025	3070	3072	-1.49%	-1.55%
7	3153	3173	3182	-0.63%	-0.92%
8	3021	3023	3021	-0.07%	0.00%

HDDS Unit	BQ03				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
9	980	1011	1009	-3.16%	-2.96%
10	946	954	949	-0.85%	-0.32%
11	2042	2058	2051	-0.78%	-0.44%
12	2960	2988	2983	-0.95%	-0.78%
13	2592	2621	2623	-1.12%	-1.20%
14	3033	3041	3053	-0.26%	-0.66%
15	3571	3559	3558	0.34%	0.36%
16	1658	1655	1665	0.18%	-0.42%
17	1630	1641	1642	-0.67%	-0.74%
18	1757	1779	1788	-1.25%	-1.76%
19	2580	2565	2567	0.58%	0.50%
20	2706	2695	2698	0.41%	0.30%
21	3833	3863	3858	-0.78%	-0.65%
22	1275	1261	1264	1.10%	0.86%
23	1410	1403	1410	0.50%	0.00%
24	2653	2662	2668	-0.34%	-0.57%
25	2347	2310	2300	1.58%	2.00%
26	3697	3703	3696	-0.16%	0.03%
27	2350	2350	2350	0.00%	0.00%
28	3710	3667	3670	1.16%	1.08%
29	1886	1889	1884	-0.16%	0.11%
30	1910	1880	1885	1.57%	1.31%
31	1240	1222	1219	1.45%	1.69%
32	1150	1135	1127	1.30%	2.00%
33	3222	3201	3203	0.65%	0.59%
34	2320	2309	2309	0.47%	0.47%
35	3290	3277	3278	0.40%	0.36%
36	2335	2334	2341	0.04%	-0.26%
37	2066	2028	2026	1.84%	1.94%
38	2730	2702	2708	1.03%	0.81%
39	3000	3010	3006	-0.33%	-0.20%
40	1341	1328	1326	0.97%	1.12%
41	3665	3636	3636	0.79%	0.79%
42	1856	1859	1856	-0.16%	0.00%
43	1235	1241	1238	-0.49%	-0.24%
44	1071	1081	1087	-0.93%	-1.49%
45	3800	3798	3793	0.05%	0.18%
46	2311	2307	2310	0.17%	0.04%

HDDS Unit	BQ03				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
47	3800	3775	3781	0.66%	0.50%
48	2355	2350	2355	0.21%	0.00%
49	1345	1334	1333	0.82%	0.89%
50	4697	4711	4706	-0.30%	-0.19%
51	2705	2777	2777	-2.66%	-2.66%
52	2608	2670	2679	-2.38%	-2.72%
53	4976	4980	4975	-0.08%	0.02%
54	3210	3235	3246	-0.78%	-1.12%
55	3120	3125	3138	-0.16%	-0.58%
56	3105	3126	3120	-0.68%	-0.48%
57	3585	3579	3587	0.17%	-0.06%
58	1669	1702	1701	-1.98%	-1.92%
59	2652	2695	2697	-1.62%	-1.70%
60	1810	1812	1810	-0.11%	0.00%
61	1805	1842	1835	-2.05%	-1.66%
62	934	920	918	1.50%	1.71%
63	947	956	964	-0.95%	-1.80%
64	2080	2118	2113	-1.83%	-1.59%
65	2610	2590	2593	0.77%	0.65%
66	3004	3049	3045	-1.50%	-1.36%
67	3606	3591	3591	0.42%	0.42%
68	2028	2058	2065	-1.48%	-1.82%
69	2993	3018	3020	-0.84%	-0.90%
70	2928	2953	2943	-0.85%	-0.51%
71	1966	1961	1953	0.25%	0.66%
Variance				0.01%	0.01%

Table 24: QTO and MATLAB generated data for HDDS (BQ04) with calculated relative error.

HDDS Unit	BQ04				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	3194	REFERENCE	REFERENCE		
2	4943	4964	4940	-0.42%	0.06%
3	2674	2715	2722	-1.53%	-1.80%
4	3591	3581	3572	0.28%	0.53%
5	1639	1681	1684	-2.56%	-2.75%
6	2997	3081	3076	-2.80%	-2.64%

HDDS Unit	BQ04				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
7	3133	3194	3190	-1.95%	-1.82%
8	3027	3021	3014	0.20%	0.43%
9	920	954	943	-3.70%	-2.50%
10	984	943	941	4.17%	4.37%
11	2081	2065	2057	0.77%	1.15%
12	2962	2988	2959	-0.88%	0.10%
13	2613	2612	2604	0.04%	0.34%
14	3045	3061	3054	-0.53%	-0.30%
15	3620	3623	3616	-0.08%	0.11%
16	1662	1641	1643	1.26%	1.14%
17	1746	1693	1694	3.04%	2.98%
18	1799	1780	1775	1.06%	1.33%
19	2618	2618	2620	0.00%	-0.08%
20	2705	2687	2660	0.67%	1.66%
21	3725	3701	3689	0.64%	0.97%
22	1299	1283	1293	1.23%	0.46%
23	1378	1393	1380	-1.09%	-0.15%
24	2649	2672	2666	-0.87%	-0.64%
25	2320	2311	2308	0.39%	0.52%
26	3679	3704	3696	-0.68%	-0.46%
27	2326	2335	2334	-0.39%	-0.34%
28	3717	3712	3701	0.13%	0.43%
29	1869	1871	1873	-0.11%	-0.21%
30	1879	1889	1890	-0.53%	-0.59%
31	1246	1220	1226	2.09%	1.61%
32	1074	1119	1100	-4.19%	-2.42%
33	3291	3255	3250	1.09%	1.25%
34	2328	2318	2317	0.43%	0.47%
35	3322	3288	3261	1.02%	1.84%
36	2327	2354	2339	-1.16%	-0.52%
37	2212	2201	2199	0.50%	0.59%
38	2721	2667	2639	1.98%	3.01%
39	3156	3110	3095	1.46%	1.93%
40	1319	1331	1327	-0.91%	-0.61%
41	3658	3618	3619	1.09%	1.07%
42	1861	1839	1820	1.18%	2.20%
43	1204	1242	1226	-3.16%	-1.83%
44	1065	1072	1065	-0.66%	0.00%

HDDS Unit	BQ04				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
45	3799	3800	3772	-0.03%	0.71%
46	2315	2309	2285	0.26%	1.30%
47	3782	3774	3753	0.21%	0.77%
48	2330	2379	2367	-2.10%	-1.59%
49	1375	1343	1335	2.33%	2.91%
50	4691	4724	4714	-0.70%	-0.49%
51	2711	2778	2771	-2.47%	-2.21%
52	2671	2689	2694	-0.67%	-0.86%
53	4956	4962	4948	-0.12%	0.16%
54	3208	3231	3225	-0.72%	-0.53%
55	3128	3148	3134	-0.64%	-0.19%
56	3033	3143	3123	-3.63%	-2.97%
57	3555	3576	3570	-0.59%	-0.42%
58	1647	1721	1711	-4.49%	-3.89%
59	2688	2689	2672	-0.04%	0.60%
60	1824	1822	1810	0.11%	0.77%
61	1822	1820	1795	0.11%	1.48%
62	902	943	942	-4.55%	-4.43%
63	986	971	983	1.52%	0.30%
64	2116	2097	2100	0.90%	0.76%
65	2611	2646	2639	-1.34%	-1.07%
66	3018	3066	3075	-1.59%	-1.89%
67	3656	3603	3595	1.45%	1.67%
68	1947	2073	2068	-6.47%	-6.21%
69	3011	3014	2998	-0.10%	0.43%
70	2931	2973	2964	-1.43%	-1.13%
71	2007	2009	2004	-0.10%	0.15%
Variance				0.03%	0.03%

Table 25: QTO and MATLAB generated data for HDDS (BQ05) with calculated relative error.

