Scale-up of a High Technology Manufacturing Start-up:  
Framework for Analysis of Incoming Parts, Inspection Procedure and Supplier Capability

By

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ABSTRACT

It is imperative for all manufacturing setups to have a structured system and culture of quality control to maintain product performance and customer satisfaction. An integral part of this system is to check incoming parts through inspection and to ensure that suppliers uphold the same standards of quality. As a company scales up, quality failures become costlier and at the same time, use of data and statistics presents opportunities for immense savings. NVBOTS is a 3D Printer manufacturing startup that is currently at the juncture of ramping up its production volume. The skeleton of its product is, in effect, a three axis frame with sourced machined components that build it up. In this thesis, one axis was taken up as a case study to develop a framework for analysing incoming parts. The proposed framework has a logical progression starting with analysis of part features and inspection procedure followed by a study of existing supplier capability and subsequent correlation of part geometry to final frame geometry. To perform this analysis, past Co-ordinate Measuring Machine (CMM) data from measurement of incoming parts was compiled and used. This document also makes some actionable recommendations based on the output of the framework. These include use of software packages that can help facilitate and speed up the use of this framework through efficient data logging and real time analysis. Subsequently, future use of statistical tolerancing is suggested to enhance manufacturability while reducing costs and finally, certain additions of platform features to the product were suggested to make full use network effects as the organization scales up.

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1 CHAPTER 1: INTRODUCTION

There are two types of startup businesses in the world: those that scale-up and those that do not. The businesses that do not scale up either fail or settle into a truly small business with little or no growth potential. These so-called “lifestyle businesses” have their place within the economy and among entrepreneurs who are perfectly at peace with running a small business. However, the businesses that do scale-up are the ones looking to change the world, impact customers’ lives in a profound way, and obviously, make significant financial gains along the way [1].

Scale-up in entrepreneurial business refers to the process of rapid growth and expansion of a company to adapt to a larger workload without compromising performance, revenues, and operational controls [2]. Scaling up can only occur once a startup has validated its business model through repeat revenue generation [2]. Once the foundation is in place, rapid growth in market access, employees, operations, and revenues can occur.

Scaling up is an absolute necessity for those startup businesses funded by external investors such as angel investors and venture capital (VC) firms. Venture capitalists (VCs) invest in early-stage startups when the risk is high, the technology is unproven, and the market is uncertain, but the potential upside is also very high. In return, they own equity in the company and demand a significant return on their investment within a short period of time, achieved through either sale to or merger with another company (merger and acquisition, or M&A) or less commonly, registering as a publicly traded company via an initial public offering (IPO). The significant investor pressure necessitates the need for scaling up the business as soon as feasible.

However, scale-up requirements significantly depend on the type of business. Software by nature is very scalable. The initial investment is spent on developing the back-end software and user experience. Once completed and released, subsequent iterations only cost a fraction of the initial development cost and time. Software also does not require significant capital investment, has almost instant global market reach via the Internet, and has a very rapid lifecycle of only a few years [3]. By far, software startups are the easiest to scale-up and thus have commanded the largest amount of VC attention and funding [4].

1According to data collected from the U.S. Department of Commerce, Bureau of the Census, and U.S. Department of Labor, 592,410 businesses closed and 28,322 declared bankruptcy in 2007 [1].
Startups involving a physical product, such as in consumer goods, manufacturing, and high technology industries, or startups involving strict regulatory requirements such as in the biopharmaceuticals industry do not have the same luxuries as software or service-based startups. Significant up-front capital costs, a high burn-rate\(^2\), and a longer horizon before a sizeable return on investment is realized are additional barriers to scale-up that causes VCs to shy away from funding startups in these industries and instead focus their funds on less risky, though sometimes less profitable in the long run, software startups [3].

Scale-up is absolutely critical even for companies without the added pressure from VCs. A company is only solvent and in business as long as it has sufficient liquid assets to meet current liabilities. Without a plan in place to rapidly increase company revenues, and the fortitude to execute the plan, the business will quickly be unable to meet its liabilities and become insolvent.

However, the financial risks discussed such as raising investor funding or generating revenues are only one type of risk faced by startups during scale-up. A risk by definition is any situation where there is a possibility of an outcome resulting in the loss of something of value [1]. Unforeseen circumstances and their negative consequences in startup businesses manifest themselves within the following types of risks, adapted from Hirai [1]:

**Market:** the possibility of insufficient demand for the offering at the chosen price. True market demand is only realized once the company tries to sell; everything up until then is speculation.

**Competitive:** the possibility of competitors having a better product, being first-to-market, deliberately underselling your offering, filing intellectual property disputes, poaching employees, et cetera.

**Technology and operational:** any variety of risks associated with product design, functionality as intended, manufacturability, product quality and reliability, production and distribution logistics, supplier management, et cetera.

**Financial:** aside from raising investor funding and generating revenues, there are risks associated with customer credit (defaulting on payments), commodity

\(^2\)Burn rate is the amount of cash a company spends per month.
prices, currency exchange rates, interest rates, price of assets used as
collateral, et cetera.

**People:** any number of risks associated with employees of the company, their fit with
corporate culture and vision, their productivity, the necessary combination of
experience, contacts, and skill, et cetera.

**Legal and regulatory:** any number of risks associated with corporate governance,
taxation, intellectual property, liability claims, and regulatory approval.

**Systemic:** risks that threaten the viability of entire market and not just one firm, such
as fuel costs affecting the entire airline industry.

All these risks can be systematically identified, monitored, and mitigated through appropriate
risk management, which begins with driving a culture of risk management throughout the
organization. The technology and operational risks associated with a high technology
manufacturing startup are further explored in the subsequent section.

### 1.1 Scale-up of High Technology Manufacturing Startups

Manufacturing is well regarded as the engine that drives innovation. The U.S. Bureau of
Economic Analysis has determined that for every dollar spent on manufacturing, it generates
$1.48 in economic activity [5]. Manufacturing only represents 12% of the U.S. Gross
Domestic Product (GDP) and 9% of U.S. jobs, but two-thirds of all private research and
development funding and employs one-third of all engineers [5].

Increasingly, the innovation behind manufacturing, whether it is new products or processes,
is found in smaller startups rather than larger corporations [3]. Often these innovations come
out of research laboratories at universities across the nation, or through companies founded
by employees of larger corporations [3]. VC funding allows these startups to prove their
technology, however when it comes time to scale-up, VCs prefer to exit via an M&A with a
large corporation and let them scale-up in-house. An example of this is DuPont’s acquisition
of Uniax in 2000, a start-up spun out of Professor Alan Heeger’s laboratory at the University
of California Santa Barbara [3]. Uniax developed organic light-emitting diodes (OLEDs). It
was only in late 2011, after 11 years of in-house development and scale-up that DuPoint announced the first commercialization project, under license to a major display manufacturer.

High-technology manufacturing startups face a significant barrier to scale-up due to upfront capital investments required before production of their physical product can begin. This poses a financial risk well known within the entrepreneurial ecosystem of VCs and startups. However, there are significant risks associated with the technology and operational side of the business as well, specifically associated with manufacturing of the product.

1.1.1 Risks Associated with Scaling-up Manufacturing at High Technology Startups

High technology startups often mistake a successful prototype or the first iteration of the product as the scaling product, and the first customers as scaling users [6]. This is hardly ever the case. The first customers are typically lead users or early adopters that provide input for improvement. In fact these early sales should be thought of as market research input [6]. Early customers also are willing to put up product design and manufacturing quality shortfalls always present in the first product iteration; something that the mass market would reject. Startups often try to include as many features as possible in their initial offering in order to attract as many customers within their target market as possible. In doing so they lose focus of their most basic features, the competitive advantage that would win over their customers in the first place. The scaling customers prefer a simple, robust product with the basic differentiating feature [7].

Quality and reliability are the most important features of any product. Marc Barros, serial entrepreneur and former CEO of Contour LLC, an action sports camera company, reflected on his experience with the following: “Shipping quality devices is by far the hardest part of building a hardware company. Customers don’t care about how small you are or the difficulties you face. They expect you deliver on and surpass on your promise not just once, but multiple times, over thousands of units” [7].

Achieving this level of quality and reliability is a tremendous effort that involves the entire company to be focused on documenting and fixing problems during both initial product development and production scale-up. Having the right talent driving the manufacturing scale-up is critical. They must have a combination of skills, industry knowledge and experience, and network of contacts to ensure the product is manufactured at the highest level
of quality [3]. Barros recommends also having at least one person solely dedicated to product testing, and quality and reliability improvement, and also working with an experienced production engineer from the beginning of the design phase to ensure a quality, manufacturable product with high yield rates. The company must always be willing to compromise of materials, methods, and location of production to ensure the highest level of quality and reliability is achieved at the lowest cost.

It is very common for a startup to outsource production to contract manufacturers and suppliers. Contract manufacturers, both domestic and foreign, are an invaluable source of in-depth volume manufacturing knowledge. However, it is critical to select suppliers that have the right specialized skills required for the startups product, prioritize speed and quality over cut-throat cost reduction, and are willing to work with company to improve the entire production process [3]. There is significant tacit knowledge during the initial pilot production runs that is very complex, and not easily reduced to simple instruction [8]. Therefore, face-to-face time with suppliers on-site is required during these stages to qualify their process and continuously improve, and take the leanings back to the company.

Finally, scaling up production requires a diligent effort in tracking the company’s cash cycle. Payment for production is usually due upfront for a startup that is not well established in the industry yet, but revenues from sales are not expected for months [9]. Also there are large cash implications associated with sustaining and customer service if the product quality suffers and customers require repairs or replacements. This could leave the company in a cash-flow insolvency situation. Careful planning in terms of supply contracts, payment terms, and product sustaining must be executed from before the scale-up begins.

1.2 Research Motivation and Overall Problem Statement

New Valence Robotics Corporation (NVBOTS), founded in March 2013, is a Boston, Massachusetts-based robotics startup company that has developed the world’s first fully automated cloud 3D printing management suite [10]. The 3D printing hardware, called the NVPro, is based on the material extrusion additive manufacturing process. NVBOTS is in the process of completing its in-house pilot production run and is faced with the problem of scaling-up its production to meet customer demand. The scale-up project is the result of collaboration between the Massachusetts Institute of Technology (MIT) and NVBOTS. The project was a team effort conducted by the author, Ali Shabbir [11], and Derek Straub [12],
all students in the Master of Engineering in Manufacturing (MEngM) program at MIT, between February and August of 2015.

1.2.1 Overall Problem Statement

The MEngM team consulted on the overall scale up project and specifically focused on integrating NVBOTS’ business model into its operations. NVBOTS does not directly sell its printers to customers but rather leases them on 5-year terms, which includes a service package. This unique business model requires careful consideration by engineering and production as the company scales up.

Product reliability and quality were identified to be the most important factors to focus on during the scale-up process. As NVBOTS transitions from producing a few units per month entirely in-house to producing hundreds of units per month in partnership with contract manufacturers in the near future, a significant shift in current engineering and production operations would need to occur. The costs associated with unreliable or sub-par quality product are unsustainable with rapid growth.

Analysing the complete product value chain, from design, to incoming supplier parts, assembly, and the complete product, identified opportunities for process improvement. These opportunities form the basis of each MEngM team member's individual sub-project and thesis, further discussed in Section 1.2.2.

In addition to specific improvement opportunities, the research and work completed by the MEngM team also included:

- Establishing a framework and foundation of critical processes for future implementation;
- Inculcating discipline, structure, and industry best practices in engineering and production operations through learnings from industry experience; and
- Providing case studies of process improvement implementation at NVBOTS as reference for future use.
1.2.2 Overview of Sub-Projects

Analyzing the complete product value chain identified specific opportunities for process improvement with regards to product reliability and quality. The first subproject is the subject of this thesis and focused on early stages of the value chain by analyzing incoming part quality and was conducted by the author. As hardware startups initiate operation, their main focus is on product development efforts. When they scale up, they need to give more importance to suppliers, quality control and inspection procedures. This project focused on developing a framework for and analyzing these attributes. Analyzing the outcomes of using this framework, key recommendations were made in this project for tolerancing techniques, data acquisition and inspection procedure. Also, suggestions were made to streamline strategy and operations and make full use of network effects.

