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Process Capability in a Computer Integrated Manufacturing Cell

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PROCESS CAPABILITY IN A COMPUTER INTEGRATED MANUFACTURING CELL

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PROCESS CAPABILITY IN A COMPUTER
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I dedicate this thesis to my parents, Charles and Karen Austin, who have always given me the support I need. I also dedicate this work to the Architecture and Manufacturing Sciences department, as well as the entire faculty, staff, and students who made this research possible.

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With the rise of automation in traditional manufacturing processes, more companies are beginning to integrate computer integrated manufacturing (CIM) cells on their production floors. Through CIM cell integration, companies have the ability to reduce process time and increase production. One of the problems created with CIM cell automation is caused by the dependency the sequential steps have on one another. Dependency created by the previous step increases the probability that a process error could occur due to previous variation. One way to eliminate this dependency is through the use of an in-process measuring device such as a Renishaw spindle probe used in conjunction with a computer numerical control (CNC) milling machine.

Western Kentucky University (WKU) utilizes a CIM cell in the Senator Mitch McConnell Advanced Manufacturing and Robotics laboratory. The laboratory is located in the Architectural and Manufacturing Sciences department and gives students the opportunity to learn how automated systems can be integrated. The CIM cell consists of three Mitsubishi six-axis robots, a Haas Mini-mill, a Haas GT-10 lathe, an AXYZ, Inc. CNC router table, 120 watt laser engraver, an Automated Storage and Retrieval System (ASRS), material handling conveyor, and vision station. The CIM cell functions throughout the curriculum as a means for applied learning and research. The researcher used this CIM cell in order to determine if an in-process measuring device, such as the Renishaw spindle probe, had the ability to affect process capability.

The researcher conducted the study to see if an in-process measuring device can be integrated into the CIM cell located in the Senator Mitch McConnell Advanced Manufacturing and Robotics laboratory to eliminate compounding variation. The researcher discovered that through the use of a Renishaw 40-2 spindle probe used in conjunction with a CNC Haas Mini Mill, process capability has the potential to be improved in a CIM cell by accounting for compounding variation present in the process.

Introduction

As globalization expands and new technology spreads, companies look to many different ways to expand their business through the use of new innovative technologies. One way that companies are remaining competitive is through the use of automation in their manufacturing processes. With increased automation, companies have the potential to improve upon one key business metric; increased production. Companies are experiencing increased production because automation has the ability to save time, and reduce scrap/rework. One downfall of the implementation of automation is that companies fail to fully integrate the automation into the entire system. Instead, the automation functions as an island in the manufacturing process that can lead to problems such as bottlenecks and inefficient work flow. Since the automation is not fully integrated, the company will be unable to reach the full potential of their automated equipment. One way to combat islands of automation is through the use of Computer Integrated Manufacturing (CIM). A CIM cell allows the integration of automation into the entire manufacturing process from ordering raw materials to the production of final goods. Process integration eliminates broken processes and is crucial to optimizing the manufacturing environment (Saygin, 2004). By fully integrating the automation, the company has the potential to further improve production and remain competitive (Zhou & Chuah, 2002).

CIM has increased in popularity as companies begin to realize the full potential CIM cells have to offer. Along with seeing the benefits CIM cells have to offer, the increase in user friendly technology has also increased the prominence of integrated systems. These integrated systems allow companies to use computer operating systems to control manufacturing processes. One specific example is computer aided design (CAD) and computer aided manufacturing (CAM) software that has become a vital part of integrating computer numerical control (CNC) machining centers into CIM cells. These two software packages have increased the user friendliness, making CNC integration a practical approach for businesses both small and large. Overall, improved integration software will allow more companies to use CIM cells during their manufacturing processes (Saygin, 2004).

Universities are seeing the rise of CIM cells in manufacturing companies and are realizing the need to train students entering the field of engineering and manufacturing on CIM cell implementation. Many universities are actually implementing CIM cells into their laboratories so students have the ability to learn about a CIM cell in a hands-on manner. These CIM cells show students robots, programmable logic controllers (PLC), CNC equipment, and computers integrated as one complete manufacturing process. Western Kentucky University (WKU) is a prime example of a university that has implemented a CIM cell into their Senator Mitch McConnell Advanced Manufacturing and Robotics Laboratory. The laboratory is located in the Architectural and Manufacturing Sciences department and gives students the opportunity to learn how automated systems are integrated. The CIM cell consists of three Mitsubishi six-axis robots, a Haas Mini-mill, a Haas GT-10 lathe, an AXYZ, Inc. CNC router table, 120 watt laser engraver, an Automated Storage and Retrieval System (ASRS), material handling conveyor, and vision station. The CIM cell functions throughout the curriculum as a means for applied learning and research.