HDDS Unit	BQ05				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	3234	REFERENCE	REFERENCE		
2	4948	4983	4984	-0.71%	-0.73%
3	2709	2710	2693	-0.04%	0.59%
4	3532	3634	3614	-2.89%	-2.32%

HDDS Unit	BQ05				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
5	1602	1642	1632	-2.50%	-1.87%
6	3011	3061	3045	-1.66%	-1.13%
7	3130	3149	3158	-0.61%	-0.89%
8	3015	3016	3021	-0.03%	-0.20%
9	885	902	907	-1.92%	-2.49%
10	991	979	980	1.21%	1.11%
11	2178	2165	2165	0.60%	0.60%
12	2926	3019	3009	-3.18%	-2.84%
13	2600	2600	2603	0.00%	-0.12%
14	3054	3069	3080	-0.49%	-0.85%
15	3615	3617	3624	-0.06%	-0.25%
16	1643	1635	1648	0.49%	-0.30%
17	1795	1780	1769	0.84%	1.45%
18	1815	1814	1814	0.06%	0.06%
19	2611	2600	2608	0.42%	0.11%
20	2700	2761	2768	-2.26%	-2.52%
21	3655	3622	3615	0.90%	1.09%
22	1330	1371	1380	-3.08%	-3.76%
23	1361	1346	1329	1.10%	2.35%
24	2659	2654	2651	0.19%	0.30%
25	2329	2321	2331	0.34%	-0.09%
26	3699	3676	3672	0.62%	0.73%
27	2336	2339	2326	-0.13%	0.43%
28	3697	3683	3698	0.38%	-0.03%
29	1873	1839	1846	1.82%	1.44%
30	1863	1867	1857	-0.21%	0.32%
31	1258	1234	1207	1.91%	4.05%
32	1037	1011	1024	2.51%	1.25%
33	3341	3331	3332	0.30%	0.27%
34	2329	2321	2329	0.34%	0.00%
35	3330	3321	3328	0.27%	0.06%
36	2310	2300	2304	0.43%	0.26%
37	2276	2249	2259	1.19%	0.75%
38	2680	2691	2694	-0.41%	-0.52%
39	3250	3202	3206	1.48%	1.35%
40	1268	1291	1288	-1.81%	-1.58%
41	3667	3644	3650	0.63%	0.46%
42	1861	1874	1889	-0.70%	-1.50%

HDDS Unit	BQ05				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
43	1245	1204	1203	3.29%	3.37%
44	1081	1082	1069	-0.09%	1.11%
45	3809	3799	3811	0.26%	-0.05%
46	2321	2322	2287	-0.04%	1.46%
47	3754	3786	3795	-0.85%	-1.09%
48	2366	2301	2287	2.75%	3.34%
49	1344	1418	1420	-5.51%	-5.65%
50	4678	4735	4746	-1.22%	-1.45%
51	2708	2756	2753	-1.77%	-1.66%
52	2678	2686	2675	-0.30%	0.11%
53	4957	4956	4969	0.02%	-0.24%
54	3212	3227	3239	-0.47%	-0.84%
55	3128	3167	3165	-1.25%	-1.18%
56	3030	3100	3054	-2.31%	-0.79%
57	3552	3565	3569	-0.37%	-0.48%
58	1656	1673	1679	-1.03%	-1.39%
59	2680	2681	2684	-0.04%	-0.15%
60	1826	1815	1821	0.60%	0.27%
61	1835	1890	1903	-3.00%	-3.71%
62	901	919	911	-2.00%	-1.11%
63	995	1005	995	-1.01%	0.00%
64	2120	2168	2165	-2.26%	-2.12%
65	2618	2617	2629	0.04%	-0.42%
66	3022	3077	3081	-1.82%	-1.95%
67	3650	3669	3669	-0.52%	-0.52%
68	1936	2021	2025	-4.39%	-4.60%
69	3010	3039	3056	-0.96%	-1.53%
70	2930	2951	2949	-0.72%	-0.65%
71	2061	2060	2056	0.05%	0.24%
Variance				0.02%	0.03%

Table 26: QTO and MATLAB generated data for HDDS (BQ06) with calculated relative error.

HDDS Unit	BQ06				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	3210	REFERENCE	REFERENCE		
2	4935	5010	5008	-1.52%	-1.48%

HDDS Unit	BQ06				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
3	2670	2662	2650	0.30%	0.75%
4	3580	3597	3627	-0.47%	-1.31%
5	1662	1720	1739	-3.49%	-4.63%
6	2955	3032	3014	-2.61%	-2.00%
7	3115	3160	3163	-1.44%	-1.54%
8	3045	3059	3064	-0.46%	-0.62%
9	895	923	914	-3.13%	-2.12%
10	1015	1042	1070	-2.66%	-5.42%
11	2019	2070	2078	-2.53%	-2.92%
12	2941	2999	2992	-1.97%	-1.73%
13	2642	2651	2632	-0.34%	0.38%
14	3041	3071	3069	-0.99%	-0.92%
15	3679	3699	3673	-0.54%	0.16%
16	1660	1701	1693	-2.47%	-1.99%
17	1831	1866	1854	-1.91%	-1.26%
18	1835	1895	1891	-3.27%	-3.05%
19	2661	2649	2650	0.45%	0.41%
20	2720	2731	2732	-0.40%	-0.44%
21	3681	3689	3686	-0.22%	-0.14%
22	1346	1221	1224	9.29%	9.06%
23	1344	1369	1391	-1.86%	-3.50%
24	2646	2667	2669	-0.79%	-0.87%
25	2318	2290	2291	1.21%	1.16%
26	3679	3748	3745	-1.88%	-1.79%
27	2333	2284	2262	2.10%	3.04%
28	3692	3723	3703	-0.84%	-0.30%
29	1859	1881	1892	-1.18%	-1.78%
30	1889	1819	1809	3.71%	4.24%
31	1227	1234	1268	-0.57%	-3.34%
32	1062	1022	1012	3.77%	4.71%
33	3320	3283	3265	1.11%	1.66%
34	2330	2296	2317	1.46%	0.56%
35	3340	3282	3300	1.74%	1.20%
36	2332	2314	2312	0.77%	0.86%
37	2244	2244	2236	0.00%	0.36%
38	2718	2651	2641	2.47%	2.83%
39	3198	3158	3147	1.25%	1.59%
40	1335	1232	1215	7.72%	8.99%

HDDS Unit	BQ06				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
41	3653	3585	3568	1.86%	2.33%
42	1863	1864	1857	-0.05%	0.32%
43	1194	1210	1195	-1.34%	-0.08%
44	1069	1069	1051	0.00%	1.68%
45	3779	3793	3801	-0.37%	-0.58%
46	2323	2299	2318	1.03%	0.22%
47	3763	3741	3775	0.58%	-0.32%
48	2324	2346	2361	-0.95%	-1.59%
49	1372	1327	1328	3.28%	3.21%
50	4668	4705	4701	-0.79%	-0.71%
51	2715	2730	2733	-0.55%	-0.66%
52	2681	2698	2693	-0.63%	-0.45%
53	4945	4937	4951	0.16%	-0.12%
54	3207	3259	3271	-1.62%	-2.00%
55	3125	3123	3139	0.06%	-0.45%
56	3032	3045	3036	-0.43%	-0.13%
57	3548	3501	3512	1.32%	1.01%
58	1650	1717	1729	-4.06%	-4.79%
59	2647	2681	2680	-1.28%	-1.25%
60	1821	1849	1865	-1.54%	-2.42%
61	1813	1877	1878	-3.53%	-3.59%
62	882	901	912	-2.15%	-3.40%
63	993	1040	1077	-4.73%	-8.46%
64	2130	2133	2127	-0.14%	0.14%
65	2618	2603	2618	0.57%	0.00%
66	3025	3100	3122	-2.48%	-3.21%
67	3640	3759	3776	-3.27%	-3.74%
68	1934	1941	1955	-0.36%	-1.09%
69	3020	3064	3069	-1.46%	-1.62%
70	2925	2982	2963	-1.95%	-1.30%
71	2032	2042	2050	-0.49%	-0.89%
Variance				0.05%	0.08%

Table 27: QTO and MATLAB generated data for HDDS (BQ07) with calculated relative error.

HDDS Unit	BQ07				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	3215	REFERENCE	REFERENCE		
2	4954	4962	4961	-0.16%	-0.14%
3	2696	2708	2724	-0.45%	-1.04%
4	3582	3569	3581	0.36%	0.03%
5	1653	1685	1693	-1.94%	-2.42%
6	2992	3003	3000	-0.37%	-0.27%
7	3138	3120	3114	0.57%	0.76%
8	3038	3032	3027	0.20%	0.36%
9	917	904	899	1.42%	1.96%
10	1005	1003	1017	0.20%	-1.19%
11	2091	2128	2138	-1.77%	-2.25%
12	2958	2945	2942	0.44%	0.54%
13	2629	2656	2648	-1.03%	-0.72%
14	3053	3036	3043	0.56%	0.33%
15	3645	3622	3622	0.63%	0.63%
16	1678	1654	1655	1.43%	1.37%
17	1782	1789	1782	-0.39%	0.00%
18	1820	1819	1814	0.05%	0.33%
19	2636	2604	2618	1.21%	0.68%
20	2761	2742	2720	0.69%	1.48%
21	3689	3719	3709	-0.81%	-0.54%
22	1382	1423	1412	-2.97%	-2.17%
23	1361	1393	1396	-2.35%	-2.57%
24	2666	2678	2678	-0.45%	-0.45%
25	2302	2310	2311	-0.35%	-0.39%
26	3671	3664	3661	0.19%	0.27%
27	2344	2353	2353	-0.38%	-0.38%
28	3719	3749	3748	-0.81%	-0.78%
29	1841	1865	1862	-1.30%	-1.14%
30	1931	1908	1907	1.19%	1.24%
31	1230	1241	1240	-0.89%	-0.81%
32	1049	1043	1054	0.57%	-0.48%
33	3355	3329	3327	0.77%	0.83%
34	2345	2384	2405	-1.66%	-2.56%
35	3381	3419	3409	-1.12%	-0.83%
36	2351	2367	2354	-0.68%	-0.13%
37	2293	2294	2292	-0.04%	0.04%