The second subproject focused on establishing a proper failure mitigation strategy at NVBOTS consisting of failure tracking, analysis, and failure resolution. The aim of this project was to create a foundation, framework, and methodology for NVBOTS to use in order to mitigate costly failures throughout the product life cycle. Failures, especially those that occur in the hands of the customer, can have devastating consequences to any company and even more so to a startup. This project details a structured plan to capture all failure data, how to analyze it statistically and objectively based on its cost to the company, and how to best resolve the failure for future units. As for profit companies exist to produce profits, the failure mitigation strategy is based on a least-cost model. The goal is to minimize the cost impact of failures by preventing them from occurring or by lessening their impact though multiple methods. This project details how to learn from failures and how use that knowledge to create a product with increased reliability, quality, and performance, while reducing manufacturing and service costs. This is critical for NVBOTS as the cost of failures will only increase as they begin to scale up production. Establishing a proper failure mitigation strategy will allow them to continually reduce the cost and impact of failures, allowing them to successfully scale up and providing them a commanding competitive advantage for the future. Straub conducted this project and the reader is referred to his thesis for all details [12].

The third subproject was conducted by Shabbir[11]. It focused on product reliability and life and was conducted by the author. A reliable product is absolutely critical to NVBOTS due to their renting business model. The costs associated with repeatedly servicing an unreliable
product are unsustainable as the business scales up, and there is the potential to lose the customer entirely if unreliability is persistent. However, currently there is no estimate of the life of the NVPro product. Furthermore, there are no processes in-place to predict, analyze, and test potential in-service failures and mitigate these risks during product development or production. These oversights pose a significant financial risk if the future costs of service are unmanageable.

Therefore, this subproject focused on two key process improvements. The first was to implement a structured approach to predict future in-service failure modes and understand their impact. This was accomplished through Failure Modes and Effects Analysis (FMEA). The second was to establish a methodology of actually testing the product to determine its reliability and predict its life. This was accomplished through Design of Experiments, accelerated life testing, and statistical analysis. A theoretical background on statistical reliability analysis was provided along with the experimental hardware design required to estimate the life of a product. Finally, the subproject served to establish a culture of reliability through systematic testing and analysis.

The opportunities identified and covered in detail between the three theses provide recommendations for near term implementation, as this would be of immediate benefit to NVBOTS. However, each subproject is also a process improvement that should be adopted by operations to ensure long-term success during the entire scale up process.

1.3 Thesis Overview

1.3.1 Thesis Objective and Scope

All hardware startups, in their initial stages of operation, have their main focus on product development efforts. As the demand and production volume of their product increases, it becomes imperative for them to inculcate a structured and systematic approach towards quality control. The objective of this thesis is to develop a framework to establish this and then analyse the outcomes of the framework to make actionable recommendations. The framework starts with an extensive study of the important features of the incoming sourced parts, next previously collected data is analysed to establish existing supplier capability and finally a correlation between incoming part quality and final assembly geometry is studied.
Through the use of this method, key findings are documented and analysed to make recommendations.

As a result of this framework, certain well-established industry practices have been proposed which would allow hardware startups such as NVBOTS to reap full benefits of production at scale and steer clear of the pitfalls of high volume production. One important feature of a quality control culture is the collection of inspection and process data and its real time analysis to ensure final part quality and also to evaluate suppliers. A conscious effort is made in this thesis to elucidate some of the analysis techniques and software tools that are available in the industry to achieve the same. Statistical Tolerancing of parts is another important recommendation but it comes with pre-requisites. To fully use statistical tolerancing, it is important to correlate how individual part geometry will affect final assembly geometry and have a thorough understanding of the supplier’s control over their process. Both of these pre-requisites are duly investigated in this thesis along with a layout of the procedures and benefits of statistical tolerancing.

Finally, this theses explains why it is important for businesses to align their operations, organisation and overall business strategy. An important aspect of businesses today is their natural progression from just product based businesses to services and finally to becoming platforms. This thesis suggests how high technology hardware startups can add features in their offerings to achieve the same.

1.3.2 Thesis Structure

The current chapter, Chapter 1 has been written to establish the setting of the project and the nature of the study that was performed. Chapter 2 deals with the current additive manufacturing market and technologies in an attempt to put the additive manufacturing space and NVBOT’s place in it into perspective. Chapter 3 tells the reader briefly about the company NVBOTS and also about its product features and company goals. It also contains an analysis of the company on the basis of key metrics of importance for startups.

The skeleton of the NVBOTS printer is, in effect, a three axis frame with sourced machined components that build it up. In this thesis, one axis was taken up as a case study to develop
the framework for analysing parts, inspection procedures and suppliers followed by actionable recommendations based on the framework’s findings.

The framework is divided into three distinct blocks which are explained in detail in Chapter 4 of this thesis. In block 1, the axis of consideration and its parts are closely investigated. In this section, the part drawings are analysed and the important features of the parts that add to final frame geometry are identified along with additional geometrical relationships which affect either quality or life of the final machine. In block 2 of the framework, an extensive analysis of the part data previously collected using the Co-ordinate Measuring Machine (CMM) is performed and the existing supplier capability established. Finally, in block 3, an attempt has been made to correlate part geometry to output frame geometry and to draw conclusions from this to make additional recommendations. These three sections together make up the framework for analysis of incoming parts, suppliers and inspection procedures.

Based on the findings of the framework established in Chapter 4, actionable recommendations are made in detail in Chapter 5. The output from block 1 include identification of features and relationships to be inspected and use of logical datum allocation in part drawings. After block 2 of the framework is used to establish existing supplier capability, use of continuous data acquisition and analysis is suggested to speed up the analysis process and catch faults in the initial stage itself. Finally, as a result of the study of correlation in block 3, use of a more robust output metric is suggested and a layout for adoption of statistical tolerancing in the future is laid out.

In Chapter 6, a study is performed on the importance of aligning strategy, operations and organisation for businesses and recommendations are made to fully tap network effects through basic additional platform features. The conclusion in Chapter 7 consists of a layout of the complete framework with a summary of final findings and directions on future work based on those findings.
Additive Manufacturing (AM) is a field of manufacturing processes that creates objects through successive addition of layers of material. Generally, the parts are built from digital three-dimensional (3D) computer aided design (CAD) data, but this need not always be the case. AM has been referred to by many different names, 3D Printing, Rapid Prototyping, and Freeform Fabrication, just to name a few; but the term Additive Manufacturing best differentiates this field of manufacturing processes from conventional manufacturing techniques, which usually involve subtraction, deformation, or formation of material as well as changes to material properties. AM has been around commercially since the late 1980s, but the industry really gained traction and momentum in the 2000s and it has continued to increased rapidly ever since, with an compound annual growth rate of 33.8% over the last three years [13]. In 1995, AM was only a $295 million industry; as of 2014 the AM industry has grown to $4.1 billion and is expected to exceed $12.7 billion by 2018 and $21.1 billion by 2020 [13].

AM has opened up the design space to engineers, designers, and artists allowing them to produce complex geometry that was once impossible or restricted by cost and/or time. Geometrical freedom is just one of the many benefits offered by AM. Speed, customization, increased part performance, flexibility, material and energy efficiency, in-house manufacturing, and reduction of the design cycle are some of the many benefits realized through use of AM. AM is a novel tool for part production, but it is not the solution to all manufacturing needs as there are some drawbacks. Cost, speed, and time are unfavourable compared to conventional manufacturing when dealing with parts of simple geometry. Surface finish, limited materials, material properties, and lack of standards are some of the other drawbacks to AM. The key for users is to understand the capabilities and limitations and to know when it is best to use AM or rather chose a conventional manufacturing process instead.

Depending on the desired object(s) and machine to be used there is a certain work flow process to go from CAD data to having a physical part. This process can vary slightly for each job and machine but in general all AM processes follow the same seven generic steps adapted from Gibson[14]. The seven steps, in order are: CAD, Conversion to STL, STL
There are many factors such as geometry, material, intended use, cost, speed, etc. that factor into which AM machine to use for any given build. The American Society of Testing and Materials, now known as ASTM International, has categorized all of the current machines by their AM process. There are currently seven process methodology or technology categories defined by ASTM International: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination, and Vat Photopolymerization [15]. The seven generic steps and seven AM technology categories will be described in more detail in the immediately following sections.

2.1 General AM Process Work Flow

The detailed AM process will vary slightly from machine to machine and from build to build but these seven generic steps cover the majority of all AM process work flows. Depending on the machine, part(s), orientation of part, material, build quality, support material required, etc. certain steps will be more extensive than others, while some may be skipped all together. Regardless, the following steps derived from Gibson portray the typical work flow required to transform CAD data into a physical object via AM [14]:

Step 1: CAD

All AM parts must start from a software model that fully describes the geometry. This can involve the use of almost any CAD solid modelling software, but the output must be a 3D solid or surface representation. Reverse engineering equipment (e.g., laser and optical scanning) can also be used to create this representation.

Step 2: Conversion to STL

Nearly every AM machine accepts the STL file format, which has become a de facto standard, and nowadays nearly every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.
Step 3: STL File Manipulation/Slicing/Transfer to AM Machine

The order of these three sub-steps may vary, but the STL file describing the part must be transferred to the AM machine. There may be some general manipulation of the file so that it is the correct size, position, and orientation for building. The STL file is sliced into build layers and support material and corresponding support layers are generated, if need be. These slices or layers represent the physical build layers of material during the build. STL manipulation and slicing may occur on the AM machine or at a computer before transfer.

Step 4: Machine Setup

The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc. Setup usually involves cleaning, clearing, and resetting of the build area altered from previous builds.

Step 5: Build

The part is built out of the given material(s) layer by layer according to the slice data. Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc. Newer and more industrial machines are beginning to monitor for errors and anomalies in order to notify the operator.

Step 6: Removal

Once the AM machine has completed the build, the parts must be removed. This may require interaction with the part, raw material, and machine, which may have safety interlocks to ensure for example that the operating
temperatures are sufficiently low or that there are no actively moving parts. Removal must be performed carefully and by experienced operators as many parts are damaged during this step.

Step 7: Post-processing

1: CAD
2: STL Conversion
3: Slicing and Transfer
4: Machine Setup
5: Build
6: Removal
7: Post Processing

Figure 1: AM Process Work Flow Steps[14]

Once removed from the machine, parts may require an amount of additional work before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation. Post processing is usually the most laborious step and yet the most commonly unknown step for those outside of the industry.

2.2 Additive Manufacturing Technologies

In 2014 there were 49 industrial grade AM machine manufacturers, many selling multiple models. In the same year there were hundreds of mostly smaller companies selling desktop grade machines as well [13]. All machine models are similar in that they build sequentially, layer by layer, defined by the slice data of the 3D CAD model. Yet all these AM machine models are different from one another in many ways, each with the technology and features the manufacturer believes their customers want. Still, they all fall into one of the seven AM process/technology categories defined by ASTM International. Below are the definitions of the seven standard AM process categories according to ASTM International [15]:

---

3 Industrial grade and desktop grade machines are defined in Section 2.4
2.2.1. Binder Jetting

An additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

2.2.2. Directed Energy Deposition

An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

2.2.3. Material Extrusion

An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.

2.2.4. Material Jetting

An additive manufacturing process in which droplets of build material are selectively deposited.

2.2.5. Powder Bed Fusion

An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

2.2.6. Sheet Lamination

An additive manufacturing process in which sheets of material are bonded to form an object.
2.2.7. Vat Photopolymerization

An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

Figure 2: ASTM International Process Categories[12]

Within the seven categories there are many machine models employing multiple variants of the general process, yet they can all be summarized by the ASTM International categories. More advanced AM machines are beginning to incorporate conventional manufacturing processes in parallel to the additive processes. These machines still fit into one of the seven categories, but are now being referred to as hybrid machines that are capable of both additive and subtractive processes. Some future AM machines currently in the research and design phase may not fit into one of these seven categories or actually blend two or more of the categories, but for now these seven categories will suffice.