One of the main concerns with a CIM cell is that, due to complete automation, each step is dependent on the previous step. Dependency created by the previous step increases the probability that a process error could occur due to previous variation. Throughout the CIM cell, each step in the process has a set amount of variation introduced by the various inputs into the final product. Some of the inputs are; material, operation, tooling, equipment, and program with each contributing to the variation and process capability. The different components in the CIM cell introduce these inputs. Integrated components in the CIM cell such as the ASRS, the ASRS robot, and the CNC vice all introduce variation into the process.

The purpose of this research study was to determine changes in process capability in a CIM cell through the manufacturing of a set of aluminum blocks. Process capability was analyzed amongst six sets of data: initial process capability X, initial process capability Y, final process capability without in-process measuring device X, final process capability without in-process measuring device Y, final process capability with in-process measuring device X, and final process capability with in-process measuring device Y. Process capability is used to measure how close a process is operating within specification requirements. As the variation decreases within a process and the measurements become closer to the nominal value, the overall process capability will increase. This results in a process that produces fewer defects due to less variation present in the process (Chen, Lai, & Nien, 2010).

Problem Statement

In a CIM cell, each process is dependent on the previous step and the dependency limits process capability. The previous step limits process capability due to the increased variation that each step introduces. More variation introduced into the process causes the process capability to continue to decrease and the dispersion to increase. In the process capability study, a square aluminum block measuring 130mm X 130mm had a square pocket measuring 25mm X 25mm milled in the center of the work piece by a Haas CNC Mini-Mill. The process contained multiple steps leading up to the milling of the pocket that increases variation and each step had the potential to diminish process capability. An initial process capability established by the manufacturer was present due to the variation that existed dimensionally in the aluminum blocks both in length and width. The researcher believed that theoretically, the process capability should decrease from the manufacturer's process capability as the CIM cell completed each sequential step.

The process in the CIM cell started out with the ASRS that holds the aluminum squares that had the square pocket milled in the center of the piece. The aluminum squares used in the study were placed on pallets that were located on the ASRS. Each pallet used six pins to locate the square aluminum blocks. Just the ASRS alone introduced considerable variation while the aluminum blocks remained stationary. Location of the pallets on the ASRS, location of the pins on the pallets, and pallet size all introduced variation. The next step in the process involved the ASRS robot moving the pallet and the square aluminum block to the buffering stage. The ASRS robot used a sliding arm to slide under the pallets and pick up the pallets from the ASRS. Once the ASRS robot had picked up the pallets, the ASRS placed the pallets on four locater pins located at the buffering station. Simply moving the aluminum block from the ASRS to the buffer station introduced a considerable amount of variation. The ASRS robot introduced variation when it picked up the pallet due to programming deviations and normal operating tolerances of the ASRS robot. The location of the four alignment pins on the buffer station and the four alignment holes on the bottom of the pallets both added to the variation as well. After the ASRS robot placed the pallets on the buffer station, the Mitsubishi Robot then grabbed the aluminum block using a set of grippers. The robot then moved down a linear slide to place the aluminum part in the vice on the CNC milling machine. Using the grippers, the robot placed the part in the CNC vice against two positive stops. The robot then released the part and the vice closed on the part while the robot returned to the home position. The process of moving the aluminum blocks to the vice also increased the variation in the CIM cell. The robot's gripper and linear slide already contained a tolerance established by the manufacturer that automatically introduced variation. The location of the vice and the position of the block in the vice also added variation. The vice could be located in the part loading position, but due to the variation in the CNC machine, the vice was located in a slightly different place every time. The previous stated variation is not a comprehensive list of every form of variation that the CIM cell introduced, but the amount of variation covered shows how each process added to an automated process introduces new variation and decreases process capability (Hart, 1992).

The goal of the study was to measure process capability as the aluminum blocks were processed in the CIM cell to determine changes in the initial process capability, final process capability without the in-process measuring device, and final process capability with the in-process measuring device. To eliminate variation, the study proposed the use of a Renishaw 40-2 spindle probe to function as the in-process measuring device for the CIM cell. The Renishaw probe measured the coordinate positioning of the work piece to determine where the CNC milling machine created the internal pocket. Even though the entire process consisted of integrated automated steps, the spindle probe allowed the CNC machine to make different adjustments for each work piece. Instead of relying on the set home position of a location pin acting as a positive stop to position the part in the vice, the spindle probe physically measured the location of the work piece. Physically measuring the part location with the Renishaw probe eliminated positioning errors caused by the pallets, ASRS, ASRS robot, buffer station, Mitsubishi robot, linear slide, and CNC vice.