HDDS Unit	BQ07				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
38	2756	2725	2710	1.12%	1.67%
39	3217	3218	3227	-0.03%	-0.31%
40	1369	1342	1344	1.97%	1.83%
41	3633	3650	3647	-0.47%	-0.39%
42	1851	1889	1890	-2.05%	-2.11%
43	1178	1205	1206	-2.29%	-2.38%
44	1061	1077	1090	-1.51%	-2.73%
45	3779	3779	3793	0.00%	-0.37%
46	2322	2301	2287	0.90%	1.51%
47	3761	2787	2780	25.90%	26.08%
48	2311	2342	2348	-1.34%	-1.60%
49	1436	1425	1422	0.77%	0.97%
50	4709	4683	4667	0.55%	0.89%
51	2760	2763	2757	-0.11%	0.11%
52	2687	2696	2710	-0.33%	-0.86%
53	4923	4900	4910	0.47%	0.26%
54	3200	3208	3199	-0.25%	0.03%
55	3141	3140	3153	0.03%	-0.38%
56	3067	3053	3056	0.46%	0.36%
57	3572	3591	3583	-0.53%	-0.31%
58	1641	1680	1681	-2.38%	-2.44%
59	2622	2634	2638	-0.46%	-0.61%
60	1831	1817	1835	0.76%	-0.22%
61	1855	1844	1835	0.59%	1.08%
62	866	847	865	2.19%	0.12%
63	995	995	1008	0.00%	-1.31%
64	2161	2190	2198	-1.34%	-1.71%
65	2614	2621	2620	-0.27%	-0.23%
66	3047	3038	3038	0.30%	0.30%
67	3649	3629	3639	0.55%	0.27%
68	1970	1986	2000	-0.81%	-1.52%
69	3028	3037	3036	-0.30%	-0.26%
70	2930	2921	2913	0.31%	0.58%
71	2071	2086	2092	-0.72%	-1.01%
Variance				0.11%	0.11%

Table 28: QTO and MATLAB generated data for HDDS (BQ08) with calculated relative error.

HDDS Unit	BQ08				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	3205	REFERENCE	REFERENCE		
2	4944	4958	4969	-0.28%	-0.51%
3	2686	2712	2698	-0.97%	-0.45%
4	3560	3562	3553	-0.06%	0.20%
5	1643	1679	1681	-2.19%	-2.31%
6	2982	2996	2993	-0.47%	-0.37%
7	3128	3124	3109	0.13%	0.61%
8	3028	3033	3028	-0.17%	0.00%
9	907	904	907	0.33%	0.00%
10	995	1003	987	-0.80%	0.80%
11	2081	2057	2055	1.15%	1.25%
12	2948	2938	2923	0.34%	0.85%
13	2619	2649	2670	-1.15%	-1.95%
14	3043	3038	3062	0.16%	-0.62%
15	3635	3615	3623	0.55%	0.33%
16	1668	1651	1660	1.02%	0.48%
17	1772	1787	1777	-0.85%	-0.28%
18	1810	1823	1812	-0.72%	-0.11%
19	2600	2594	2607	0.23%	-0.27%
20	2715	2736	2736	-0.77%	-0.77%
21	3698	3715	3694	-0.46%	0.11%
22	1331	1324	1318	0.53%	0.98%
23	1365	1387	1389	-1.61%	-1.76%
24	2654	2679	2684	-0.94%	-1.13%
25	2325	2311	2315	0.60%	0.43%
26	3691	3659	3667	0.87%	0.65%
27	2336	2351	2360	-0.64%	-1.03%
28	3708	3738	3741	-0.81%	-0.89%
29	1870	1858	1875	0.64%	-0.27%
30	1889	1898	1901	-0.48%	-0.64%
31	1244	1245	1241	-0.08%	0.24%
32	1070	1037	1048	3.08%	2.06%
33	3318	3322	3309	-0.12%	0.27%
34	2336	2376	2393	-1.71%	-2.44%
35	3338	3333	3348	0.15%	-0.30%
36	2334	2371	2358	-1.59%	-1.03%
37	2241	2274	2293	-1.47%	-2.32%

HDDS Unit	BQ08				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
38	2720	2723	2723	-0.11%	-0.11%
39	3193	3207	3212	-0.44%	-0.60%
40	1325	1334	1327	-0.68%	-0.15%
41	3659	3646	3636	0.36%	0.63%
42	1867	1879	1875	-0.64%	-0.43%
43	1210	1197	1222	1.07%	-0.99%
44	1073	1072	1091	0.09%	-1.68%
45	3791	3771	3742	0.53%	1.29%
46	2324	2303	2331	0.90%	-0.30%
47	3650	3612	3618	1.04%	0.88%
48	2336	2333	2342	0.13%	-0.26%
49	1375	1381	1384	-0.44%	-0.65%
50	4684	4687	4674	-0.06%	0.21%
51	2718	2757	2740	-1.43%	-0.81%
52	2682	2689	2665	-0.26%	0.63%
53	4954	4921	4925	0.67%	0.59%
54	3212	3202	3216	0.31%	-0.12%
55	3132	3137	3146	-0.16%	-0.45%
56	3037	3047	3033	-0.33%	0.13%
57	3556	3589	3585	-0.93%	-0.82%
58	1656	1669	1692	-0.79%	-2.17%
59	2671	2634	2645	1.39%	0.97%
60	1828	1812	1785	0.88%	2.35%
61	1825	1841	1834	-0.88%	-0.49%
62	897	861	847	4.01%	5.57%
63	998	994	1005	0.40%	-0.70%
64	2129	2128	2134	0.05%	-0.23%
65	2620	2619	2598	0.04%	0.84%
66	3028	3029	3045	-0.03%	-0.56%
67	3658	3632	3631	0.71%	0.74%
68	1943	1981	2010	-1.96%	-3.45%
69	3020	3037	3012	-0.56%	0.26%
70	2932	2910	2890	0.75%	1.43%
71	2033	2030	2038	0.15%	-0.25%
Variance				0.01%	0.02%

SASS Units

The tables below represent the relative error between the building specification and the traditional measurements obtained for the SASS units:

Table 29: Processed traditional data for SASS (Units 1 - 7).

Measurement ID	10932	10933	10934	10935	10930	10929	10927
1	0.53%	-0.18%	0.89%	1.07%	-2.24%	-0.04%	2.59%
2	1.02%	1.70%	3.06%	3.30%	1.05%	-0.61%	-0.85%
3	1.71%	-2.29%	0.57%	0.69%	-0.91%	-0.80%	1.71%
4	-20.97%	-24.19%	-4.03%	-3.55%	-16.29%	-20.65%	-29.35%
5	2.06%	1.03%	1.39%	1.55%	1.55%	0.57%	3.14%
6	1.72%	7.33%	2.16%	1.98%	4.01%	-0.60%	5.00%
7	0.53%	1.95%	0.53%	0.46%	1.35%	-0.11%	-0.60%
8	0.71%	2.86%	-0.71%	-1.71%	0.93%	-0.04%	0.61%
9	-2.06%	-0.52%	0.77%	-1.86%	0.31%	-0.82%	-1.49%
10	5.10%	3.06%	2.89%	2.96%	0.82%	-0.34%	-0.71%
11	2.03%	-0.29%	0.72%	0.38%	0.70%	1.48%	-0.26%
12	2.33%	0.00%	0.00%	0.35%	-5.00%	1.16%	0.93%
13	-0.13%	-1.01%	0.38%	0.28%	0.51%	-1.26%	0.45%
14	1.67%	-21.67%	-35.00%	-34.83%	-2.67%	-1.17%	-32.17%
15	-8.33%	0.00%	16.67%	17.00%	-10.50%	-30.00%	20.33%
16	0.00%	-0.26%	-1.06%	-1.22%	-0.26%	-4.66%	-0.79%
17	0.00%	8.75%	19.63%	19.25%	-1.25%	-2.13%	1.88%
18	0.00%	1.11%	0.28%	-0.56%	-1.72%	-1.94%	-9.94%
19	-2.50%	-6.25%	-3.75%	-13.50%	-0.88%	0.88%	-2.13%
20	-1.00%	-5.00%	-1.00%	-1.80%	-3.80%	0.20%	-1.50%
21	1.25%	11.25%	0.00%	0.38%	0.00%	-6.63%	0.00%
Variance	0.28%	0.69%	0.97%	1.05%	0.20%	0.60%	1.19%