2.3 Additive Manufacturing Applications

Additive manufacturing has many applications and uses and more are being continuously thought of and put into use every year. As the machines and processes evolve and improve the application space continues to grow. Originally AM parts were used solely as visual models to better convey a conceptual design. Currently, AM part applications can fit into one or many of the following categories: visual models, fit check models, functional models, end use parts, tooling and moulds, assembly guides and fixtures, education, and research. In recent years the percentage of parts built for end use has continued to climb and in 2014 end use parts accounted for 29% of all parts built, now the most popular application [13]. This can be attributed to the steady increase in performance and quality of the AM machines as well as the increased adoption and confidence from engineers, designers, and other users. Fit check models was the second most popular category in 2014 accounting for 17.8%, while the least popular use was that of tooling [13]. 2015 will see a rise in both end use parts and tooling as the AM machines are as capable as ever, there are increased material options, and these two categories have the most untapped potential, and leading manufacturers have been heavily spotlighting these applications in their advertisements as well as at trade shows and conferences.
Many industries have realized the benefits of AM and its use has increasingly become more and more widespread in industries such as automotive, aerospace, industrial/business machines, consumer products and electronics, medical and dental, academic, government and military, architectural and others. The automotive and aerospace sectors were early adopters to AM and still represent a combined 30.9% of the total AM user-base, while consumer products and electronics are catching up with 16.6% [13]. The vast range of uses can be attributed to the widespread adoption throughout all the major sectors as they begin to truly realize the many benefits of AM. One of the most popular benefits that most sectors look to capture is that of reducing the development cycle time for new products. AM can speed up rounds of design, prototyping, and testing through quick or even parallel production of multiple iterations of a design. Typically after the development cycle there is a manufacturing cycle required to tailor the final development design to the manufacturing equipment, for quality and efficiency in mass production. When AM is used for production of end use parts the development cycle and manufacturing cycle are reduced even further, as the manufacturing cycle is no longer needed. The last iteration of parts that were built for the development cycle now become the manufacturing design and require no further work, as they are already being manufactured on the final manufacturing equipment. Because of this reduction in time and cost, among many other benefits, many sectors are looking to increase their use of AM.

2.4 Industry and Market

The AM industry consists of two major classes of machines: desktop grade and industrial grade. For the intent of this publication any AM machine that retails for more than $5,000 USD is considered industrial grade. Any AM machine retailing for less than $5,000 USD is considered desktop grade. This provides a clear cut line between the two but their differences are quite obvious and extend well past their price tags.

Industrial grade machines are just that; they are built for industrial use and are intended to be operated in an industrial setting by trained operators. The machines range from $5,000 to over $2,000,000 USD and are very capable. Industrial machines can process the widest range of materials including, but not limited to, polymers, metals, ceramics, composites, and bio-matter. In general they have higher reliability, quality, resolution, layer thickness options, advanced build control, speed, efficiency, and robustness when compared to desktop models. Industrial grade machines are usually much more complex, yet easier to work with than
Desktop machines, due to better software and a more automated process. Typically they have larger build volumes and are able to build multiple parts in parallel. Industrial grade machines span all seven process categories and are starting to include hybrid machines that are capable of both additive and subtractive processes. Uses include all of the previously noted uses but in contrast to the desktop models, industrial grade machines are used more frequently for end use parts, tooling, and fit checks, due to their material selection and build quality/resolution. In 2014 Wohlers estimates that nearly 13,000 industrial grade machines were produced and sold. In total last year, industrial AM machine sales accounted for 86.6% of revenue from sales worldwide [13].

Desktop grade machines are designed for low cost and are able to fit on a desktop at work or at home. They range in price from about $400 to $5000 USD. These machines have not been around as long as their industrial counterparts, first breaking into the commercial market in 2007 and only truly being sold in large quantities beginning in 2011 [13]. Desktop models are notoriously known for being difficult to work with and lack in quality, resolution, and speed. The software, user interfaces, and calibration setting are weak points and cause most of the issues associated with this class of machines. Due mainly to their low cost, desktop grade machines have a very good price to performance ratio and are much less expensive to operate. They are limited to only a few simple material choices but usually have many build colour options. These machines are more tailored to home, educational, artistic, and recreational uses. Currently desktop models are only available in one of two process/technology categories: extrusion and vat photopolymerization. Last year nearly 140,000 desktop machines were sold worldwide accounting for 13.4% of revenues from all AM machines, up from 9% the previous year [13].

The AM market is dominated by industrial and desktop machines but there is very little in-between. Recently hundreds of companies have started to produce thousands of desktop AM machines to satisfy the general public’s craving for access to 3D printing. There is truly an untapped market sitting directly between the two current machine grades. A very accurate analogy can be made to conventional printers: Industrial grade AM machines are similar to large printing presses and desktop grade AM machines resemble conventional desktop inkjet and laser printers, but there is currently nothing similar to that of the networked office printer. Xerox, Canon, HP, and others have truly excelled in the networked office printer market, yet not a single AM machine has been designed for a similar 3D market. NVBOTS aims to tackle this untapped market with their NVPro 3D printer. The NVPro is networked and
designed for speed and autonomy. This should be a good fit for this open market but it’s safe
to say that many of the existing industrial and desktop manufacturers are looking to fill this
void as well. The classroom and office space may well be the next battleground for AM
machine manufacturers.
3  CHAPTER 3: NVBOTS COMPANY OVERVIEW

3.1  Company Background

New Valence Robotics, or NVBOTS, is a 3D Printer manufacturing startup founded in March 2013 by four MIT students. The company’s logo is shown in Figure 3. At present, NVBOTS has all of its operations in Boston, MA. The vision of NVBOTS is to build a globally distributed network of on-demand intelligent automated 3D printers in order to deliver high quality printed parts. The team here believes that the current additive manufacturing process is full of hassles and this acts as an encumbrance against increasing the user base of the technology. There’s a steep learning curve involved in designing for 3D printing, part removal is cumbersome and there is a lack of queuing that makes 3D printers difficult to share. To tackle these problems, NVBOTS has developed the world’s only 3D printer with automated part removal, which through their cloud-based interface can run continuously by itself and be controlled by any device [10].

![Figure 3: NVBOTS logo](10]

Their current business model is to rent out their printers is to lease out printers at different pricing and packages to their educational and industrial customers with full service offered as a part of every package[16]. The company recently closed a successful $2M seed round of funding.

3.1.1  The Product

The NVPro is a dual extrusion based printer with a resolution of 100 microns and an accuracy of 25.4 microns. The build volume is a cube of 8 inches and achievable printing speed is as high as 180 mm/s. The completely assembled NVPro with its protective casing is shown in Figure 4.
NVPro’s user interface makes the printing process very easy for the consumer. Figure 5 shows the print preview tab of the interface where users can choose parameter levels of the build and also preview the parts. Other exciting features of the NVPro include automated part removal that obviates manual presence to clear build area for subsequent prints. A built-in camera allows real time viewing of the printing process from any device. The view from the camera for an ongoing build in the Dashboard tab of the interface is shown in Figure 6. All the printer management is through the cloud so no extra software is required[17].
The NVPro caters to the education market as their target audience. Additional offerings in the package include 3D printable curricula. These modules encourage project based and applicative learning and lessons include life sciences, earth or space sciences, engineering and many more[19]. The user interface is intuitive and easy to navigate. Its features include print preview with size, shape and quality adjustments, administrative control for queue management and a printer dashboard with a live video feed and other real time monitoring add-ons[18].

3.1.2 The Market

NVBOTS leases out printers on a yearly contract and ensures recurring consumables revenue (plastic filament) and cloud services fees. Their beachhead market is the education space in an attempt to capture the future designers and scientists early and also, through their data, learn what is desired from 3D printing. They currently have 16 printers rented by educational customers, 10 printers working internally and 12 printers currently on the assembly line. Once they successfully penetrate the education marketplace, they will approach the industrial marketplace with more technology offerings in an attempt to make a stronghold there.

3.2 Company Analysis

Professor Michael Cusumano of the Sloan School of Management identifies eight key points of successful startup ventures[20]. The following section looks closely at how NVBOTS is currently positioned on the basis of these metrics.
1. **Management Team**

The founding team of NVBOTS includes CEO AJ Perez, CTO Forrest Pieper, COO Chris Haid and VP of Engineering Mateo Peña Doll, all of them MIT mechanical engineers. NVBOTS also has an esteemed board of advisors in former experts of manufacturing and 3 D printing industry and also experienced professors at MIT. With new hires, including experienced people in key areas of supply chain, sales, and production, this metric seems well cleared for NVBOTS.

2. **Attractive Market:**

The McKinsey Global Institute estimates the total economic impact of 3D printing by 2025 to be up to $0.6 trillion[21]. Hence, an attractive market certainly exists. With NVBOTS’s beachhead market being largely untapped and their value proposition being specifically advantageous to capture it, they are well on track. They are also targeting industrial markets with improved technologies.

3. **Compelling new product:**

The NVPro is a compelling product in itself but it must be put in reference to the competition that they face. In terms of feature offerings such as 24/7 printing without human intervention, ease of sharing among consumers and use of data for future improvements, it is the only product that achieves it.

4. **Strong evidence of customer interest:**

NVBOTS already has customers using the product and a high anticipated demand for FY15. Besides, NVBOTS is currently catering to its beachhead market and at the same time working on product innovations that will serve them well in the industrial marketplace. The true litmus test will come when they attempt to pitch to industrial customers and compete with other well-established players in that field.

5. **Overcoming the “Credibility Gap”:**

Professor Cusumano describes this as “the fear among customers that the venture will fail, leaving the buyer without technical support or a future stream of product upgrades.” In order to avoid this, startups must use present customers as references
for new customers[20]. This requires exceptional customer service and also a product that is reliable and does not face critical issues in the field. This is one concern area.

6. **Demonstrating early growth and profit potential:**
NVBOTS has a well charted financial plan for growth and an existing customer base. Successful seed funding rounds are indicative of the company’s merit.

7. **Flexibility in Strategy and Technology:**
This metric cannot be assessed through plans made in advance but only after the company has been running for a certain period of time and proves to be responsive to market needs and technological changes in such disruption prone markets.

8. **Potential for large investor pay-off:**
A new venture that has established sources of funding beyond angel investors and family, friends etc. shows promise for large pay-off and looks better to potential investors[20].

<table>
<thead>
<tr>
<th>Elements for evaluation</th>
<th>NVBOTS</th>
<th>Key</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management Team</td>
<td></td>
<td>Strengths</td>
<td>Green</td>
</tr>
<tr>
<td>Attractive Market</td>
<td></td>
<td>Opportunity</td>
<td>Yellow</td>
</tr>
<tr>
<td>Compelling New Product</td>
<td></td>
<td>Threats</td>
<td>Red</td>
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<tr>
<td>Strong Evidence of Customer Interest</td>
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<tr>
<td>Overcoming the Credibility Gap</td>
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<tr>
<td>Demonstrating Early Growth and Profit Potential</td>
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<tr>
<td>Flexibility in Strategy and Technology</td>
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<tr>
<td>Potential for large investor pay-off</td>
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**Table 1: NVBOTS Evaluation**
A consolidation of the results seen above is shown in Table 1 with all metrics bucketed into strengths, opportunities and threats. In conclusion, the company has a bright future ahead with their strong performance in almost all of the above mentioned metrics. NVBOTS should have a strong focus on capitalising on opportunities by generating customer interest and also staying nimble and flexible in their strategy. By refining their product design and manufacturing process, they can eliminate the initial concerns that their product faces in the field and ward off their single potential problem.
4 CHAPTER 4: FRAMEWORK FOR ANALYSIS

4.1 Overview of Framework

The objective of this framework is to firstly, establish a systematic approach to analyse the sourced machine parts for the printer frame. Secondly, it is to evaluate existing supplier capability and finally, to correlate incoming part quality to final geometry of the machine frame. Based on these objectives, the framework is divided into three distinct blocks as shown in Figure 7.