Purpose of the Research

The researcher conducted a case study to determine the changes in process capability. The study attempted to determine if the integration of the Renishaw spindle probe functioning as an in-process measuring device had the ability to eliminate variation in a CIM cell. If variation is eliminated through the use of the in-process measuring device then this presents the opportunity to improve final process capability. The ability to eliminate variation with the use of an in-process measuring device had the potential to shed new light on the topic of process capability in a CIM cell. Conventional teaching says that increasing final process capability over initial process capability is not possible due to the increased variation that each step in the process introduces. Since the whole process consisted of automated process execution, errors such as misaligned part placement had a direct effect on the next step. Each time increased variation occurs process capability suffers. Process capability is determined by the previous steps of the process according to *The Six Sigma Handbook, a Complete Guide for Green Belts, Black Belts, and Managers at All Levels*. The information gained from the process capability study has the potential to change the traditional definition of process capability. The knowledge gained on process capability will be useful to companies who have integrated CNC machining centers into their CIM cells. The study showed if the integration of an in-process measuring device had the capability to make a difference to the process capability (Pyzdek & Keller, 2010).

By increasing process capability, the company has the potential to reduce scrap and rework, that will save time and increase profits. The Renishaw spindle probe has the potential to save time when integrated into a CIM cell even though using the probe adds an extra step in the process. Time can be saved by preventing extra work from being dedicated to scrapping parts or investing time into reworking the work piece. The amount of time the probe can save increases with the increased complexity of the manufactured part due to the longer machine time invested in the component. Some parts can take several hours to machine from raw material to final product making it crucial to prevent scrapping of parts after a large amount of time has been invested into the machining process. Improving process capability is a vital part to Six Sigma so improving process capability in a CIM cell will also be beneficial to companies who are trying to increase their Sigma level. Reaching Six Sigma requires reducing defects to 3.4 defects per million opportunities. There are two ways to decrease the amount of defects in a process: the company can extend the upper and/or lower control limit or the company can improve the process capability (Pyzdek & Keller, 2010).

Hypothesis

$H_0 1$: There was no difference between initial process capability and final process capability without the use of the in-process measuring device.

$H_1 1$: There was a difference between initial process capability and final process capability without the use of the in-process measuring device.

$H_0 2$: There was no difference between initial process capability and final process capability with the use of the in-process measuring device.

$H_1 2$: There was a difference between initial process capability and final process capability with the use of the in-process measuring device.

$H_0 3$: There was no difference between final process capability with the in-process measuring device and final process capability without the in-process measuring device.

$H_1 3$: There was a difference between final process capability with the in-process measuring device and final process capability without the in-process measuring device.

The study's objective was to measure changes in process capability to determine the capability to eliminate variation in a CIM cell through the use of an in-process measuring device.

Assumptions

The researcher made several assumptions about the process capability study in order to prevent the study from becoming overbearing. Due to the capabilities of the measuring equipment available in the Architecture and Manufacturing Sciences (AMS) department, the study assumed that the Mitsubishi robot, the Haas CNC Mini Mill, the ASRS, and the Renishaw 40-2 spindle probe were operating within the manufacturer's supplied tolerances.

Another assumption the study made directly linked with the physical make-up of the aluminum blocks. Even though each aluminum block contained different physical properties, the researcher made the assumption that the differences were insignificant.

The researcher assumed that the differences would not affect the Haas CNC Mini Mill's ability to machine the pocket in the aluminum block while maintaining consistent tolerances throughout the entire machining process.

The study also assumed that normal tool wear would be minimal. When two materials rub together, the friction created removes material from both objects. Since the milling bit is made of high speed steel and the blocks used in the study were aluminum, the tool wear should be minimal. Tool wear would be more significant if the study machined a harder material like steel or cast iron. Since the tool wear was assumed to be minimal, the Haas CNC Mini Mill was assumed to be able to maintain consistent tolerances for the aluminum blocks while using a ¼" HSS four-fluted end mill. The end mill was swapped out every 25 parts or whenever excessive tool fatigue occurred.

The last assumption made in the study pertained to the means used to gather the data for the process capability study. The study assumed that the metric Mitutoyo caliper had the ability to continuously make accurate measurements to one hundredth of a millimeter. The researcher assumed the consistency of the Mitutoyo caliper to eliminate the possibility that the caliper could induce inaccurate measuring errors into the study. The study assumed this based on Mitutoyo's supplied manufacturer specifications that stated the accuracy of their digital caliper to be to one hundredth of a millimeter.