Table 30: Processed traditional data for SASS (Units 8 - 16)

Measurement ID	10926	10922	10918	12127	12126	12148	12157	12071	Variance
1	-0.96%	0.64%	0.60%	0.53%	0.92%	0.99%	1.17%	1.03%	0.011%
2	-5.85%	-2.35%	-28.30%	2.89%	-1.70%	-3.57%	-2.41%	-5.41%	0.556%
3	1.26%	2.51%	1.03%	2.06%	1.49%	2.29%	1.37%	2.63%	0.019%
4	-19.03%	-14.84%	-73.23%	-17.10%	-6.77%	-17.10%	-20.32%	-27.42%	2.607%
5	0.62%	-1.65%	0.26%	0.62%	0.41%	-0.72%	0.93%	-0.52%	0.013%
6	-1.08%	1.25%	-16.16%	1.55%	0.04%	1.38%	1.29%	1.55%	0.249%

Measurement ID	**10926**	**10922**	**10918**	**12127**	**12126**	**12148**	**12157**	**12071**	**Variance**
7	-0.18%	0.53%	0.75%	0.57%	1.24%	0.50%	0.53%	0.64%	0.004%
8	0.64%	1.50%	-15.54%	-0.39%	0.11%	2.21%	0.54%	0.25%	0.174%
9	-2.16%	0.62%	0.46%	-1.19%	0.10%	-0.36%	0.46%	0.46%	0.011%
10	0.37%	1.02%	-14.66%	-1.80%	-0.75%	0.20%	-0.48%	-1.36%	0.183%
11	-1.97%	0.32%	-9.97%	2.90%	-0.09%	0.67%	0.75%	-0.12%	0.082%
12	1.98%	0.12%	7.56%	4.88%	-24.77%	-23.60%	-4.42%	1.51%	1.056%
13	-0.58%	-1.04%	-0.18%	-1.52%	2.78%	2.70%	0.43%	-0.56%	0.017%
14	5.17%	-5.17%	6.00%	-9.83%	-9.83%	34.67%	17.33%	-3.50%	4.572%
15	-9.00%	0.17%	-10.67%	9.50%	-3.17%	-42.33%	-25.00%	2.67%	3.709%
16	-0.69%	-3.65%	-2.75%	-0.42%	-1.01%	-2.91%	-1.75%	-3.33%	0.034%
17	2.75%	5.75%	3.63%	3.13%	1.38%	-1.75%	-0.25%	-2.75%	0.469%
18	-0.50%	-1.72%	-1.22%	-0.61%	-0.89%	-1.11%	-0.28%	-1.39%	0.062%
19	0.25%	-0.88%	-1.00%	2.75%	1.38%	4.38%	2.25%	3.00%	0.185%
20	16.90%	-1.80%	1.60%	20.80%	-10.60%	20.10%	-0.20%	-4.40%	0.845%
21	-22.50%	-0.75%	-3.13%	-25.00%	11.88%	-27.88%	-0.75%	5.00%	1.439%
Variance	0.63%	0.15%	3.04%	0.80%	0.49%	2.48%	0.67%	0.42%	

QTO and MATLAB was used to generate measurements from drone images and compared to the traditional measurement data collected. Noting that the first measurement for each unit was used as the input to calibrate the analysis (i.e., "reference")

{Box and whisker diagram of variation between the QTO measurements of each unit, as well as the MATLAB measurements for each unit discussed in main text, refer to the table below for data reference}

Table 31: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	**10918**				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2798	REFERENCE	REFERENCE		
2	3772	3785	3800	-0.34%	-0.74%
3	866	873	891	-0.81%	-2.89%
4	1074	1104	1100	-2.79%	-2.42%
5	1935	1946	1950	-0.57%	-0.78%
6	2695	2744	2739	-1.82%	-1.63%
7	2794	2831	2840	-1.32%	-1.65%
8	3235	3206	3196	0.90%	1.21%
9	1931	1954	1944	-1.19%	-0.67%
10	3371	3392	3405	-0.62%	-1.01%
11	3794	3805	3810	-0.29%	-0.42%
12	795	765	758	3.77%	4.65%
13	3967	3943	3950	0.60%	0.43%
14	564	610	631	-8.16%	-11.88%
15	664	658	675	0.90%	-1.66%
16	1942	1928	1949	0.72%	-0.36%
17	771	766	760	0.65%	1.43%
18	1822	1822	1818	0.00%	0.22%
19	808	818	834	-1.24%	-3.22%
20	984	988	1001	-0.41%	-1.73%
21	825	794	824	3.76%	0.12%
Variance				0.059%	0.094%

Table 32:QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10922				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2797	REFERENCE	REFERENCE		
2	3009	2997	3014	0.40%	-0.17%
3	853	848	835	0.59%	2.11%
4	712	709	705	0.42%	0.98%
5	1972	1988	1998	-0.81%	-1.32%
6	2291	2261	2256	1.31%	1.53%
7	2800	2798	2807	0.07%	-0.25%
8	2758	2731	2736	0.98%	0.80%
9	1928	1952	1955	-1.24%	-1.40%
10	2910	2927	2924	-0.58%	-0.48%
11	3439	3444	3461	-0.15%	-0.64%
12	859	869	879	-1.16%	-2.33%
13	4001	4033	4034	-0.80%	-0.82%
14	631	603	615	4.44%	2.54%
15	599	576	588	3.84%	1.84%
16	1959	1969	1989	-0.51%	-1.53%
17	754	798	811	-5.84%	-7.56%
18	1831	1887	1874	-3.06%	-2.35%
19	807	792	800	1.86%	0.87%
20	1018	1037	1026	-1.87%	-0.79%
21	806	861	862	-6.82%	-6.95%
Variance				0.071%	0.069%

Table 33: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10926				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2842	REFERENCE	REFERENCE		
2	3112	3126	3117	-0.45%	-0.16%
3	864	854	845	1.16%	2.20%
4	738	689	664	6.64%	10.03%
5	1928	1902	1892	1.35%	1.87%
6	2345	2350	2359	-0.21%	-0.60%
7	2820	2888	2868	-2.41%	-1.70%
8	2782	2787	2797	-0.18%	-0.54%
9	1982	2030	2047	-2.42%	-3.28%

SASS Unit	10926				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
10	2929	2919	2917	0.34%	0.41%
11	3518	3511	3523	0.20%	-0.14%
12	843	837	844	0.71%	-0.12%
13	3983	3957	3939	0.65%	1.10%
14	569	589	603	-3.51%	-5.98%
15	654	657	664	-0.46%	-1.53%
16	1903	1924	1943	-1.10%	-2.10%
17	778	756	737	2.83%	5.27%
18	1809	1800	1795	0.50%	0.77%
19	798	866	887	-8.52%	-11.15%
20	831	876	887	-5.42%	-6.74%
21	980	973	970	0.71%	1.02%
Variance				0.095%	0.189%

Table 34: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10927				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2742	REFERENCE	REFERENCE		
2	2965	2973	2964	-0.27%	0.03%
3	860	857	871	0.35%	-1.28%
4	802	776	791	3.24%	1.37%
5	1879	1895	1911	-0.85%	-1.70%
6	2204	2194	2206	0.45%	-0.09%
7	2832	2828	2840	0.14%	-0.28%
8	2783	2815	2834	-1.15%	-1.83%
9	1969	1951	1946	0.91%	1.17%
10	2961	2940	2936	0.71%	0.84%
11	3459	3467	3462	-0.23%	-0.09%
12	852	822	813	3.52%	4.58%
13	3942	3927	3945	0.38%	-0.08%
14	793	788	782	0.63%	1.39%
15	478	477	479	0.21%	-0.21%
16	1905	1942	1970	-1.94%	-3.41%
17	785	783	816	0.25%	-3.95%
18	1979	1967	1982	0.61%	-0.15%
19	817	804	816	1.59%	0.12%

SASS Unit	10927				
	Measurement (m)			Relative error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
20	1015	1013	1001	0.20%	1.38%
21	800	839	838	-4.88%	-4.75%
Variance				0.030%	0.044%

Table 35: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10929				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2816	REFERENCE	REFERENCE		
2	2958	2908	2930	1.69%	0.95%
3	882	924	913	-4.76%	-3.51%
4	748	731	726	2.27%	2.94%
5	1929	1983	1984	-2.80%	-2.85%
6	2334	2387	2392	-2.27%	-2.49%
7	2818	2825	2846	-0.25%	-0.99%
8	2801	2813	2805	-0.43%	-0.14%
9	1956	1989	1973	-1.69%	-0.87%
10	2950	2945	2934	0.17%	0.54%
11	3399	3382	3375	0.50%	0.71%
12	850	885	876	-4.12%	-3.06%
13	4010	3971	3969	0.97%	1.02%
14	607	634	616	-4.45%	-1.48%
15	780	816	827	-4.62%	-6.03%
16	1978	1983	1959	-0.25%	0.96%
17	817	812	831	0.61%	-1.71%
18	1835	1777	1769	3.16%	3.60%
19	793	822	813	-3.66%	-2.52%
20	998	955	970	4.31%	2.81%
21	853	796	787	6.68%	7.74%
Variance				0.100%	0.093%