![Figure 7: Framework Overview](image)

Each block is expanded upon in the subsequent parts of this chapter and finally a complete and detailed explanation with layout of this framework is provided. In the subsequent chapter, recommendations are provided on the basis of the findings of this framework. Given below is a brief explanation of each of these blocks.

**Block 1: Incoming Parts Analysis**

In this block the machine is broken down into different functional sub-assemblies and each individual part is analysed for features that contribute to output geometry. Critical relationships within the part are also identified and then inspection procedures set to measure all of these dimensions on the CMM.

**Block 2: Supplier Analysis**

Through the analysis of CMM data measured according to Block 1, the supplier’s control on his process and ability to meet specifications is established through the use of statistical techniques.

**Block 3: Correlating Incoming Part Quality to Output**

Finally the incoming part data measured on the CMM is correlated with the output data of the final assembly to see if any trends exist and to draw important conclusions.
4.2 BLOCK 1: Incoming Parts Analysis

4.2.1 Machine Setup and Incoming Parts

In order to understand how the final geometry comes about on assembling the printer, it is important to break the printer down into its functional subassemblies and look at different components in each of these sub-assemblies. The focus of this thesis is on the machined components that are sourced from an external supplier and make up the frame of the printer. The skeleton of the printer is actually a three axes frame that provides the structural stability to all other sub-assemblies of the printer and that contributes to the accuracy of the printed part by deciding the final geometry of the traversal system.

The printer frame can be divided into three axes as shown in the Figure 8. The X-axis, the Y-axis and the Z-axis. Each axis consists of machined components that finally make up the geometry of that particular axis and also connect one axis to the other.

![NVPro Frame - Axes](image)

**Figure 8: NVPro Frame – Axes**

The three different Axes encompass the components that allow traversal in that dimension

The geometry of the printed part depends on the final frame geometry that in turn depends on the geometrical relationship among the axes. The machined components and the important features of these parts decide the axis geometry with a varying degree of sensitivity of each part.
4.2.1.1 Required Frame Output

The frame achieves motions in two directions along each axis. The requirements from the frame to achieve required output frame geometry are as follows:

1. Parallelism:
   This is the parallelism required between shafts on the same axis. The parallelism specification between the shafts of each axis is shown in Figure 9. The X-axis and the Y-axis have parallel shafts that dictate the traversal of their mounted assemblies. There must be an upper limit on the specification of this metric of misalignment. The main considerations in deciding this metric are:

   a. Output Part Quality
      The accuracy required in the features of the output part should decide through back calculation the maximum allowable misalignment of the final frame and thus, the shaft parallelism.

   b. Machine Component Life
      As the misalignment between the shafts increases, the stress on the mounted components, the shafts and the bearings collectively increases. This not only wears the parts out faster but also draws more work from the motors that drive the mechanism.

![Figure 9: NVPro Frame – Outputs]

These are the parallelisms between shaft pairs on each axis.
2. Perpendicularity:
This is the perpendicularity required between two axes of the printer frame. The output part quality as explained above dictates the deviation of this specification from perfect perpendicularity. The inaccuracy in the frame geometry will carry forward directly to the actual part as well.

4.2.2 X-axis components and Important Dimensions
To develop the framework, throughout the thesis, the X-axis has been taken as a case study. Looking at the X-axis itself, it can be broken down into different components that alone can contribute to its output geometry. The different components are then broken down into their fundamental features that are integral to maintaining final quality and life requirements.

4.2.2.1 Basic Frame
In order to analyse the X-axis frame for its contribution to output geometry, it can be simplified into a two part, two shaft assembly. Figure 10 shows the functional break-up of the X-axis into its constituent components.

![Figure 10: X-axis frame schematic](image)

This is a functional break-up of X-axis into constituent components

The picture above shows a schematic of the X-axis frame with all the functional components of the basic skeleton. On the shafts 1 and 2 shown above a common plate holds the extruder
sub assembly. As explained in the previous section, the parallelism of the shafts is critical for both part quality and the life of the machine.

All the components of the basic frame have been listed as follows:

1. **Part 1 and 2**
   These parts hold the end of the shaft in two holes on each part. The position of the holes decide the orientation of the shafts and hence are an important part of the geometry.

Now important dimensions of parts 1 and 2 are explored. Part 1 and Part 2 can be considered identical for all functional purposes of their contribution to final parallelism. Figure 11 shows the break-up of Part 1 into its constituent important features and relationships.

![Figure 11: Important dimensions of Part 1 and 2](image)

The features identified geometrically contribute to the final output metric of parallelism described in Figure 9.
Important dimensions of part 1 and 2:

1. **Part 1 or Part 2 Individual:**
   a. Diameter of hole 1 and 2
   b. Cylindricity of hole 1 and 2
   c. Position of hole centre 1 and 2
      i. X position left of origin: X₁ and X₂
      ii. Z position above origin: Z₁ and Z₂

2. **Part 1 and Part 2 Relationship:**
   a. **Difference in X position – ΔX**
      The difference in X deviation denoted by ΔX in Figure 11 for part 1 and part 2 must be between an upper and lower limit to accommodate the shafts absolutely straight with respect to each other and absolutely perpendicular with respect to the centre axis of part 1 and part 2. In case the misalignment is too much, it will stress the shafts and cause parallelism to be out of specification.

   b. **Difference in Z-position – ΔZ**
      The difference in Z deviation denoted by ΔZ in Figure 11 for part 1 and part 2 must be within an upper limit and lower limit to avoid unacceptable misalignment between the two shafts.

### 4.2.2.2 Shaft Mount

Another important part of the X-axis assembly is the shaft mount shown in Figure 12. The bearings are placed over the shaft and then the shown shaft mount is placed on them. The bearing contacts are with the shafts on the inside and the inner surface of the shaft mount on the outside.
The important features of this part pertain to the axes of the two holes identified above.

All the important features of Part 3 are associated with the Holes 1 and 2 and the position and orientation of their axes.

**Important dimensions of part 3:**

1. **Hole 1 and hole 2 individually:**
   a. Cylindricity of holes
   b. Diameter of holes

2. **Hole 1 and hole 2 relationship:**
   The main goal of the hole relationship is to have the axes of the holes completely aligned to each other, i.e. to ensure they lie on the same straight line. Geometrically, this means that the two axes are parallel and the perpendicular distance between them is zero. Another way to check for hole axes alignment is to measure the difference in height of their centres from the origin of the part shown in the bottom left corner in Figure 12.
   a. Parallelism of the axes
   b. Perpendicular distance between the axes when projected onto a plane
   c. Difference in height of the centre points of hole 1 and hole 2
4.2.2.3 Shafts
The shafts act as channels for the bearings and the shaft mount. Their important features are:

1. Cylindricity – Circularity and Straightness
   The cylindricity feature is a three dimensional tolerance that ensures that the cylindrical part, in this case the shaft, is both round and straight according to a tolerance band along the entire axis of the part; this specification is effectively a combination of circularity and surface straightness [22].
   Effectively, it is a measure of the deviations of the shaft from an ideal cylinder along the entire surface of the shaft.

2. Diameter
The key dimensions identified for the different features of all parts in the X-axis as explained in the previous section have been consolidated and shown in Table 2.

<table>
<thead>
<tr>
<th>Key</th>
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<tbody>
<tr>
<td>not measured</td>
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<tr>
<td>Measured</td>
<td></td>
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<tr>
<td>need other measurements</td>
<td></td>
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<tr>
<td>to calculate</td>
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<table>
<thead>
<tr>
<th>Feature</th>
<th>Dimension</th>
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<tbody>
<tr>
<td>A</td>
<td>Diameter</td>
</tr>
<tr>
<td>B</td>
<td>Diameter</td>
</tr>
<tr>
<td>C</td>
<td>Cylindricity</td>
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<tr>
<td>D</td>
<td>Cylindricity</td>
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<tr>
<td>E</td>
<td>DP</td>
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<tr>
<td>F</td>
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<tr>
<td>G</td>
<td>Cylindricity</td>
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<tr>
<td>H</td>
<td>DP</td>
</tr>
<tr>
<td>Relation I-1</td>
<td>DX</td>
</tr>
<tr>
<td>Relation I-2</td>
<td>DZ</td>
</tr>
<tr>
<td>J</td>
<td>Z height</td>
</tr>
<tr>
<td>K</td>
<td>Y position</td>
</tr>
<tr>
<td>L</td>
<td>Y position</td>
</tr>
<tr>
<td>Relation M</td>
<td>K/L relation 1</td>
</tr>
<tr>
<td>Relation N</td>
<td>K/L relation 2</td>
</tr>
<tr>
<td>Relation O</td>
<td>C/D relation</td>
</tr>
<tr>
<td>Relation P</td>
<td>F/G relation</td>
</tr>
</tbody>
</table>

As it is seen in Table 2, out of the 34 important dimensions and relationships identified by breaking up the X-axis subassembly into individual components, 6 important dimensions, as
shown in green colour, out of 30 were not being measured and thus 2 important relationships, as shown in orange, out of the 4 could not be calculated.

4.2.3 Block 1: Incoming Part Analysis Outcome

![Diagram of Block 1: Incoming Part Analysis Outcome]

Figure 7: Framework Overview

The first block of the framework shown above is consolidated and defined as follows.

**Step 1: Break machine into subassemblies and components**

The division should be done on the basis of functionality of subassemblies. For example, in the case of the printer the breakup of the machined component frame was into axes of motion in different dimensions, i.e., X, Y and Z axes.

**Step 2: Identify key dimensions of these components that contribute to final output**

Look at final required output for the assembly, in this case, quality and life. This output is then translated into geometrical features. Finally, break down the components into different features that add to this geometry of the final output and also identify additional relationships that do the same.

**Step 3: Measure these dimensions on the CMM for data collection and analysis**

The purpose of this step is to gather data in order to perform the essential analysis of the remaining blocks of the framework.

This block can be summarised through the block diagram shown in Figure 13.
**Figure 13: Block 1 of Framework**

**Key Findings**

Through this analysis, all the important dimensions of the components of this axis were identified. Subsequently, it was found that many of these dimensions were not being measured and, therefore, some important relationships could not be calculated.

Hence, this shows that it is necessary to use this block of the framework and identify that are the important features to be measured on the CMM for further data analysis.

4.3 **BLOCK 2: Supplier Analysis**

The Toyota Quality principles talk about how the culture of quality must extend to the entire supply chain. The final quality of the output product depends heavily on its sourced components and in turn, the capability of the suppliers. It is imperative for hardware start-ups to pay specific attention to suppliers and supply chain issues. The failure of start-ups to carefully adapt their operations for scaling up along with other supply chain issues has been identified as one of the leading reasons for their failure[23].

Hence, it is important to qualify suppliers on the basis of their process control and their ability to meet desired specifications. This analysis is very involved with continuous back and forth between suppliers, a thorough understanding of their manufacturing process and alignment of inspection and measurement procedures[24]. Along with the use of statistical tools to analyze data and make conclusions, it is imperative to first fully understand the assumptions that one is making in performing them and to correctly identify possible sources and causes of deviations from required output.
So, in qualifying suppliers two major steps are involved:

1. Establishing that the supplier’s process is in statistical process control.
2. Establishing supplier’s ability to meet required specifications, i.e., process capability.

### 4.3.1 Statistical Process Control

All production processes have some inherent variability. The type of variation can be divided into two types:

1. **Assignable variation**
   
   These are causes over which we have a certain extent of control. They originate mainly from three sources - improper machine setup, lack of operator skill or defects in the raw material[25].

2. **Random variation**

   This is the collective result of many unavoidable and complex causes which are beyond direct control; the result of each cause is very small and other than altering the process, there is no other way of eradicating these causes of variation[26].