Limitations

The natural variation present in the study created a majority of the limitations that the study possessed. The main variations introduced were caused by the equipment used to carry out the manufacturing processes.

The RV-12SL Mitsubishi robot contained a repeatability of (±).05mm, so the Mitsubishi robot's consistency limited the study. Just like the Mitsubishi robot used in the study, the Haas Mini Mill also possessed a set amount of error. The mill contained an error measuring .01524mm in the full travel of the X-axis, and a .0127mm error in the full travel of the Y-axis. Inspected on October 31, 2007 the manufacturer established a set amount of error for the Haas Mini Mill, and the amount of error measured by the manufacturer is still accurate due to the low amount of operating hours the Haas Mini Mill contained. The ASRS also had a set amount of repeatability that factored into the variance of the study.

Along with the limitations placed by the equipment on the study, the raw material also placed initial limitations. The manufacturer limited the initial process capability due to the parameters established during the manufacturing process on the aluminum blocks. So the initial process capability was the base line for the study. Also the differing physical properties of the 100 aluminum blocks had an effect of the tolerances the Haas CNC Mini Mill was able to hold while machining with a ¼" four-fluted high speed steel end mill.

Delimitations

One of the main delimitations that was placed on the study dealt with the accuracy of the measuring equipment that was readily available in the AMS department. The study used a digital metric Mitutoyo caliper that had the capabilities to measure to one hundredth of a millimeter. The researcher used the digital caliper in the study to measure the overall X and Y dimensions of the aluminum blocks, and to measure the X and Y locations of the pocket milled in the center of the aluminum blocks. The researcher used these measures to calculate initial process capability and final process capability to create the six sets of data.

Along with the delimitations placed on the study by the measuring equipment, there were also delimitations placed by the sample size. The study was limited to the machining of 100 samples in order to measure initial and final process capability. The researcher established a sample size of 100 aluminum blocks due to the limitation on raw material. A larger sample size would increase the validity of the study, but the available raw material limited the study.

The last set of delimitations encompassed the type of equipment used to process the square aluminum blocks. The study used a Haas Mini Mill and a Renishaw 40-2 spindle probe. The type of equipment that was present in the AMS department created a majority of the delimitations placed on the study.

Delimitations are not only found in the equipment used to process the material, but also the equipment used to collect the data. MeasurLink data collection software was used in conjunction with the Mitutoyo digital caliper to record the data points gathered in the study. The data was then transferred from MeasurLink to Excel spread sheets.

Definition of Terms

- AMS- Architecture and Manufacturing Sciences department at WKU
- ASRS- An Automated Storage and Retrieval System distributes and holds materials for post and preprocessing (Jewels, 2003).
- Bottlenecks- Particular places in the manufacturing process where longer cycle times impede the flow of the process (Dennis, 2007).

- CAD- Computer Aided Design creates two dimensional drafting, and three dimensional computer based models (Hagström, Ritzén, & Johansson, 2006).
- CAM- Computer Aided Manufacturing generally uses CAD software to create tool paths for a CNC machine (Thilmany, 2007).
- CAPP- Computer Aided Process Planning involves the creation of necessary planning and mapping based on customer needs (Kuhnle, Braun, & Buhring, 1994).
- CIM- Computer Integrated Manufacturing encompasses all parts of the manufacturing process that bonded together through the integration of a computer (Saygin, 2004).
- CNC- Computer Numerical Control is using a computer to generate a code in order to run a machine automatically (Valentino & Goldenberg, 2008, p. 1).
- DMAIC – Define, Measure, Analyze, Improve, and Control is a problem solving strategy used in Six Sigma organizations. DMAIC is used to define the problem, measure the process, analyze the current situation, improve the process, and then control the improvements (Summers, 2011).
- Process Capability- “The limits within which a toll or process operate based upon minimum variability as governed by the prevailing circumstances” (Pyzdek & Keller, 2010, p.473).

- Robot- A programmable and repeatable machine that uses an arm to complete a task (Ross, Fardo, Masterson & Towers, 2011).

- Six Sigma- Six Sigma is a quality management program that uses statistics to monitor quality with the goal of producing 3.4 defects or less per million opportunities (Pyzdek & Keller, 2010).

- TQC- Total Quality Control is a term coined by A. V. Feigenbaum that looked at quality in development, maintenance, and improvement throughout the entire company (Evans & Lindsay, 2008).

- TQM- Total Quality Management, “refers to the broad set of management and control processes designed to focus an entire organization and all of its employees on providing products or services that do the best possible job of satisfying the customer” (Talha, 2004).