Table 36: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10930				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2878	REFERENCE	REFERENCE		

SASS Unit	10930				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
2	2909	2934	2922	-0.86%	-0.45%
3	883	860	871	2.60%	1.36%
4	721	722	741	-0.14%	-2.77%
5	1910	1885	1873	1.31%	1.94%
6	2227	2257	2287	-1.35%	-2.69%
7	2777	2741	2752	1.30%	0.90%
8	2774	2760	2774	0.50%	0.00%
9	1934	1929	1921	0.26%	0.67%
10	2916	2904	2920	0.41%	-0.14%
11	3426	3372	3359	1.58%	1.96%
12	903	888	905	1.66%	-0.22%
13	3940	3896	3926	1.12%	0.36%
14	616	686	721	-11.36%	-17.05%
15	663	656	662	1.06%	0.15%
16	1895	1903	1927	-0.42%	-1.69%
17	810	796	793	1.73%	2.10%
18	1831	1820	1828	0.60%	0.16%
19	807	791	820	1.98%	-1.61%
20	1038	1040	1061	-0.19%	-2.22%
21	800	800	811	0.00%	-1.38%
Variance				0.083%	0.164%

Table 37: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10932				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2800	REFERENCE	REFERENCE		
2	2910	2851	2862	2.03%	1.65%
3	860	855	863	0.58%	-0.35%
4	750	728	755	2.93%	-0.67%
5	1900	1932	1926	-1.68%	-1.37%
6	2280	2279	2288	0.04%	-0.35%
7	2800	2785	2812	0.54%	-0.43%
8	2780	2819	2811	-1.40%	-1.12%
9	1980	1978	1980	0.10%	0.00%
10	2790	2834	2821	-1.58%	-1.11%
11	3380	3350	3368	0.89%	0.36%

SASS Unit	10932				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
12	840	859	871	-2.26%	-3.69%
13	3965	3973	3994	-0.20%	-0.73%
14	590	602	607	-2.03%	-2.88%
15	650	653	660	-0.46%	-1.54%
16	1890	1914	1937	-1.27%	-2.49%
17	800	788	798	1.50%	0.25%
18	1800	1831	1859	-1.72%	-3.28%
19	820	839	841	-2.32%	-2.56%
20	1010	985	1012	2.48%	-0.20%
21	790	801	803	-1.39%	-1.65%
Variance				0.026%	0.018%

Table 38: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10933				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2820	REFERENCE	REFERENCE		
2	2890	2939	2924	-1.70%	-1.18%
3	895	869	893	2.91%	0.22%
4	770	767	759	0.39%	1.43%
5	1920	1902	1912	0.94%	0.42%
6	2150	2115	2085	1.63%	3.02%
7	2760	2765	2743	-0.18%	0.62%
8	2720	2692	2701	1.03%	0.70%
9	1950	1979	1970	-1.49%	-1.03%
10	2850	2854	2852	-0.14%	-0.07%
11	3460	3478	3461	-0.52%	-0.03%
12	860	851	834	1.05%	3.02%
13	4000	3969	3980	0.78%	0.50%
14	730	776	760	-6.30%	-4.11%
15	600	574	583	4.33%	2.83%
16	1895	1899	1887	-0.21%	0.42%
17	730	736	757	-0.82%	-3.70%
18	1780	1765	1775	0.84%	0.28%
19	850	896	916	-5.41%	-7.76%
20	1050	1018	1028	3.05%	2.10%
21	710	711	727	-0.14%	-2.39%

SASS Unit	10933				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
Variance				0.063%	0.070%

Table 39: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10934				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2790	REFERENCE	REFERENCE		
2	2850	2862	2856	-0.42%	-0.21%
3	870	850	845	2.30%	2.87%
4	645	627	598	2.79%	7.29%
5	1913	1939	1918	-1.36%	-0.26%
6	2270	2339	2329	-3.04%	-2.60%
7	2800	2807	2783	-0.25%	0.61%
8	2820	2828	2815	-0.28%	0.18%
9	1925	1945	1978	-1.04%	-2.75%
10	2855	2888	2860	-1.16%	-0.18%
11	3425	3488	3479	-1.84%	-1.58%
12	860	938	916	-9.07%	-6.51%
13	3945	3967	3945	-0.56%	0.00%
14	810	827	800	-2.10%	1.23%
15	500	482	450	3.60%	10.00%
16	1910	1913	1918	-0.16%	-0.42%
17	643	658	652	-2.33%	-1.40%
18	1795	1831	1828	-2.01%	-1.84%
19	830	816	799	1.69%	3.73%
20	1010	1075	1042	-6.44%	-3.17%
21	800	876	883	-9.50%	-10.38%
Variance				0.119%	0.189%

Table 40: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	10935				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2785	REFERENCE	REFERENCE		
2	2843	2848	2848	-0.18%	-0.18%
3	869	862	860	0.81%	1.04%

SASS Unit	10935				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
4	642	665	666	-3.58%	-3.74%
5	1910	1886	1901	1.26%	0.47%
6	2274	2241	2250	1.45%	1.06%
7	2802	2771	2807	1.11%	-0.18%
8	2848	2836	2868	0.42%	-0.70%
9	1976	1980	1994	-0.20%	-0.91%
10	2853	2838	2836	0.53%	0.60%
11	3437	3479	3470	-1.22%	-0.96%
12	857	871	872	-1.63%	-1.75%
13	3949	3943	3947	0.15%	0.05%
14	809	817	828	-0.99%	-2.35%
15	498	488	530	2.01%	-6.43%
16	1913	1959	1982	-2.40%	-3.61%
17	646	633	612	2.01%	5.26%
18	1810	1839	1842	-1.60%	-1.77%
19	908	936	946	-3.08%	-4.19%
20	1018	1026	1014	-0.79%	0.39%
21	797	796	789	0.13%	1.00%
Variance				0.026%	0.062%

Table 41: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	12071				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2786	REFERENCE	REFERENCE		
2	3099	3111	3083	-0.39%	0.52%
3	852	923	923	-8.33%	-8.33%
4	790	876	876	-10.89%	-10.89%
5	1950	1941	1947	0.46%	0.15%
6	2284	2233	2256	2.23%	1.23%
7	2797	2791	2796	0.21%	0.04%
8	2663	2679	2692	-0.60%	-1.09%
9	1931	1945	1947	-0.73%	-0.83%
10	2850	2861	2856	-0.39%	-0.21%
11	3576	3578	3589	-0.06%	-0.36%
12	847	890	912	-5.08%	-7.67%
13	4082	4111	4120	-0.71%	-0.93%

SASS Unit	12071				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
14	621	551	558	11.27%	10.14%
15	584	517	534	11.47%	8.56%
16	1953	1968	1945	-0.77%	0.41%
17	822	831	820	-1.09%	0.24%
18	1825	1856	1876	-1.70%	-2.79%
19	776	783	786	-0.90%	-1.29%
20	1044	1025	1031	1.82%	1.25%
21	760	772	747	-1.58%	1.71%
Variance				0.257%	0.230%

Table 42: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	12126				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2789	REFERENCE	REFERENCE		
2	2990	2997	3003	-0.23%	-0.43%
3	862	882	876	-2.32%	-1.62%
4	662	679	692	-2.57%	-4.53%
5	1932	1920	1879	0.62%	2.74%
6	2319	2316	2303	0.13%	0.69%
7	2780	2777	2765	0.11%	0.54%
8	2667	2665	2625	0.07%	1.57%
9	1938	1893	1872	2.32%	3.41%
10	2832	2841	2849	-0.32%	-0.60%
11	3628	3628	3639	0.00%	-0.30%
12	1073	1022	1060	4.75%	1.21%
13	3850	3824	3844	0.68%	0.16%
14	659	688	722	-4.40%	-9.56%
15	619	643	662	-3.88%	-6.95%
16	1909	1913	1893	-0.21%	0.84%
17	789	801	798	-1.52%	-1.14%
18	1816	1800	1812	0.88%	0.22%
19	789	803	805	-1.77%	-2.03%
20	1106	1126	1124	-1.81%	-1.63%
21	705	733	742	-3.97%	-5.25%
Variance				0.048%	0.104%