If a process has no assignable causes of variation, it should be random and normally distributed with certain characteristics like a stationary mean and variance; a process fulfilling these criteria is said to be in-control[26].

#### 4.3.1.1 Normal Process and Probability Plot

A normal process suffers from only random causes of variation as defined above. Hence, one measure of looking at the state of control of a process is to check the process for normality. A process is said to be normal if it follows the following distribution[25].

\[
f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x-\mu}{\sigma} \right)^2}
\]

Where, \(-\infty < x < \infty\)

The mean of the normal distribution is \(\mu\) \((-\infty < \mu < \infty\)\)

And the variance \(\sigma^2 > 0\)
One way of visually depicting and analyzing the normality of a process is through the use of a normal probability plot. In this graphical technique, data is plotted against a perfect normal distribution such that the data points together should ideally form a straight line. Deviations of the data set from normality manifest themselves in deviations of the plot from the ideal straight line[27]. For the purposes of this study, JMP software from SAS was used to develop all normal probability plots. One sample plot for explanation has been shown in Figure 14 with 95 pc confidence limits.

![Normal Probability Plot](image)

**Figure 14: Sample normal probability plot**

Note that in this plot, the circled cluster of points at the 95pc confidence boundary shows a deviation from normality

4.3.1.2 Process Control Chart

The visual depiction of the state of a process is highly beneficial in not only understanding its state and deviations but also for real time control and responsiveness. The chart contains a center line that is the average of the data set of the measured characteristic on the part. The actual measurements are plotted on the chart along with upper and lower control limits[25]. The generally used control limits are called 3 sigma limits that are plotted at 3 standard deviations above and below the center line. A sample Process Control chart with its metrics identified has been shown in Figure 15.
The output of the process over time is shown in blue and the upper and lower control limit signify the natural spread of the process.

If there is any specific trend or any points in the data set that lie outside the control limits, the process is out of control, meaning the deviation has been caused through assignable causes. Hence the normal probability plot and process control charts are a basic way that can be used to characterise the state of process control of the supplier and have been extensively used in this block of the framework.

4.3.2 Process Capability

Process capability is a measure of how well the process can meet target specifications. It is descriptive of the relationship between the natural spread of the process and the allowable spread according to target specifications. The target specifications are set based on the requirements of the design and allowable tolerance limits above and below the nominal value. Figure 27 shows the probability distribution of a sample normal process with its associated specification and control limits. The process will always meet target specifications as the natural spread of the process signified by UCL and LCL always falls between the required specification limits of USL and LSL. One metric that is used to gauge this phenomenon quantitatively is described as follows.
Figure 16: Process Capability [28]

The LCL and UCL limits show the natural spread of the process and the USL and LSL limits show the tolerance band of the required specifications.

$C_p$ is a measure of the spread of the process and ignores any mean shifts existing in the process. It takes into account the natural spread of the process and the required specifications; $C_{pk}$ measures how centred the data is between specification limits [29].

The numerical value of $C_{pk}$ can be defined as follows [29]:

$$C_{pk} = \min \left( \frac{USL - \bar{X}}{3\sigma_x}, \frac{\bar{X} - LSL}{3\sigma_x} \right)$$

The numerical value of $C_p$ can be defined as follows [29]:

$$C_p = \frac{USL - LSL}{6\sigma_x}$$

Where,
- $USL = \text{Upper Specification Limit}$
- $LSL = \text{Lower Specification Limit}$
- $\text{Target} = \text{Nominal Specification}$
- $X_{bar} = \text{Sample Mean}$
- $\sigma_x = \text{Sample Standard Deviation}$
For a general indication of process capability with respect to \( C_{pk} \), we can note that for a centred process with minimized variation the \( C_{pk} \) value is around 2.0, as the centred process increases in variation its value drops to around 1.0 and as the process goes off centre its value goes below 1.0 to about 0.7 even if the variation is minimised; large variation and off centre process have even lower values of \( C_{pk} \) [30].

The following Figure 17 shows the relationship between \( C_p \) and \( C_{pk} \) for two different kinds of variations. One is a centred process which lies outside the specification limits and the other is a non-centred process which lies completely within the specification limits.

The relationship between \( C_p \) and \( C_{pk} \) is indicative of both the ability of the process to meet target specifications and also how centred the process is in between USL and LSL. If \( C_p > 1 \), the process will lie between customer upper and lower limits if it is centred. If \( C_{pk} > 1 \), then not only is the process within specification limits, but it is also centred between those limits. An important insight is that in cases where \( C_p > C_{pk} \), the process is off centre.

Another important conclusion that can be made from the \( C_{pk} \) value is the percentage of out of specification parts that are expected to be made from a process. Consider the situation in Figure 17 b, where the process is centred but the natural spread of the process lies beyond the specification limits. The first step in order to calculate the expected percentage of out of specification parts for this distribution is to calculate the number of standard deviations the
specification is from the mean, this value is also known as the Z-value and has the following equation[31].

\[
Z = \frac{(USL - X_{bar})}{\sigma_x} - \frac{(X_{bar} - LSL)}{\sigma_x}
\]

Where,
- USL = Upper Specification Limit
- LSL = Lower Specification Limit
- Target = Nominal Specification
- \(X_{bar}\) = Sample Mean
- \(\sigma_x\) = Sample Standard Deviation

The normal probability table can then be used in order to get the percent of distribution which would lie outside the specification limits.

The percentage out of specification parts for generic one sigma, two sigma and three sigma control limits for a completely centred process are shown below in Figure 18.

![Figure 18: Percentage out of specification parts][32]

This analysis becomes very important when qualifying suppliers while considering costs of rework and scrap based on the expected number of rejected parts.
4.3.3 **Analysis Setting**

Based on the important features of X-axis identified in Block 1 of the framework, the analysis as explained above was performed to look at the process control of the suppliers and also their process capability.

The last step of Block 1 directed CMM measurement of all important features. The previously collected measurement data of 70 parts was used in order to illustrate the use of these analysis techniques.

The important features of the X-axis subassembly’s components were divided into four buckets that were representative of all the capabilities of the supplier. The buckets are as follows:

1. Diameter
2. Cylindricity
3. Parallelism
4. Lengths

As explained in the previous sections, two studies were conducted for the features identified in Block 1 of the framework and the representative results of some of these have been displayed in the subsequent section.

1. Process Control
   a. Normal Probability Plot
   b. Process Control Chart

2. Process Capability
   a. C_p calculation

Finally a consolidated table was constructed in order to draw conclusions and to identify problem areas and form actionable recommendations.

Along with the primary analysis performed for the purposes of the framework, additional observations were made that were critical to the understanding and use of this framework. These observations include the importance of consistent data, problems of post facto analysis of part data and the time consuming nature of analysis through non-specialized software.
4.3.4 Feature-wise Analysis of Suppliers

4.3.4.1 Diameter Process Control

We will look at the normal probability plots of the various diametrical features to ascertain the process control of the supplier with this feature. The plots of two of these are shown in Figure 19 below.

![Normal Probability Plot of Diameters](image)

*Figure 19: Normal Probability Plot of Diameters*

Note that all the data lies between falls between the 95 pc confidence lines, indicating a normally distributed process.

These two normal probability plots are well-representative of all the other diametrical features as well. By the proximity of the plotted points to their fitted ideal line as shown in the plots of Figure 19, it can be said that the data is well described by a normal distribution, suggesting that the process variation is purely random, and at least over this data set, the process is in a state of statistical control.

**Process Capability**

While the process is in control, the supplier’s ability to achieve target specifications is studied through the Process Control Chart shown in Figure 20. While some diametrical features are in general within specification limits, some are drastically out as shown below. The calculated $C_{pk}$ value for the data set of this process control chart came out to be -0.2, which is extremely low and accurately depicts the low process capability of this particular process. The $C_p$ value for this process is 0.42, this is higher than the $C_{pk}$ value and clearly suggests an off-centred process on the supplier’s part. Since both the values are low, there is a lack of process capability.
Figure 20: Diameter Process Chart

Note that most of almost all points lie outside the specification limits showing low process capability.

4.3.4.2 Cylindricity Process Control

Sourced Machine Parts

The cylindricity feature displays a certain concentration of data points on one side of the distribution, yet all points lie within the 95 pc confidence interval represented by the red dotted curves in the plot as shown in Figure 21. Thus, it can again be said that the data is well described by a normal distribution, suggesting that the process variation is purely random, and at least over this data set, the process is in a state of statistical control.

Figure 21: Normal Probability Plot of Cylindricity

Note that all the data lies between falls between the 95 pc confidence lines, indicating a normally distributed process.
Shafts
The cylindricity feature of the shafts shows a very interesting result. In order to put it into context, the shafts are measured for their cylindricity after they are loaded onto the X-axis and the remaining axes are also assembled. The normal probability plot for the cylindricity feature of shafts is shown below in Figure 22.

![Normal Probability Plot for Cylindricity of Shafts](image)

**Shaft 1 Cylindricity**  **Shaft 2 Cylindricity**

**Figure 22: Normal Probability Plot for Cylindricity of Shafts**

It can be seen that the process is not in control, but it is important to understand that this conclusion cannot be drawn as the measurement of these shafts were done after they were assembled onto the X-axis and subsequently onto the rest of the frame.

In the assembly process of the frame, these shafts are constrained in the X-axis parts 1 and 2 which in turn are subsequently loaded with components of other axes. Because of this constraint and lack of adjustment capability of the shaft end positions, the stress of all the misalignment of this assembly comes on to the shafts. This causes the shafts to bend along different planes and hence their cylindricity measure changes on assembly.

Hence, it is important to measure these shafts before they go onto the frame in order to make useful conclusions about the shaft supplier.
4.3.4.3 Parallelism

Process Control

Parallelism is an important feature since it directly governs both the accuracy and life of the machine. The normal probability plot for the parallelism features of the Part 3 axes is shown in Figure 23. A and B subscripts in the figure signify the two different units of Part 3 used on the same printer.

![Normal Probability Plot for Parallelism](image)

**Part 3A Parallelism**

**Part 3B Parallelism**

Figure 23: Normal Probability Plot for Parallelism

Note that all the data lies between falls between the 95% confidence lines, indicating a normally distributed process with the exception of one outlier in Part 3B Parallelism.

As it can be seen from the plots, the process is in control with the exception of one outlier. The state of the process capability for the parallelism feature is however similar to that of the diameter.

Process Capability

The process charts with upper and lower specification limits are shown in Figure 24. The $C_{pk}$ value for the Part 3A Parallelism Chart comes out to be -0.27 and the $C_{pk}$ value for the Part 3B Parallelism Chart comes out to be -0.33. The $C_p$ values for these processes are 0.13 and 0.16 respectively. A better $C_p$ than a $C_{pk}$ shows that along with being unable to meet specifications, the process is also off-centred and correspond to large percentage of rejection.
Figure 24: Process Charts for Parallelism

Note that most of almost all points lie outside the specification limits showing low process capability

4.3.4.4 Lengths Process Control
In the important dimensions and relations identified in the Block 1 of the framework, the largest number is that of lengths. The normal probability plots for this feature as shown in Figure 25 indicate that this feature is not as well controlled as the diameter or the parallelism. Even though the data set has a large number of parts that are normally distributed, there are many outliers. This can be seen from the high density of nearly linear points in the centre of both the plots.

Figure 25: Normal Probability Plots for Lengths
Note that the presence of too many outliers causes the normal probability plots to show out of control process
Process Capability

It is a general trend in the analysis of this supplier to see a well-controlled process not meeting the target specifications and that is the case with lengths here as well. Figure 26 shows the Process Control Chart for one of the length features. The $C_{pk}$ value for this particular length feature is -0.09. This low value signifies the low process capability that can be seen from this graph as well. The $C_p$ value for this process is 0.03, which is very low and again signifies an off centre process.