Review of Literature

Process Improvement

The researcher used define, measure, analyze, improve, and control (DMAIC) in the process capability study to design and implement the process in order to institute continuous improvement on the CIM cell. While conducting a review of literature, a Six Sigma study revealed the use of DMAIC to improve the process capability of an internal process at an electronics company. Written by Drs. Hung, Wu, and Sung, the article titled *Application of Six Sigma in the TFT-LCD Industry: A Case Study* discussed the implementation of DMAIC (2011). In the TFT-LCD case study the company applied Six Sigma by using DMAIC to a particular process in order to improve process capability. The study used the DMAIC phases to define, measure, analyze, improve, and control the process. The company had already identified one major defect in their manufacturing process caused by the three components not sealing properly, resulting in a seal open defect. The company wanted to determine if the implementation of a Six Sigma project would result in improved process capability and process control. The company monitored the Six Sigma success by comparing the final project results to the original problem defined in the beginning of the project. After comparing the new number of defects at the end of the project to the baseline data, the company was able to gain $1,500,000 annually through the implementation of the Six Sigma project dealing with defects caused by the three components improperly sealing.

Other companies have monitored the effects of Six Sigma project implementation to determine if the Six Sigma quality management practice has the ability to improve an internal process through the use of DMAIC. In the article, *Using Six Sigma to Improve*

Replenishment Process in a Direct Selling Company, Mr. Wei, Mr. Sheen, Mr. Tai, and Mr. Lee explored the effects of implementing Six Sigma on Amway Taiwan Company. The goal of the project was to improve the replenishment process by decreasing errors and improving customer satisfaction. In order to improve the replenishment process, the company formed a Six Sigma team to carry out the project by using the steps of DMAIC. The Six Sigma team defined the problem and created a project outline that the team used to carry out the process. The team then proceeded to the measure step in order to identify the variables by creating a fish bone diagram by using the 6M's (machine, measurement, manpower, materials, Mother Nature, and methodology). After the researcher defined all of the variables, the team determined prominent variables that had the largest effect on the process. The Six Sigma team then proceeded to the analysis step in order to identify variance and investigate the defined problem. Determining variance then allowed the Six Sigma team to improve the process and maintain these improvements over an extended period of time. When the final Six Sigma project was completed, the company measured several metrics to determine if the project had a beneficial effect on the replenishment process. The project resulted in a $20,000 savings along with an elimination of shipping errors. The project also affected the planner by shortening the time the planner took to create a replenishment plan from sixty minutes to forty minutes resulting in an increased efficiency. Based on the Six Sigma replenishment project implementation, Six Sigma had a positive effect on the Amway Taiwan Company (Wei, Sheen, Tai, & Lee 2010).

In-Process Measuring Device

The study attempted to determine the ability to affect process capability through the use of a Renishaw spindle probe used in conjunction with a CNC milling machine.

Jim Destefani covers the use of Renishaw machine spindle probes in CNC machining in the article titled *On-Machine Probes Make Impact*. Mr. Destefani specifically discussed the use of the Renishaw probe to measure tool and part offsets. When a CNC machine performs complex processes, several tool changes can take place in order to produce one part. During each of these tool changes there is the potential to induce increased variables causing the product to be either above or below the specification limits. One way to combat tool wear is through the use of a Renishaw tool detection probe. The tool detection probe measured tool length and diameter to determine the appropriate offsets for the selected tool. The probe can take measurements of the tool anytime during the production cycle. Frequent tool probe measurements allow the process to maintain tighter tolerances on the work piece, because the probe has the ability to measure tool wear and detect broken tools. Along with the tool probes, Renishaw has also designed spindle probes used for pre-process, in-process, and post-process measurements of work piece dimensions. Spindle probes have the ability to save time and reduce scrap through their accurate measurement of work offsets. The spindle probe has the capabilities to manually touch the part and determine the work offsets up to 1 µm. Work offsets can eliminate part positioning errors allowing for increased dimensional accuracy. Improving the dimensional accuracy resulted in decreased scrap rates resulting in increased profitability. Alongside reducing scrap, the Renishaw spindle probe saves time by reducing setup time and part measurement. Instead of manually measuring part size and location, the probe allows the CNC program to use automation to determine the part parameters. The CNC equipment monitors these parameters, during the run cycle to prevent compounding of errors during the sequential steps in the process. Overall, the amount of time saved and the improved quality are the two major contributions that Renishaw probes can offer CNC manufacturing (Destefani, 2003).