Table 43: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	12127				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2800	REFERENCE	REFERENCE		
2	2855	2910	2907	-1.93%	-1.82%
3	857	874	882	-1.98%	-2.92%
4	726	721	733	0.69%	-0.96%
5	1928	1936	1916	-0.41%	0.62%
6	2284	2272	2251	0.53%	1.44%
7	2799	2802	2810	-0.11%	-0.39%
8	2681	2674	2670	0.26%	0.41%
9	1963	1980	1999	-0.87%	-1.83%
10	2863	2869	2847	-0.21%	0.56%
11	3480	3474	3476	0.17%	0.11%
12	818	854	860	-4.40%	-5.13%
13	4120	4094	4092	0.63%	0.68%
14	659	661	651	-0.30%	1.21%
15	543	576	588	-6.08%	-8.29%
16	1898	1903	1913	-0.26%	-0.79%
17	775	775	767	0.00%	1.03%
18	1811	1795	1801	0.88%	0.55%
19	778	799	793	-2.70%	-1.93%
20	792	820	821	-3.54%	-3.66%
21	1000	1014	999	-1.40%	0.10%
Variance				0.035%	0.060%

Table 44: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	12148				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2787	REFERENCE	REFERENCE		
2	3045	3035	3088	0.33%	-1.41%
3	855	832	869	2.69%	-1.64%
4	726	715	746	1.52%	-2.75%
5	1954	1937	1969	0.87%	-0.77%
6	2288	2309	2364	-0.92%	-3.32%
7	2801	2812	2807	-0.39%	-0.21%
8	2738	2739	2750	-0.04%	-0.44%
9	1947	1906	1968	2.11%	-1.08%

SASS Unit	12148				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
10	2934	2958	3011	-0.82%	-2.62%
11	3427	3414	3405	0.38%	0.64%
12	1063	1084	1114	-1.98%	-4.80%
13	3853	3862	3908	-0.23%	-1.43%
14	392	387	449	1.28%	-14.54%
15	854	830	859	2.81%	-0.59%
16	1945	1950	1956	-0.26%	-0.57%
17	814	820	875	-0.74%	-7.49%
18	1820	1849	1841	-1.59%	-1.15%
19	765	767	805	-0.26%	-5.23%
20	799	826	826	-3.38%	-3.38%
21	1023	1029	1092	-0.59%	-6.74%
Variance				0.024%	0.123%

Table 45: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	12149				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2786	REFERENCE	REFERENCE		
2	3076	3051	3053	0.81%	0.75%
3	853	903	896	-5.86%	-5.04%
4	834	846	822	-1.44%	1.44%
5	1924	1933	1927	-0.47%	-0.16%
6	2265	2278	2250	-0.57%	0.66%
7	2804	2820	2812	-0.57%	-0.29%
8	2633	2677	2651	-1.67%	-0.68%
9	1964	1970	1947	-0.31%	0.87%
10	2810	2794	2796	0.57%	0.50%
11	3525	3569	3557	-1.25%	-0.91%
12	1051	1035	1049	1.52%	0.19%
13	3877	3869	3859	0.21%	0.46%
14	384	390	429	-1.56%	-11.72%
15	838	830	805	0.95%	3.94%
16	1831	1818	1828	0.71%	0.16%
17	795	797	792	-0.25%	0.38%
18	1783	1798	1802	-0.84%	-1.07%
19	796	789	790	0.88%	0.75%

SASS Unit	12149				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
20	1021	1080	1091	-5.78%	-6.86%
21	741	751	757	-1.35%	-2.16%
Variance				0.038%	0.116%

Table 46: QTO and MATLAB generated data for SASS (Units 10918) with calculated relative error.

SASS Unit	12157				
	Measurement (m)			Percentage error	
Measurement ID	**Traditional**	**QTO**	**MATLAB**	**QTO**	**MATLAB**
1	2782	REFERENCE	REFERENCE		
2	3011	2994	3001	0.56%	0.33%
3	863	857	868	0.70%	-0.58%
4	746	752	759	-0.80%	-1.74%
5	1922	1941	1949	-0.99%	-1.40%
6	2290	2280	2288	0.44%	0.09%
7	2800	2828	2828	-1.00%	-1.00%
8	2655	2664	2667	-0.34%	-0.45%
9	1931	1958	1969	-1.40%	-1.97%
10	2824	2825	2824	-0.04%	0.00%
11	3544	3560	3551	-0.45%	-0.20%
12	898	918	936	-2.23%	-4.23%
13	4018	4043	4043	-0.62%	-0.62%
14	496	467	480	5.85%	3.23%
15	750	728	726	2.93%	3.20%
16	1923	1904	1913	0.99%	0.52%
17	802	782	788	2.49%	1.75%
18	1805	1823	1829	-1.00%	-1.33%
19	782	782	800	0.00%	-2.30%
20	1002	1024	1042	-2.20%	-3.99%
21	806	794	817	1.49%	-1.36%
Variance				0.036%	0.037%

APPENDIX E – GCC (2015): THE CONTRACTOR

Table 47. Clauses from the GCC (2015) which are applicable to the Contractor

THE CONTRACTOR		
CLAUSE		**ACCOUNTABILITY**
4.1.1.	*The Contractor shall, save insofar as it is legally or physically impossible, design (to the extent provided in the Contract), carry out and complete Works and remedy any defects therein in accordance with the provisions of the Contract (GCC, 2015: 14).*	The Contractor is responsible for carrying out works and remedy defects in accordance with the Contract. The Contractor must be sure of all requirements stipulated in the Contract. This includes all drawings, specifications, laws etc.
4.1.2.	*Where the Contract expressly provides that the Permanent Works, or part of the Permanent Works, shall be designed by the Contractor, he shall, notwithstanding approval by the Employer's Agent, be liable for any error or deficiency in any drawing or document supplied by him for that part of the Works, and for any loss or damage arising out of such error or deficiency. (GCC, 2015: 14)*	The Contractor must be certain of all specifications, requirements, laws, regulations etc. pertaining to quality and must conform to these requirements. This refers to all SABS, SANS, NHBRC, NBR and other guidelines and specifications mentioned in the previous section
4.2.1.	*The Contractor shall, in carrying out his aforesaid obligations, comply with the Employer's Agent instructions on all matters relating to the Works (GCC, 2015: 14)*	The Contractor has the responsibility to comply with any Instructions pertaining to Quality. Although, it is the responisibility of the Employer's Agent to issue instructions, the Contractor should attempt to mitigate these occurrences as far as possible to avoid cost- and time overruns.
4.2.2.	*The Contractor shall take instructions only from the Employer's Agent, the Employer's Agent's Representative or a person authorised by the Employer's Agent in terms of Clause 3.3.4*	Same as 4.2.1.
4.3.1.	*The Contractor shall, in fulfilling the Contract, comply with all applicable laws, regulations, statutory provisions and agreements, and shall, at the request of the Employer's Agent, provide proof that he has complied therewith*	The Contractor must be certain of all specifications, requirements, laws, regulations etc. pertaining to quality and must conform to these requirements. This refers to all SABS, SANS, NHBRC, NBR and other guidelines and specifications mentioned in the previous section
4.4.3.	*The Contractor shall be liable for the acts, defaults and negligence of any subcontractor, his agents or employees as fully as if they were the acts, defaults or negligence of the Contractor*	The Contractor is responisble for all Quality concerns arising from the Subcontractor. The Contractor is held accountable for the actions of the Subcontractor as well.
4.12.1.	*The Contractor shall provide all necessary superintendence while carrying out the Works*	The Contractor must ensure that they provide competent superintendence which is capable of carrying out the Works as stipulated in all previous Clauses.

Table 48. Clauses from the GCC (2015) which are applicable to the Contractor (Continued)

CONTINUED…		
THE CONTRACTOR		
CLAUSE		**ACCOUNTABILITY**
7.5.1.	*No part of the Works or excavations shall be covered up or put out of view without the consent of the Employer's Agent, and the Contractor shall afford full opportunity for the Employer's Agent to examine and measure the Works to inspect excavations before any Permanent Works are placed thereon.*	The Contractor is held accountable for all Works that are covered up (e.g. blockwork which is covered by plastering). The Contractor must be able to provide of attempting to obtain consent from the Employer's Agent before covering up such Works.
7.5.3.	*The Contractor shall give adequate written notice to the Employer's Agent… (concerning Works that are covered up)*	*It is the responsibility of the Contractor to ensure that he lets the Employer's Agent know timeously when to inspect the works before covering up. Also to ensure that works are up to standard, so as to reduce time required for inspections*
7.8.2.	*All such remedial work shall be carried out by the Contractor,*	The Contractor is held responsible for remedial work which results out of their own errors (read 7.8.2.1.)
7.8.2.1.	*At his own expense, if the necessity therefor is due to Plant, or the use of materials or workmanship not in accordance with the Contract, or to neglect or failure on the part of the Contractor to comply to any obligation under the Contract.*	The Contractor is held responsible for remedial work which results out of their own errors.
7.8.2.2.	*However, if such remedial work is due to any other cause, such work, if carried out by the Contractor, shall be valued and paid in accordance with Clause 6.4.*	Gives the Contractor reason to ensure that they comply to all defined guidelines and specifications mentioned in the previous section.