![Figure 26: Process Control Chart for Length](image)

*Note that most of almost all points lie outside the specification limits showing low process capability*

The following section shows a consolidated result in Table 3. This is followed by a description of the second block of the framework and the key findings that came out of this analysis of CMM data.
### 4.3.5 Consolidated Result

<table>
<thead>
<tr>
<th>Part</th>
<th>Feature</th>
<th>Avg.</th>
<th>Stdev</th>
<th>Target</th>
<th>USL</th>
<th>LSL</th>
<th>Cpk</th>
<th>Cp</th>
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<td></td>
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<td></td>
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<td>14.775</td>
<td>14.73</td>
<td>-0.1</td>
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<td>9.8025</td>
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<td>-0.2</td>
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</tr>
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<td>Diameter</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

**Key**

- **not measured on the CMM currently**
- **Measured on the CMM currently**
- **These specification limits have not been set as yet**
- **need other measurements to be calculated**

**Table 3: Consolidated Result of Supplier Analysis**
4.3.6 Block 2: Supplier Analysis Outcome

Block 2 of the framework can be explained as follows.

**Step 1: Consolidate and clean collected CMM data**
The CMM data is collected in a format that needs some time consuming work to convert into analysable form. Also, one needs to be wary of inconsistent data as that can alter results.

**Step 2: Analyse data for process control and process capability**
The analysis for process control is performed through the use of normal probability plots and process control charts. For process capability, $C_{pk}$, $C_p$ and percentage of parts out of specification limits should be calculated.

**Step 3: Take action with suppliers and team**
The out of control processes or out of specification processes need to communicated to the suppliers and the engineering team needs to look at the unset tolerance limits and re-evaluate their design specifications in case their tolerances cannot be easily met. Figure 27 shows the procedural steps of Block 2 of the framework.
STEP 1
- Consolidate and clean collected CMM data

STEP 2
- Analyse data for process control and process capability

STEP 3
- Take action with suppliers and team

Figure 27: Block 2 of Framework

Key Findings
1. Processes are in control but do not meet specification limits
   This shows that the supplier’s process has no assignable causes but his process capability is not enough to meet the desired specifications set by the design team. Two actions need to be taken as a result of this finding.

   a. Supplier meeting
      The supplier needs to be made aware of the fact that he is not meeting desired specifications and if in case he is being paid more to achieve these tolerances then a price renegotiation needs to take place.

   b. Tolerance Analysis
      The consistently small value of $C_{pk}$ suggests that the process capability is low and also that the tolerances are very tight. Not only this, a consistently low value of $C_p$ also suggests that the supplier’s process is off centre. The fact that a lot of parts are out of specification limits yet make good, functional printers shows that the tolerances need to be reconsidered. Two things need to be carried out.
      i. Thorough engineering analysis to set specification limits
      ii. Exploration of statistical tolerancing to widen tolerance bands
2. **Specification Limits not set**

It can be seen in the table of the consolidated result that many of the important dimensions identified do not have set specification limits. Failures have been seen then back-tracked to a seemingly out of specification part but there can be no structure to this system of quality control unless each dimension is qualified and then inspected.

**Shaft data**

The shafts are being measured after they are put on the frame and this data does not represent the capability of the supplier but reveals how stresses are being induced into the shafts causing their cylindricity to change.

In the assembly process of the frame, these shafts are constrained in the X-axis parts 1 and 2 which in turn are subsequently loaded with components of other axes. Because of this constraint and lack of adjustment capability of the shaft end positions in some directions, the stress of all the misalignment of this assembly comes on to the shafts. This causes the shafts to bend along different planes and hence their cylindricity measure changes on assembly. Hence, in order to qualify shaft suppliers, the shafts need to be inspected before they are put onto the frame.

3. **Data inconsistency and bad hits**

Bad hits mean that the CMM made an incorrect measurement of a feature on a part that caused a highly improbable reading to be recorded. This reading when put along with other meaningful data alters the results of the data analysis. This is a serious problem and needs to be mitigated with a Standard Operating Procedure for measurement. The subsequent recommendation section shows how bad hits alter analysis.

4. **Understanding supplier’s process**

Apart from the analysis of process capability, the process control charts can also show how the process performance changed over time and reveal certain events like mean shifts or a particular time for out of specification parts. Other observations can also be subsequently made, for example, if a particular machine in the supplier’s shop is producing poor parts or a certain machinist is not being able to meet specifications. A prerequisite for performing this analysis is to understand the process flow that the supplier uses to make the parts and to ask him to document the order in which the parts were made, the machines they were made on and the machinist for each individual batch [24].

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4.4 BLOCK 3: Correlating Incoming Parts to Output

Once the intrinsic characteristics of each part and the supplier’s ability to achieve those dimensions within limits has been established, it is beneficial to understand how the inaccuracies manifest themselves in the final geometry of the frame.

4.4.1 Current Output Metric

As explained in section 4.2.1.1., the output required from the frame in terms of its geometry is:

1. Parallelism between shafts of the same axis
2. Perpendicularity between two different axes

With respect to the X-axis which we have taken up as a case study, the required output is the parallelism between the shafts. Hence, the current specification to decide whether the output frame is acceptable or not is an upper limit on the parallelism value of the shafts.

The current value for this metric was decided upon by intuitively feeling for the smoothness of traversal of the shaft mounts on the shafts. After a number of frames were measured for this, two values of parallelism were decided upon by the company to divide frames into ideal, unacceptable and non-ideal but acceptable. A colour key for the frames has been shown in Table 4 to signify the current metric.

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<tr>
<th>Key</th>
<th>Colour</th>
<th>Parallelism Specification</th>
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</thead>
<tbody>
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<td>Ideal</td>
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<td>Level A</td>
</tr>
<tr>
<td>Non-Ideal but acceptable</td>
<td></td>
<td>Level B</td>
</tr>
<tr>
<td>Unacceptable</td>
<td></td>
<td>Level C</td>
</tr>
</tbody>
</table>

Table 4: Output Metric for Frames

The parallelism specification is such that Level C > Level B > Level A

The flaws with this output metric are as follows:

1. The metric was being measured before the rest of the axes were attached to the X-axis. Under stress, even an acceptable frame could lose its parallelism.
2. The output metric was not robust. It depended on operator skill to gauge and was not an easily repeatable or dependable process.
4.4.2 Correlation between Incoming Parts and Output

Using the division based on the above mentioned levels of parallelism, the important features' dimensions were averaged by bucketing them according to the kind of frame they finally made.

Table 5 was then made in order to gauge trends and analyse how individual part features contribute to final frame geometry.

A "trend" for the purposes of this thesis is an indication of correlation between the parallelism specification levels explained in Table 4 and the average of the important features' dimensions according to specification level buckets as shown in Table 6.

As explained earlier the parallelism specification has different levels, a trend is said to exist or not exist based on how the average of the important feature's dimensions changes as the parallelism specification bucket for it changes from red to yellow to green, this can be explained using the following Table 5.

<table>
<thead>
<tr>
<th>Parallelism Specification</th>
<th>Feature average</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>red frames &gt; yellow frames &gt; green frames</td>
<td>Trend exists</td>
</tr>
<tr>
<td>Feature average</td>
<td>red frames &lt; yellow frames &lt; green frames</td>
<td>Trend exists</td>
</tr>
</tbody>
</table>

Table 5: Meaning of trend

Note that any other combination of order of feature averages is not considered a trend
<table>
<thead>
<tr>
<th>Part</th>
<th>Feature</th>
<th>Level C</th>
<th>Level B</th>
<th>Level A</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Diameter</td>
<td>9.9895</td>
<td>9.988473</td>
<td>9.989383</td>
</tr>
<tr>
<td></td>
<td>Cylindricity</td>
<td>0.00805</td>
<td>0.007882</td>
<td>0.006907</td>
</tr>
<tr>
<td>B</td>
<td>Diameter</td>
<td>9.8407</td>
<td>9.93655</td>
<td>9.977359</td>
</tr>
<tr>
<td></td>
<td>Cylindricity</td>
<td>0.1553</td>
<td>0.057644</td>
<td>0.016028</td>
</tr>
<tr>
<td></td>
<td>Cylindricity</td>
<td>0.1597</td>
<td>0.018214</td>
<td>0.019049</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
<td>9.0102</td>
<td>9.01499</td>
<td>9.00759</td>
</tr>
<tr>
<td></td>
<td>Cylindricity</td>
<td>0.1549</td>
<td>0.057644</td>
<td>0.016028</td>
</tr>
<tr>
<td>E</td>
<td>DP</td>
<td>0.3205</td>
<td>0.196314</td>
<td>0.285449</td>
</tr>
<tr>
<td></td>
<td>Parallelism</td>
<td>0.02667</td>
<td>0.019493</td>
<td>0.02602</td>
</tr>
<tr>
<td>F</td>
<td>Cylindricity</td>
<td>0.01377</td>
<td>0.017857</td>
<td>0.019269</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>19.0219</td>
<td>19.01501</td>
<td>19.01581</td>
</tr>
<tr>
<td>G</td>
<td>Cylindricity</td>
<td>0.01497</td>
<td>0.019313</td>
<td>0.018734</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>19.0162</td>
<td>19.01501</td>
<td>19.01581</td>
</tr>
<tr>
<td>H</td>
<td>DP</td>
<td>0.23967</td>
<td>0.226207</td>
<td>0.309423</td>
</tr>
<tr>
<td></td>
<td>Parallelism</td>
<td>0.02107</td>
<td>0.017936</td>
<td>0.027411</td>
</tr>
<tr>
<td>Relation I-1</td>
<td>DX</td>
<td>78.1202</td>
<td>78.13468</td>
<td>78.12231</td>
</tr>
<tr>
<td>Relation I-2</td>
<td>DZ</td>
<td>0.03213</td>
<td>0.03822</td>
<td>0.037803</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>10.8105</td>
<td>10.80822</td>
<td>10.81171</td>
</tr>
<tr>
<td></td>
<td>Width</td>
<td>10.0282</td>
<td>10.03053</td>
<td>10.02181</td>
</tr>
<tr>
<td></td>
<td>Z position</td>
<td>0.01733</td>
<td>0.015036</td>
<td>0.01536</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>10.0072</td>
<td>10.01329</td>
<td>10.02122</td>
</tr>
<tr>
<td>L</td>
<td>Y position</td>
<td>10.0072</td>
<td>10.01329</td>
<td>10.02122</td>
</tr>
<tr>
<td></td>
<td>Z position</td>
<td>0.01733</td>
<td>0.015036</td>
<td>0.01536</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>10.0072</td>
<td>10.01329</td>
<td>10.02122</td>
</tr>
<tr>
<td></td>
<td>Cylindricity</td>
<td>0.01733</td>
<td>0.015036</td>
<td>0.01536</td>
</tr>
<tr>
<td>Relation M</td>
<td>K/L relation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relation N</td>
<td>K/L relation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relation O</td>
<td>C/D relation</td>
<td>0.32</td>
<td>0.188187</td>
<td>0.286788</td>
</tr>
<tr>
<td>Relation P</td>
<td>F/G relation</td>
<td>0.2379</td>
<td>0.22692</td>
<td>0.307737</td>
</tr>
</tbody>
</table>

**Key**
- not measured on the CMM currently
- Measured on the CMM currently and trend does not exist
- Features where trend exists need other measurements to be calculated

These columns highlighted in pink show a consistent increase or decrease in value over the three parallelism levels hence they follow a trend.

All other feature dimensions that are shown in white had no specific trend as laid out in Table 5.

The dimensions in green were not being measured on the CMM, hence existence of any trends in them could not be identified.

The dimensions in orange needed other dimensions to be measured as an input for their calculation and hence no trend analysis could be performed.

**Table 6: Correlating Incoming Parts to Output**
4.4.3 Block 3: Outcome

Figure 7: Framework Overview

The third block of the framework as explained above is consolidated and defined as follows:

**Step 1: Identify and analyse current output metric**
This step involves identifying the current output metric, which in this case was the parallelism of the shafts of the X-axis. Then the current output metric should be analysed on the basis of its repeatability and accuracy. The current output metric relies heavily on operator skill to be used effectively and thus, it is not a robust solution.