CIM Cell Process Capability

The process capability study attempted to increase final process capability over initial process capability through the use of a Renishaw CNC spindle probe. The CNC milling machine used in the study is only one part of the entire CIM cell. In the article *Three Dimensions of CIM*, Mr. Weston looked at the implications of Computer Integrated Manufacturing (CIM) in three different subgroups; engineering, information systems, and the operations area. Before Weston explored these three dimensions further, Weston defined CIM as, "The automation and integration of information, processes, and functions in a manufacturing environment, including customers and vendors, with the result being a closed-loop, functionally integrated manufacturing planning and control system" (Weston, 1994, p.59). The first subgroup discussed in CIM is engineering that covers how computer aided integration is used in the planning and implementation phase of the manufacturing process. Areas such as computer aided design, computer aided manufacturing, and the use of integrated robots and computer numerical control machining centers are included in the engineering subgroup. Each of these parts of engineering are designed to function as one unit to perform complex manufacturing steps while monitoring quality. The goal of integrating these groups is to shorten lead time while focusing on reducing cost. The next dimension covered in the article was the use of information systems in CIM. Information systems in CIM focus on integrating networking and databases into the manufacturing process in order to, "link the various elements of the organization" (Weston, 1994, p.59). Linking the elements allows individual users throughout the entire company to access the same data at any given time during the manufacturing process. The last dimension covered in the article is the use of the operations area in CIM. According to Weston,

> The third dimension of CIM speaks to the question of how products are actually produced and placed in the hands of the customer at the time and of the quality desired, at a reasonable price, and with total expectation that the product will perform as designed and represented to the customer (Weston, 1994, p.60).

Some operating areas used in CIM cells are Just in Time, Material Resource Planning, and Total Quality Management. Integration of Just in Time, Material Resource Planning, and Total Quality Management is important in order for a CIM cell to function properly. Keeping the areas separate will result in negative side effects and prevent the company from maintaining a competitive edge (Weston, 1994).

With CIM cells, process capability is one of the major measures of how efficient the process is running. In the article, *Measuring Process Capability Index Cpm with Fuzzy Data* the researchers took a closer look at the different process capability measures. According to the researchers, process capability is a vital part of decision making in a manufacturing process. *Cp* and *Cpk* represent process capability and determine if the products produced are within customer requirements. The researchers stated, "Process capability indices *Cp* and *Cpk* have been used in the manufacturing industry not only to provide numerical measures on process potential and performance, but also to quantify the relationship between the actual process performance and the specification limits" (Chen, Lai, & Nien, 2010, pp. 529-530). The researchers showed process capability as listed below.

$$Cp = (USL - LSL)/ 6\sigma \quad (1)$$

$$Cpk = (1 - K) \times Cp \quad (2)$$

$$K = 2\,|\mu - M|\,/(USL - LSL) \quad (3)$$

$$M = (USL + LSL)/2 \quad (4)$$

K = capability index

M = midpoint

μ = *process mean*

σ = *standard deviation*

USL = Upper Specification Limit

LSL = Lower Specification Limit

Overall these two measures *Cp* and *Cpk* determine if a process is in control and if action needs to take place in order to move the process within acceptable control limits (Chen, Lai, & Nien, 2010).

Researchers have realized the need to continuously monitor quality during a manufacturing process in order to successfully implement TQM (Total Quality Management) and TQC (Total Quality Control). Reimann and Sarkis discussed the need for continuous quality monitoring in their article, *An Architecture for Integrated Automated Quality Control*. The researchers discussed how companies are focusing on improving CIM through the use of CAM, CAD, and CAPP, but companies are focusing little effort on using inspection equipment to monitor quality in a CIM cell. The incorporation of inspection equipment in an automated manufacturing cell has the ability to improve the process and result in improvements to the product. Through the use of integrated inspection, the equipment has the ability to monitor the quality of the part and make adjustments during the process to account for in-process variations. Reimann and Sarkis stated, “A properly integrated system enhances flexibility, increases through put, reduces setup time, minimizes operator error, improves accuracy, improves product quality, and lowers costs” (Reimann & Sarkis, 1993, p. 341). In order for these potential benefits to materialize, the CIM cell must be functioning as one unit with the incorporation of flexible inspection units. If the inspection units are operating separately from the cell, then the equipment is unable to make adjustments and improve quality during the manufacturing process (Reimann & Sarkis, 1993)

The review of literature gathered for this study covered many of the topics used in this research. Companies have experienced success through the implementation of DMAIC as a continuous improvement initiative. This showed the importance of defining a problem within a process and the value of combating this problem by discovering the source of the issue. Along with the information gained on process improvement, the researcher also discovered the potential to effectively use Renishaw measuring components as effective in-process measuring devices in conjunction with a CNC machine. The information revealed the capability of the Renishaw measuring components to measure variation present in the machining processes. The last area covered in the review of literature took a closer look at CIM cell operation and how to effectively measure a CIM cell’s capabilities. The various components covered in the review of literature backed up the researcher’s study, even though a similar study was not found.