APPENDIX F – GCC (2015): THE EMPLOYER

Table 49. Clauses from the GCC (2015) which are applicable to the Employer

THE EMPLOYER		
CLAUSE		ACCOUNTABILITY
3.2.3.	*In the event of the Employer's Agent being required in terms of his appointment by the Employer to obtain specific approval of the Employer for carrying out any part of his functions or duties, such requirements shall be set out in the Contract Data.*	It is the responsibility of the Employer to ensure that the Employer's Agent can carry out all duties required to ensure conformance to quality. Either through Clauses already defined or through additional requirements in the Contract Data
7.2.1.	*... all workmanship shall be carried out and all materials shall be of the respective kinds specified in the Contract and shall comply with the requirements set in the Scope of Works and in the Employer's Agent's instructions. Failing requirements or instructions, the Plant, workmanship and materials of the respective kinds shall be suitable for the purpose intended*	The Employer is accountable for ensuring that all regulations, guidelines and policies, for which they are responsible, clearly define quality compliance. This Clause highlights the need for a combined effort. All parties must be involved albeit in different phases of the project.
7.3.1.	*The Employer, Employer's Agent and any person authorised by either of them shall, during working hours, have access to the Works and the Site and to all workshops and places where work is being prepared, or where Plant, materials, manufactured articles and machinery are being manufactured or obtained for the Works, to inspect, examine and test such Plants. Materials and workmanship and verify progress in accordance with the programme. The Contractor shall afford any necessary facility for and assistance in obtaining the right to such access.*	The Employer has the responsibility to ensure that adequate inspections, examinations and tests are then performed to this regard. They must show commitment to quality by either conduct tests themselves or ensure that their Agent or a governmental representative.
7.6.3.2.	*The Employer's Agent shall, during the progress of the Works, have the power to order, in writing, from time to time, within such time or times as specified in the order: The removal and proper reconstruction (notwithstanding any previous test thereof or interim payment therefore) of any work which, in respect of materials or workmanship, is not in accordance with the Contract.*	Same as 7.2.1.
7.8.2.2.	*However, if such remedial work is due to any other cause, such work, if carried out by the Contractor, shall be valued and paid in accordance with Clause 6.4.*	Same as 7.2.1.

APPENDIX G – GCC (2015): THE EMPLOYER'S AGENT

Table 50. Clauses from the GCC (2015) which are applicable to the Employer's Agent

THE EMPLOYER'S AGENT		
CLAUSE		ACCOUNTABILITY
2.4.1.	*If an ambiguity or discrepancy between the documents is found, the Employer's Agent shall provide necessary clarification or instruction. (GCC, 2015: 10).*	Employer's Agent lies between the Employer and the Contractor and should act independently when it comes to quality.
3.2.1.	*The function of the Employers Agent is to administer the Contract as agent of the Employer, in accordance with the provisions of the Contract. (GCC, 2015: 11).*	Employer's Agent lies between the Employer and the Contractor and should act independently when it comes to quality.
3.2.2	*Whenever the Employer's Agent intends, in terms of the Contract, to exercise any discretion, or make or issue any ruling, contract interpretation or price determination, he shall first consult with the Contractor and the Employer in an attempt to reach an agreement. Failing agreement, the Employer's Agent shall act impartially and make a decision in accordance with the Contract, taking into account all relevant fact and circumstances. (GCC, 2015: 11).*	Employer's Agent lies between the Employer and the Contractor and should act independently when it comes to quality.
3.2.3.	*In the event of the Employer's Agent being required in terms of his appointment by the Employer to obtain specific approval of the Employer for carrying out any part of his functions or duties, such requirements shall be set out in the Contract Data.*	The Employer's Agent should be familiar with the Contract and should ensure that Contract Data is included so as to allow the most effective QC throughout the project.
4.1.3.	*Where the Contract expressly provides that the Permanent Works, or part of the Permanent Works, shall be designed by the Contractor, he shall,* ***notwithstanding approval by the Employer's Agent,*** *be liable for any error or deficiency in any drawing or document supplied by him for that part of the Works, and for any loss or damage arising out of such error or deficiency. (GCC, 2015: 11).*	This means it is still the responsibility of the Employer's Agent to practise thorough investigation of plans submitted to him. He should not accept that it is solely the responsibility of the Contractor.
4.2.1.	*The Contractor shall, in carrying out his aforesaid obligations,* ***comply with the Employer's Agent instructions on all matters relating to the Works (*** *GCC, 2015: 14).*	The Employer's Agent should also have a deep knowledge of standards and specifications to ensure that the Contractor can be monitored and instructed to complete Works according to these standards and specifications.
4.2.2.	*The Contractor shall take instructions only from the Employer's Agent, the Employer's Agent's Representative or a person authorised by the Employer's Agent in terms of Clause 3.3.4 (GCC, 2015: 14).*	The Employer's Agent should also have a deep knowledge of standards and specifications to ensure that the Contractor can be monitored and instructed to complete Works according to these standards and specifications.
4.3.1.	*The Contractor shall, in fulfilling the Contract, comply with all applicable laws, regulations, statutory provisions and agreements, and shall, at the request of the Employer's Agent, provide proof that he has complied therewith*	With reference to 4.2.1., 4.2.2. and 4.3.1: This means it is important for the Employer's Agent to be concise with regards to Quality and his instructions pertaining to matters relating to quality assurance. Also although it is responsibility of Contractor to comply, the Employer's Agent must keep the Contractor accountable by requesting proof of compliance.

Table 51. Clauses from the GCC (2015) which are applicable to the Employer's Agent (Continued)

CONTINUED…		
THE EMPLOYER'S AGENT		
CLAUSE		**ACCOUNTABILITY**
5.9.2.	*The Employer's Agent shall deliver to the Contractor from time to time, during the progress of the Works, drawings for construction purposes, or instructions as shall be necessary for the proper and adequate construction, completion and defect correction of the Works (GCC, 2015: 26).*	see 7.2.1.
5.9.4.	*The aforesaid instructions and/or drawings referred to in Clause 5.9.3. shall be delivered in good time taking the approved programme into account (GCC, 2015: 27).*	see 7.2.1.
5.9.7.	*If the Contract expressly provides for the preparation by the Contractor of designs and details of any work to be supplied, he shall, taking into account of the approved programme, in good time submit for approval by the Employer's Agent, drawings giving full details, dimensions and particulars, together with all relevant information and erecting or operating instructions (if any) and shall obtain the Employer's Agent's written approval, in accordance with the said programme, before commencing the work.*	see 7.2.1.
7.2.1.	*… all workmanship shall be carried out and all materials shall be of the respective kinds specified in the Contract and shall comply with the requirements set in the Scope of Works and in the Employer's Agent's instructions. Failing requirements or instructions, the Plant, workmanship and materials of the respective kinds shall be suitable for the purpose intended*	With reference to Clause 5.9.2., 5.9.4, 5.9.7. and 7.2.1: Once again, the responsibility of the Employer's Agent to ensure that he provided drawings and instructions to ensure Quality Assurance, and that all drawing are thoroughly inspected. These drawings should also clearly state the requirements of workmanship regarding quality.
7.3.1.	*The Employer, Employer's Agent and any person authorised by either of them shall, during working hours, have access to the Works and the Site and to all workshops and places where work is being prepared, or where Plant, materials, manufactured articles and machinery are being manufactured or obtained for the Works, to inspect, examine and test such Plants. Materials and workmanship and verify progress in accordance with the programme. The Contractor shall afford any necessary facility for and assistance in obtaining the right to such access.*	The Employer's Agent therefore also has a responsibility to ensure that checks are done either by the Employer's Agent themselves or by external appointed representatives. Thereby, showing commitment to quality within the project.
7.5.1.	*No part of the Works or excavations shall be covered up or put out of view without the consent of the Employer's Agent, and the Contractor shall afford full opportunity for the Employer's Agent to examine and measure the Works to inspect excavations before any Permanent Works are placed thereon. (GCC, 2015: 54).*	It is the responsibility of the Employer's Agent to ensure that Works are examined before closing up. He has to do this without delaying Works. Therefore, it is his responsibility to be accustomed to the progress of the Works so that he knows when to inspect where.
7.6.3.	*The Employer's Agent shall, during the progress of the Works, have the power to order, in writing, from time to time, within such time or times as specified in the order:*	See 7.6.3.2.
7.6.3.2.	*The removal and proper reconstruction (notwithstanding any previous test thereof or interim payment therfor) of any work which, in respect of materials or workmanship, is not in accordance with the Contract.*	The Employer's Agent has a direct responsibility to ensure that work is rectified which is not in accordance to the Contract. The Employer's Agent should keep the Contractor responsible as set out in this Clause