**Step 2: Correlate incoming parts to output assembly**
Based on the existing output metric, average each individual important feature identified after the incoming parts analysis block was used into buckets created by the metric.

**Step 3: Look for trends and draw conclusions**
The existence of a trend can identify the problematic feature.

This procedural steps of Block 3 of the framework are shown in Figure 28.

Figure 28: Block 3 of Framework
Key Findings

1. For almost all of the important features identified, there exists no correlation or trend between the incoming part and output frame parallelism level. This suggests the following:
   a. The current output metric has flaws and is giving misleading results.
   b. The assembly process puts in variations that causes final assembly to be out of specification. If this is true, then there are two sources of variation, the dimensions of the incoming parts themselves and the variations introduced through the assembly process. This would require corrective action on both fronts in order to solve the problem.

2. Since even out of specification parts on average make acceptable or even ideal frames, the tolerances need to be reconsidered and there is potential for savings.

3. The shafts show trends over the output metric buckets for cylindricity and diameter both. This suggests the following two things:
   a. This component and its supplier need to be reviewed.
   b. The incoming shafts are in spec. but they are being stressed through assembly.
4.5 Final Framework and Description

Figure 29 shown below summarises the procedural steps involved in each block of the framework and lists out the outputs obtained at the end of each stage.

**Figure 29: Final Framework and Outcomes**
CHAPTER 5: RECOMMENDATIONS BASED ON FRAMEWORK

Using the whole framework procedure, certain key findings were identified as outcomes of each block. Through these findings, recommendations were made and in this section, they are elaborated upon individually.

5.1 Block 1 Recommendations

At the end of Block 1, we obtained a break-down of subassembly and parts of the machine along with a list of the important features and relationships of the part.

5.1.1 Features to Inspect

Once the important feature list for the X-axis was populated, it was found that the dimensions shown in green in Table 7 were not being measured on the CMM and hence, the relations shown in orange could not be calculated either. The important features and relationships not being measured here have been listed with their corresponding dimension on the part drawing on the following page.

<table>
<thead>
<tr>
<th>Part</th>
<th>Feature</th>
<th>Corresponding to drawing</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Diameter</td>
<td>hole 1 diameter</td>
</tr>
<tr>
<td>K</td>
<td>Z position</td>
<td>Z₁</td>
</tr>
<tr>
<td>L</td>
<td>Y position</td>
<td>X₂</td>
</tr>
<tr>
<td></td>
<td>Z position</td>
<td>Z₂</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>Hole 2 diameter</td>
</tr>
<tr>
<td></td>
<td>Cylindricity</td>
<td>Hole 2 cylindricity</td>
</tr>
<tr>
<td>Relation M</td>
<td>Hole 1/4 Z</td>
<td>ΔZ</td>
</tr>
<tr>
<td>Relation N</td>
<td>Hole 1/4 Y</td>
<td>ΔX</td>
</tr>
</tbody>
</table>

Table 7: Features being missed in X-axis

In order to understand why it is important to measure these dimensions on the CMM, their contribution to final frame output needs to be explained.
Figure 11: Important Dimensions of Part 1 and Part 2

The final assembly involves two shafts where one end of both the shafts goes into hole 1 and hole 2 of Part 1 and the other end of the two shafts go into corresponding holes in Part 2. This can be depicted schematically by the following figure.
The output parallelism between the two shafts is hence governed by the characteristics of the two holes, hole 1 and hole 2 on both the parts 1 and 2. The features not being measured are exactly these. The following Table 8 shows the feature not being measured and its importance for final output geometry.

<table>
<thead>
<tr>
<th>Corresponding to drawing</th>
<th>Importance to Final output parallelism</th>
</tr>
</thead>
<tbody>
<tr>
<td>hole 1 diameter</td>
<td>This is the seat of the shaft and if this is out of specification, then there will be either a play or interference causing parallelism between shafts to be affected</td>
</tr>
<tr>
<td>Z₁</td>
<td>This is the height of Hole 1 from the origin for Part 1, this must correspond to the mating hole 1 from the opposite Part 2 in order to ensure alignment of shafts in that axis. Any variation from this specification limit will lead to non-parallel shaft assembly</td>
</tr>
<tr>
<td>X₂</td>
<td>This is the distance of hole 2 from the origin for Part 1, this must match exactly with the corresponding hole on Part 2 in order to ensure shaft alignment in that axis.</td>
</tr>
<tr>
<td>Z₂</td>
<td>This is the height of Hole 2 from the origin for Part 1, this must correspond to the mating hole 1 from the opposite Part 2 in order to ensure alignment of shafts in that axis. Any variation from this specification limit will lead to non-parallel shaft assembly</td>
</tr>
<tr>
<td>Hole 2 diameter</td>
<td>Just like Hole 1, it needs to be in specification limits to avoid play or interference between shaft and hole</td>
</tr>
<tr>
<td>Hole 2 cylindricity</td>
<td>The shaft sits inside the hole to a certain depth, in case the hole loses its circularity on increasing depth, the shafts will go misaligned and the parallelism specification will not be met.</td>
</tr>
<tr>
<td>ΔZ</td>
<td>This is the difference in Z height between two holes on the same part. It needs to be zero for both shafts to have end points on the same line perpendicular to the shaft axes.</td>
</tr>
<tr>
<td>ΔX</td>
<td>This is the difference in X position as shown in the figure between hole 1 and hole 2 on Part 1, this measure must match with the corresponding measure on Part 2 to ensure shaft alignment and in turn parallelism.</td>
</tr>
</tbody>
</table>

Table 8: Importance of features to be inspected

In the same way, when this framework is used for other axes and parts of this printer, more such dimensions will come to light and will be added to the list of features to be inspected.
5.1.2 Logical Datum Allocation

The datum specification on a drawing should follow the logic of correctly depicting all the important features of a part[33]. The datum allocation effectively dictates how machining of the part takes place and hence also its inspection procedure. Thus, it is important to assign datum to part drawing keeping these things in mind.

An example of a drawing of a part of the X-axis, with its previous datum allocation and new datum allocation based on the sequence of machining required and the important features required on the part is shown in Figure 30. The old and new part drawings are shown below with their datum allocations highlighted in yellow.

In the old drawing of the part, the datum B was the axis going along both the holes as shown above. This makes sense for the designer to show a concentricity specification to the manufacturer, but as a feature it is hard for a machinist to measure and ensure. The second thing about this part drawing is that the origin is on the intersection of plane datum A and the front face of the part. Since the front face has to be machined well in order to get the required origin, this machining step could be used in a better way as shown in Figure 31, which is the new drawing of the part.
In the new datum allocation procedure, the centre axis is drawn to depict that the part is symmetrical so that the machinist has a simpler drawing. The bottom face is made datum A and the front face is made datum B. The corner at the intersection of these two faces becomes the origin and all dimensions are marked with this as reference. In order to ensure the alignment of centre axes of the two holes shown, the holes are given a positional tolerance with respect to the two datums A and B.

Like the datum re-allocation has been done for this part, it is recommended that the same procedure be followed for all other sourced machine parts of the printer.
5.2 Block 2 Recommendations

On analysing the part data collected by measurement on the CMM, a lot of important observations were made regarding the supplier and his process. A thorough review of suppliers needs to be carried out and the following section describes what the key points for discussion are. Along with this, the inspection procedure needed to be standardized and data collection made uniform. Actionable recommendations to achieve both of these are given below.

5.2.1 Supplier Review

A controlled process that does not meet target specifications was a recurring theme in the supplier analysis. It is imperative to investigate this in a more extensive way.

5.2.1.1 Process Capability and Costs

It was seen that in most cases the $C_{pk}$ value was negative or very low showing that the supplier’s ability to meet target specifications is very low. Even though the normal probability plot showed a controlled process, if the $C_{pk}$ values are low, then it could mean that the sourced machine parts are costing more than they should be. A tighter tolerance requires better machine tools, better inspection techniques and even better operators. The costs of all of these components adds on to the cost of the sourced parts. If the supplier is charging these higher costs and yet not meeting target specifications, then there is an opportunity for cost savings.

5.2.1.2 Supplier’s Production Process and Inclusion

The $C_{pk}$ measure is a method of gauging supplier capability numerically, but to conduct a thorough analysis of what is the problem area, some additional steps need to be taken. Peter Pylipow lists out these steps very succinctly in his article, “My Supplier’s Capability Is What?” It is a good idea to go and understand the complete process of the supplier and list out all the inherent steps in it and the incoming parts should be marked according to the machinist and machine they are coming from and also with the order in which they were made.[24] This is a way to make Process Control Charts more meaningful so an analysis of trends can also be performed. Also, the measuring equipment that the supplier uses should be as accurate as the measuring equipment that the company is using for incoming inspection[24]. Another important point is to involve a dependable supplier into the process of design to a degree. Also, datum allocation and engineering drawings are a method of
expressing the important dimensions and functional requirements of a part to the supplier. The supplier’s involvement in this process would be very beneficial.

5.2.2 Inspection and Analysis Process

The basis of generating measurement data for analysis and qualification of parts is the inspection procedure on the CMM\(^4\). The uniformity and thoroughness of this process dictates the efficacy of the starting point of the subsequent analysis.

5.2.2.1 Standard Operating Procedure for CMM

The need for a standard operating procedure was seen during the analysis process when the effect of outliers was seen on the probability plots. An example of this effect is shown in Figure 32 below.

![Figure 32: Effect of bad hit on CMM](image)

With bad hit

Without bad hit

Note how the removal of one extreme outlier changes the normality and the normal probability plot of the data set

A “bad hit” on the CMM is a term used to signify a lapse in the measurement process of the probe that returns an incorrect value. As it can be seen above, the presence of such an aberration can depict a normal, controlled process as out of control. This situation could easily be avoided if there is an outlier detection process in place to identify and reject readings that are for certain caused by bad hits.

\(^4\) Product Name: TESA Micro-Hite 3D 454 Dual

Model Number: 03939269

Specifications: \(\text{MPE}_p = 3\) microns

Measuring Volume = 440 x 490 x 390 mm

Manufacturer: TESA Group
Another problem that can be solved by a standard operating procedure is that of inconsistency of data. When data is not uniform throughout then running the process on Excel or other such softwares on a loop becomes very difficult and hence much more time consuming than it already is.

Hence, a standard operating procedure would eradicate these problems of bad hits and inconsistent data and will ensure the uniformity of data for subsequent analysis. One example of the usefulness of such a procedure is the case of the outliers shown in the previous plots. A simple software setup that rejects logging of readings in case they are beyond a reasonable limit and sets a call out to the operator to reset the measuring routine would be very beneficial. Other features of the procedure could be a set measurement path for all parts across different batches and also a calibration check on the CMM before a new batch of measurement to ensure accuracy.

5.2.2.2 Data Acquisition and Analysis Software

In the current system at NVBOTS, the incoming parts are inspected but that measurement data is not used to qualify parts. One of the reasons for this is that the whole process of analysing the part data is very cumbersome. There is no direct method of viewing a process chart in real time, instead, the CMM output needs to be cleaned, then compiled into EXCEL and then analysed. This post facto analysis of part data allows even the defective parts to go onto the assembly process and after subsequent value addition, they have the potential of causing quality issues in the final machine. One way to get around this problem is to make use of an integrated quality control and statistical analysis software, which not only works as a real time monitoring and quality check station but it is also a powerful tool for analysis and an efficient data management system.

A WebEx session was held at NVBOTS with a software provider called InfinityQS for their Proficient software package. It was held to check if this software can solve NVBOTS’s specific requirements and the results were highly satisfactory. Not only did the software have extensive capabilities, it could also manage inconsistent data and act as a data logger for sub assembly testing. Though this software would make sense for NVBOTS only once when they start producing at scale, the need for such a software can already be felt.