Methodology

Procedure

In order to determine changes to process capability in a CIM cell, research was conducted in the Senator Mitch McConnell Advanced Manufacturing and Robotics Laboratory. The research focused around the following hypotheses:

$H_0$1: There was no difference between initial process capability and final process capability without the use of the in-process measuring device.

$H_1$1: There was a difference between initial process capability and final process capability without the use of the in-process measuring device.

$H_0$2: There was no difference between initial process capability and final process capability with the use of the in-process measuring device.

$H_1$2: There was a difference between initial process capability and final process capability with the use of the in-process measuring device.

$H_0$3: There was no difference between final process capability with the in-process measuring device and final process capability without the in-process measuring device.

$H_1$3: There was a difference between final process capability with the in-process measuring device and final process capability without the in-process measuring device.

To effectively research these hypotheses, a quantitative study was conducted resulting in six sets of data. The study was conducted by processing 100 aluminum blocks in the CIM cell without the use of the Renishaw spindle probe and then flipping the blocks over and processing them again with the Renishaw spindle probe. Processing the aluminum blocks in the CIM cell this way allowed the researcher to gather six sets of data: initial process capability X, initial process capability Y, final process capability without in-process measuring device X, final process capability without in-process measuring device Y, final process capability with in-process measuring device X, and final process capability with in-process measuring device Y.

Before the aluminum blocks were processed in the CIM cell they were manufactured to the desired size of 130mm X 130mm. Aluminum flat stock measuring 6" wide by 12' long and ¾" thick was used to make the 100 aluminum blanks. Machining the blocks to the desired size was handled by using the following equipment: a horizontal bandsaw (see Figure 1), a waterjet, and three vertical milling machines. The first step conducted on the aluminum flat stock was to cut the 12' sticks into 4' sections using the horizontal bandsaw to help with the handling of the raw material.

Figure 1. Horizontal bandsaw used to cut aluminum flat stock.

Once the sticks were cut into 4' sections it was then placed on the waterjet table to cut the overall width of the material to around 135mm. Removing excess material in the width decreased the amount of time spent on the milling machine. After all of the 4' sections were processed on the waterjet then the material was taken back to the bandsaw and cut to around 135mm sections. This allowed the researcher to get 9 aluminum blanks out of each 4' stick. With the blanks now measuring roughly 135mm X 135mm, the final machining was handled by the three manual milling machines. Due to the way the aluminum blocks were processed, one factory edge was present on all of the blocks. This factory edge was then used as a positive stop during the machining process on the mill (see Figure 2). The aluminum blocks were placed vertically in the vice with the factory edge against the base of the vice.

Figure 2. Aluminum block with factory edge against base of vice.

A positive stop was placed in the Z axis allowing the operator to take several passes on the aluminum blank until it reached the final dimension of 130mm.   With the X dimension within the desired specification, the Y dimension was processed next. The part was then clamped in the vice with the jaws applying pressure to the two parallel X sides (see Figure 3). One of the Y sides was then machined perpendicular to the X axis to true up the edge.

Figure 3. Clamping position to machine first Y axis.

With three sides processed, the forth side was machined in the mill to bring the Y axis to its final specification. The block was then placed vertically in the vice with the previously processed Y axis resting against the base of the vice (see Figure 4).

Figure 4. Processing final Y axis with aluminum block placed vertically in vice.

A positive stop used in the Z axis allowed the operator to machine the block to 130mm in the Y axis.

With the blocks machined to 130mm X 130mm, they were next processed in the CIM cell. A rendering of the CIM cell shows a general view of the cell layout (see Appendix A). One side of the aluminum blocks was processed with the use of the Renishaw spindle probe, the other side without the Renishaw spindle probe. In order to run the blocks, the ASRS was loaded with the 100 aluminum blocks and processed in the CIM cell without the use of the Renishaw spindle probe. Due to the holding capacity of the ASRS, the ASRS was loaded in sets in order to run all 100 blocks. The process started with the ASRS robot picking up the pallet that the aluminum block was resting on, and moving the pallet to a buffering station. Once the aluminum block was loaded onto the buffer station; the Mitsubishi robot moved into position to grab the aluminum block from the pallet. The Mitsubishi robot used a set of grippers to grab the aluminum block from the pallet. Once the Mitsubishi robot had grabbed the part; the robot moved down a linear slide to place the aluminum block in the Haas Mini Mill CNC vice (see Figure 5).