APPENDIX H – MATLAB CODE

```
function spatial_calibration_demo()

global originalImage;

clc;
close all;
workspace;
format long g;
format compact;
fontSize = 20;

hasIPT = license('test', 'image_toolbox');
if ~hasIPT
        message = sprintf('Sorry, but you do not seem to have the Image Processing Toolbox.\nDo you want to try to continue anyway?');
        reply = questdlg(message, 'Toolbox missing', 'Yes', 'No', 'Yes');
        if strcmpi(reply, 'No')
                return;
        end
end

% Try to open path /Users/pieterruthven/Documents/Personal/Masters/Thesis/Drone Images
folder = fullfile('Users/pieterruthven/Documents/Personal/Masters');
%

imread('Mediamodifier-Design-Template (1).png');
imread("DJI_0025.JPG");
imread('DJI_0017.JPG');

button = menu('Use which image?','BQ01 Top Floor','BQ08 Ground Floor Unit 1','Sudden Spike','Exit');
switch button
        case 1
                baseFileName = 'Mediamodifier-Design-Template (1).png';
        case 2
                baseFileName = 'DJI_0025.JPG';
        case 3
                baseFileName = 'DJI_0017.JPG';
end

fullFileName = baseFileName;

if ~exist(fullFileName, 'file')

        fullFileName = baseFileName;
        if ~exist(fullFileName, 'file')
                errorMessage = sprintf('Error: %s does not exist in the search path folders.', fullFileName);
                uiwait(warndlg(errorMessage));
                return;
        end
end

originalImage = imread(fullFileName);

[rows columns numberOfColorBands] = size(originalImage);

figureHandle = figure;
subplot(1,2,1);
imshow(originalImage, []);
title(fullFileName, 'FontSize', fontSize);
set(gcf, 'units','normalized','outerposition',[0 0 1 1]);
set(gcf,'name','Calibration and Measurement','numbertitle','off')

message = sprintf('Spatial Calibration Required.');
reply = questdlg(message, 'Calibrate spatially', 'OK', 'Cancel', 'OK');
if strcmpi(reply, 'Cancel')
        return;
end
button = 1;
while button ~= 4
        if button > 1
                button = menu('Select a task', 'Calibrate', 'Measure Distance', 'Measure Area', 'Exit Demo');
        end
        switch button
                case 1
                        success = Calibrate();
                        while ~success
                                success = Calibrate();
            end
                        button = 99;
                case 2
                        DrawLine();
                case 3
                        DrawArea();
                otherwise
                        close(figureHandle);
                        break;
        end
end

end

%=====================================================================
function success = Calibrate()
global lastDrawnHandle;
global calibration;
try
        success = false;
```

```
        instructions = sprintf('Left click to anchor first endpoint of line.\nRight-click or double-left-click to anchor second endpoint of line.\
%       title(instructions);
        msgboxw(instructions);

        [cx, cy, rgbValues, xi,yi] = improfile(1000);
        rgbValues = squeeze(rgbValues);
        distanceInPixels = sqrt( (xi(2)-xi(1)).^2 + (yi(2)-yi(1)).^2);
        if length(xi) < 2
                return;
        end
        % Plot the line.
        hold on;
        lastDrawnHandle = plot(xi, yi, 'y-', 'LineWidth', 2);


        userPrompt = {'Enter actual units:','Enter distance in those units:'};
        dialogTitle = 'Specify calibration information';
        numberOfLines = 1;
        def = {'mm', '500'};
        answer = inputdlg(userPrompt, dialogTitle, numberOfLines, def);
        if isempty(answer)
                return;
        end
        calibration.units = answer{1};
        calibration.distanceInPixels = distanceInPixels;
        calibration.distanceInUnits = str2double(answer{2});
        calibration.distancePerPixel = calibration.distanceInUnits / distanceInPixels;
        success = true;
catch ME
        errorMessage = sprintf('Error in function DrawLine().\nDid you first left click and then right click?\n\nError Message:\n%s', ME.message);
        fprintf(1, '%s\n', errorMessage);
        WarnUser(errorMessage);
end

return;
end

function success = DrawLine()
try
        global lastDrawnHandle;
        global calibration;
        fontSize = 14;

        instructions = sprintf('Draw a line.\nFirst, left-click to anchor first endpoint of line.\nRight-click or double-left-click to anchor secc
        title(instructions);
        msgboxw(instructions);
        subplot(1,2, 1);
        [cx,cy, rgbValues, xi,yi] = improfile(1000);
        hImage = findobj(gca,'Type','image');
        theImage = get(hImage, 'CData');
        lineLength = round(sqrt((xi(1)-xi(2))^2 + (yi(1)-yi(2))^2))
        [cx,cy, rgbValues] = improfile(theImage, xi, yi, lineLength);

        rgbValues = squeeze(rgbValues);
        distanceInPixels = sqrt( (xi(2)-xi(1)).^2 + (yi(2)-yi(1)).^2);
        distanceInRealUnits = distanceInPixels * calibration.distancePerPixel;

        if length(xi) < 2
                return;
    end
        hold on;
        lastDrawnHandle = plot(xi, yi, 'y-', 'LineWidth', 2);

        subplot(1,2,2);
        [rows, columns] = size(rgbValues);
        if columns == 3
                plot(rgbValues(:, 1), 'r-', 'LineWidth', 2);
                hold on;
                plot(rgbValues(:, 2), 'g-', 'LineWidth', 2);
                plot(rgbValues(:, 3), 'b-', 'LineWidth', 2);
                title('Red, Green, and Blue Profiles along the line you just drew.', 'FontSize', 14);
    else
                plot(rgbValues, 'k-', 'LineWidth', 2);
        end
        xlabel('X', 'FontSize', fontSize);
        ylabel('Gray Level', 'FontSize', fontSize);
        title('Intensity Profile', 'FontSize', fontSize);
        grid on;

        txtInfo = sprintf('Distance = %.1f %s, which = %.1f pixels.', ...
                distanceInRealUnits, calibration.units, distanceInPixels);
        msgboxw(txtInfo);
        fprintf(1, '%\n', txtInfo);

catch ME
        errorMessage = sprintf('Error in function DrawLine().\n\nError Message:\n%s', ME.message);
        fprintf(1, '%s\n', errorMessage);
        WarnUser(errorMessage);
end
end  % from DrawLine()

%======================================================================
function DrawArea()
global originalImage;
global lastDrawnHandle;
global calibration;
try
        txtInfo = sprintf('Left click to anchor vertices.\nDouble left click to anchor final point of polygon.');
```

```
        title(txtInfo);
        msgboxw(txtInfo);

        [rows, columns, numberOfColorBands] = size(originalImage);

        if numberOfColorBands > 1
                grayImage = rgb2gray(originalImage);
        else
                grayImage = originalImage;
        end

        subplot(1,2, 1);
        [maskImage, xi, yi] = roipolyold();

        hold on;
        lastDrawnHandle = plot(xi, yi, 'r-', 'LineWidth', 2);
        numberOfPixels = sum(maskImage(:));
        area = numberOfPixels * calibration.distancePerPixel^2;

        mean_GL = mean(grayImage(maskImage));

        txtInfo = sprintf('Area = %8.1f square %s.\nMean gray level = %.2f.', ...
                area, calibration.units, mean_GL);
        fprintf(1,'%s\n', txtInfo);
        title(txtInfo, 'FontSize', 14);

        if numberOfColorBands >= 3
                redPlane = double(originalImage(:, :, 1));
                greenPlane = double(originalImage(:, :, 2));
                bluePlane = double(originalImage(:, :, 3));
                mean_RGB_GL(1) = mean(redPlane(maskImage));
                mean_RGB_GL(2) = mean(greenPlane(maskImage));
                mean_RGB_GL(3) = mean(bluePlane(maskImage));
                fprintf('%s\nRed mean = %.2f\nGreen mean = %.2f\nBlue mean = %.2f', ...
                        txtInfo, mean_RGB_GL(1), mean_RGB_GL(2), mean_RGB_GL(3));
        end

        % Just for fun, let's get its histogram within the masked region.
        [pixelCount, grayLevels] = imhist(grayImage(maskImage));
        subplot(1,2, 2); % Switch to plot axes.
        cla;
        bar(pixelCount);
        grid on;
        caption = sprintf('Histogram within area.    Mean gray level = %.2f', mean_GL);
        title(caption, 'FontSize', 14);
        xlim([0 grayLevels(end)]);
        hold on;
        maxYValue = ylim;
        line([mean_GL, mean_GL], [0 maxYValue(2)], 'Color', 'r', 'linewidth', 2);
catch ME
        errorMessage = sprintf('Error in function DrawArea().\n\nError Message:\n%s', ME.message);
        fprintf(1, '%s\n', errorMessage);
        WarnUser(errorMessage);
end

end

%=====================================================================
function msgboxw(message)
        uiwait(msgbox(message));
end
%=====================================================================
function WarnUser(message)
        uiwait(msgbox(message));
end
```

```
lineLength =
        1484
```

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