Hence, it is recommended for the company to use Block 2 of this framework on all their axes in order to qualify suppliers, standardise their operating procedures and explore more extensive Quality Control techniques.
5.3 Block 3 Recommendations

In Block 3 of the framework, the output of the final X-axis assembly was identified as the parallelism of the two shafts. NVBOTS currently has the metric divided into three buckets as shown below.

<table>
<thead>
<tr>
<th>Key</th>
<th>Colour</th>
<th>Parallelism Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td></td>
<td>Level A</td>
</tr>
<tr>
<td>Unacceptable</td>
<td></td>
<td>Level B</td>
</tr>
<tr>
<td>Non-Ideal but acceptable</td>
<td></td>
<td>Level C</td>
</tr>
</tbody>
</table>

Table 4: Output Metric for frames

When the parallelism specification of these output assemblies were correlated back to the dimensions of their inherent parts, it was seen that there was a trend only in the cylindricity of the shafts. Hence, the conclusions drawn were that the output metric is not reliable and needs to be changed. Secondly, since out of specification parts were making good final assemblies, the tolerance limits were questionable and needed further consideration.

5.3.1 Robust Output Metric

The output metric needs to be representative of the required geometry of the final part and should also be repeatable and easy to measure. The final parallelism of the output shafts is the single most important output of the assembly, yet, it has been seen that this alone cannot capture everything.

One proposed method is to calculate the force that is required to move the shaft mounts on the shafts and obtain an upper limit of this force corresponding to a maximum degree of misalignment of shafts. Along with this, an extensive DOE should be done to calculate the effect of misalignment of shafts on the final part quality and obtain a maximum value of misalignment that produces an acceptable part. Shabbir's thesis provides a very actionable framework for using DOE and should be referred to for this exercise[11].
A combination of these two important factors should make the final output metric. This is an undertaking of immense importance, and could be a possible project undertaken by future teams.

5.3.2 Tolerance Analysis

Through the consolidated result of supplier analysis shown in Table 3, the following observations were made.

1. Tolerance and specification limits for many specifications on parts were not set.
2. The Cpk values were very low, this could indicate to both, the supplier’s inability to meet specification limits because the limits are too tight or a mean shift in the supplier’s process.

Also, it has been seen that the acceptable printers are being produced by out of specification parts, which is a direct indication of the fact that the current tolerance limits need to be re-evaluated.

The first step to rectify this problem should be to using engineering design and analysis to come up with tolerance limits for all the important features and dimensions and to work on this project with the supplier so that it can be ensured that they are met. Unless the supplier’s control limits can allow him to meet the specification limits, the same situation will sustain where the supplier’s process stays in control, yet specifications are not being met.

Once this is done and the supplier’s capability is known with a certain degree of confidence and the production volumes have increased, statistical tolerancing should be explored as a method of ensuring quality while saving on costs.

In the subsequent section, an outline is presented on how to incorporate statistical tolerancing into the design of a product and a software package is also introduced to achieve the same.

5.3.2.1 Statistical Tolerancing

In tolerance analysis, the critical dimensions that need to be controlled are set up with tolerance limits through engineering design and the variation of all such dimensions stacks up and causes a degree of variation in the non-toleranced dimension on the part. There are two ways to visualise this stack-up.
Worst Case tolerancing is an approach that determines the worst case of variation for that dimension, i.e. the maximum amount of variation and then adjusts the remaining tolerances in order to limit it[34]. This makes all these tolerances extremely tight and hence costly and difficult to machine. Statistical tolerancing, on the other hand, assumes the most likely stack up of variation by adjusting for the normality of the manufacturing process; each dimension is assumed to be a mean with a standard deviation and the possibility that some over-sized dimensions will balance out other under-sized dimensions is acknowledged[34]. This approach allows the tolerances of all other dimensions on the part to be relaxed and hence makes the manufacturing process more cost-effective and machining easier.

Once there is enough part measurement data that can ascertain the supplier’s process means and standard deviations with a degree of statistical significance, statistical tolerancing techniques should be strictly followed. This technique also involves a sensitivity analysis of the contribution of each part feature dimension to the final output dimension. The SM thesis by Terry [30] as an LFM student under Dr. Dan Whitney as advisor is a very descriptive manual on performing such statistical tolerancing analysis on existing designs.

Whitney’s book on mechanical assemblies[33] is a very good source for a step by step framework for tolerance analysis applied to an existing design with an established output metric that needs to be controlled. Fischer’s book on tolerancing and stack-up [34] provides a detailed explanation of how to incorporate assembly variations into tolerance stack up and tolerance design.

A statistical tolerancing project would be a very helpful proposition for NVBOTS and is recommended as a potential project for future MEngM teams.

5.3.2.2 3D Statistical Tolerancing Software

As statistical tolerancing problems are taken to the second and third dimensions, the analysis becomes too complex and cumbersome to be done manually[30]. Even generic softwares like Excel become too time consuming and inadequate for such computation.
These complex problems can be solved with the use of specialized statistical tolerancing software. CETOL 6σ developed by Sigmetrix is one such software[35]. It has a separate capability for one dimensional analysis and an extensive feature list regarding multi-dimensional tolerancing including easy modelling, sensitivity analysis and lucid reporting tool. This software can also be integrated with existing CAD software. The level of functionality that this software provides comes at a price and it would make sense for NVBOTS to invest in it only once they have thoroughly qualified their suppliers and have developed a robust output metric.
6 CHAPTER 6: STRATEGY

6.1 Competitive Strategy and Platform Effects

All companies and organizations work in a competitive space and they are trying to achieve advantage that is sustained, hard to imitate and dynamic in the sense that it evolves and allows them to not only maintain their stance but also grow. One way of achieving this through practices of operational effectiveness in order to end up being more profitable than their competitors but this approach has a limiting point to the returns that one can achieve. In this approach, companies try to outperform in existing drivers of their industry and fall in the rut of competitive convergence[36]. Competitive convergence is a situation in which there is not enough differentiation in the product offerings of different suppliers and their primary way of earning more than their competition changes to more efficient higher volume production.

The correct way to do it is to have a strategy in place that allows all the aforementioned criteria of competitive advantage to be attained and to integrate that with efficient production and operational activities[36]. This way success becomes a function of the company’s focus segment, value proposition and execution capabilities. NVBOTS has a unique value proposition when compared to the rest of the additive manufacturing space. They need to align their product to the market they are targeting, understand the quality requirements they have to achieve and model their operations around it in order to maintain customer satisfaction and ensure cost-effectiveness.

NVBOTS is currently a product based firm, to explore new revenue streams that become viable on scaling up, it must consider inculcating a platform approach in its business model. The sorts of businesses that provide a product or service that initiates the interaction between two parties such as Uber that connects car owners and commuters create two-sided markets and such businesses are then known as platforms[37]. Platforms are served by network effects that basically make the service more valuable to both, its users and providers as the number of people participating in it increases[38]. Platform providers have the important decision to make regarding which side to monetize, the service providers, the service users or both[37].
We see all around us with examples of Facebook, Uber and the likes that platform businesses lend themselves to opportunities of exponential scale-up and value capture if the correct side is monetized. Companies like Lego and Barbie bring out an interesting perspective about what can entail a platform and bring about positive network effects. Since it is one of the best ways to scale up, all industries are thinking about it including manufacturing.

NVBOTS is at an advantage in this space because it is a startup and hence nimble in its approach towards strategy. Also, it has certain features in their product that make it highly conducive for becoming a platform. NVBOTS makes the first fully automated, cloud connected 3D printer with a focus on the education market. They push high school academia to use 3D printed models to explain scientific concepts. For example, a miniature model of a four stroke engine can be used to demonstrate the inner workings of an automobile engine.

As they expand their customer base, they can use their cloud to link those existing customers, much like Facebook has friends, and then they can open the floor up for targeted pitching by say, plastic print filament suppliers or agencies that come up with CAD data for more educational models like the engine. Another avenue could be to open their portal to advertisement from related sources such as education based module writers etc. As the portal on the cloud is accessed by teachers of schools, there is a large, pre-existing and collaborative network open to network effects. By being cloud based, automated and having a portal for users to collaborate on, NVBOTS can proactively include features in their product to accommodate platform approaches. This is easier for them to do as a start-up than it will be for a large player in 3D printing like Stratasys to do.
7 CHAPTER 7: CONCLUSION

7.1 Summary and Future MEngM Projects

The purpose of this project from the onset was to look at NVBOTS as a manufacturing startup that was in the phase of a production scale-up and to make recommendations that would allow them to do so while maintaining quality and also managing expenditure. There were many avenues where the need of a formal study and addition of structure to the system was felt. None of these avenues were more pressing or impactful than the first point of the value chain. This point being the inspection and quality management system at NVBOTS. A complete study of this juncture required a thorough analysis of the printer and its components, the suppliers of the sourced machine parts and of course, the inspection and data collection system itself.

In order to provide a structure to this system and develop a lasting methodology for the company to follow in the future, it was important to develop a framework that is extensive in the scope of its analysis but detailed in its ability to surface problems and provide recommendations.

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INCOMING PARTS ANALYSIS
SUPPLIER ANALYSIS
CORRELATING INCOMING PART QUALITY TO OUTPUT
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Figure 7: Framework Overview

The three blocks of the developed framework achieve exactly this. The recommendations that have come out of this dedicated analysis are instructive of both, short term and long term action. There are certain things that are of paramount urgency and others that draw from industry’s best practices and will prove useful once the scale of production increases.
Specific project suggestions for future MEngM teams are listed as follows.

**Formulating a Robust Output Metric**

As explained in section 4.4.1 and section 5.3.1, the current output metric is not highly dependable and hence there is a possibility of rejecting good frames or accepting bad ones. Both of these cases are unacceptable as the company scales up in the future. Shabbir’s thesis lays out a very engaging and descriptive framework for the use of Design of Experiments[11]. His directives need to be followed to perform an extensive DOE analysis for correlating the current output metric to the final printed part quality and machine life. Once this is done, a combined output metric should be formulated that incorporates both of these features.

**Statistical Tolerancing**

The key findings highlighted in section 5.3.2 necessitate an extensive study of the tolerance limits and implementation of statistical tolerancing. Once suppliers are qualified through the use of this framework and a robust output metric has been formulated, use of statistics in tolerancing can prove to be instrumental in cost saving while maintaining part quality. Finally, a complete layout of the framework, its procedural steps and recommendations for NVBOTS to follow are shown in the concluding Figure 33 of this thesis on the next page.
7.2 Final Framework and Recommendations

**BLOCK 1 PROCEDURE**

**Step 1:** Break Machine into Subassemblies and components  
**Step 2:** Identify dimensions of these components that contribute to the final output  
**Step 3:** Measure these dimensions on the CMM for data collection and analysis

**BLOCK 1 OUTCOME**

**Output:** Break-up of machine into subassemblies and parts  
Identification of important features contributing to geometry  
**Recommendations:** 1. Features to be inspected  
2. Logical Datum Allocation

**BLOCK 2 PROCEDURE**

**Step 1:** Consolidate and clean collected CMM data  
**Step 2:** Analyse data for process control and process capability  
**Step 3:** Take action with suppliers and team

**BLOCK 2 OUTCOME**

**Output:** Supplier process control and process capability charts  
Consolidated table of data, specification limits and control limits  
**Recommendations:** 1. Supplier review and understanding his process  
2. Tolerance analysis and statistical tolerancing  
3. Data acquisition and analysis software  
4. Standard operating procedure for CMM

**BLOCK 3 PROCEDURE**

**Step 1:** Identify and analyse current output metric  
**Step 2:** Correlate incoming parts to output assembly  
**Step 3:** Look for trends and draw conclusions

**BLOCK 3 OUTCOME**

**Output:** Correlation table between incoming parts and output geometry  
**Recommendations:** 1. Robust output metric  
2. Tolerance analysis and statistical tolerancing

**Figure 33: Final Framework and Recommendations**
REFERENCES


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[26] G. Wetherill, Sampling Inspection and Quality Control, Second. SPRINGER-SCIENCE+ BUSINESS MEDIA, B.V.