Figure 5. CIM cell with loaded ASRS buffer station.

The Mitsubishi robot positioned the aluminum block against two positive stops located on the backside in the Y-axis on the mill. With the aluminum block resting against the positive stops, the Mitsubishi robot released the aluminum block and returned to the home position. Next the pneumatic vice on the CNC machine securely closed on the aluminum block. With the aluminum block secured in the vice, the CNC machine proceeded to the machining process (see Figure 6).

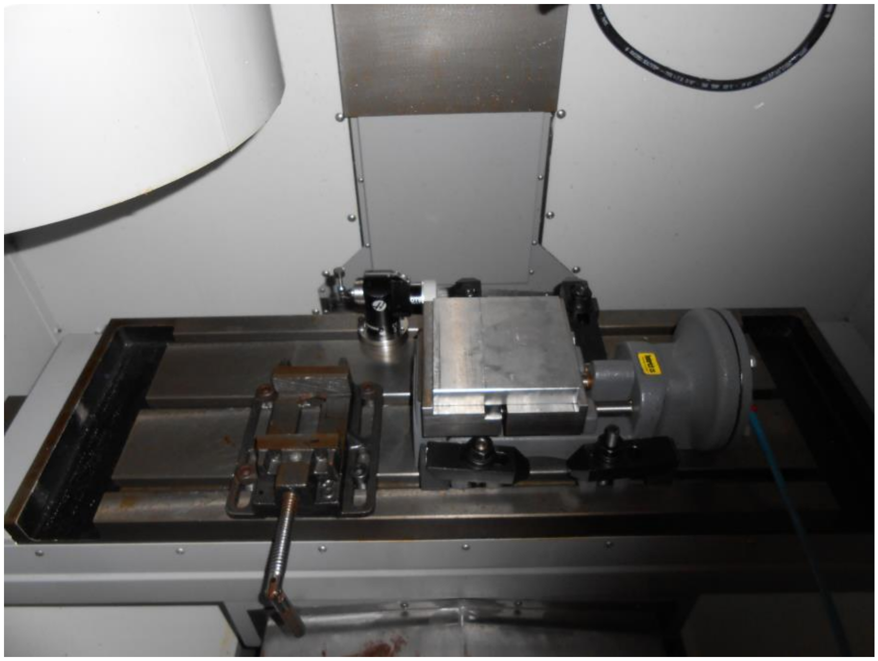


Figure 6. Aluminum block clamped in CNC vice.

The Haas Mill used a ¼” HSS four-fluted end mill to machine a square pocket in the center of the aluminum blocks. The pocket was 7mm deep and measured 25mm in the X dimension, and 25mm in the Y dimension. The CNC was programmed to move to the center of the aluminum block by moving 65mm in the –X axis, and 65mm in the +Y axis from the top left corner of the part. The top left corner of the part was programmed from the top left corner of the CNC vice. The tool bit was swapped out after 25 blocks were processed or whenever excessive tool wear occurred. When a new bit was loaded into the CNC machine, it was set up using the Renishaw tool touch off setter. After the square pocket was milled into the aluminum block, the Mitsubishi robot moved back into position to grab the aluminum block. The Mitsubishi robot secured the aluminum block by closing the grippers around the part. Once the grippers were closed on the aluminum block, the CNC vice opened, and the Mitsubishi robot moved to place the aluminum block back on the pallet located at the buffer station. With the aluminum block loaded on the pallet located at the buffer station, the ASRS robot moved into position to pick up the pallet and placed the pallet back on the ASRS. The process continued to repeat itself until the 100 aluminum blocks were machined. Once the blocks were machined, final process capability was recorded (see Appendix B).

With the CIM cell process described, the problem with process capability became prominent. The researcher defined the problem in the study to encompass process capability in a CIM cell. Process capability is defined as the problem because in a CIM cell, initial process capability of the work piece affects the final process capability of the work piece. A direct effect is created by initial process capability because each step is dependent on the previous. The dependency created causes each step to introduce more variation into the process. Increased variation causes final process capability to decrease preventing the final process capability from exceeding initial process capability. Decreased process capability caused by increased variation can be detrimental to the final product causing the product to fall outside the upper or lower specification limits established by the customer. The study planned to combat the problem of increased variation through the use of an in-process measuring device. The measuring device, a Renishaw 40-2 CNC spindle probe (see Figure 7), was used to measure the exact coordinate positioning of a part in the CNC vice.

Figure 7. Renishaw 40-2 spindle probe.

Instead of programming the center of the aluminum block off of the top right corner of the vice, the researcher used the spindle probe to measure the true center of the aluminum block. The true center of the aluminum block was found by measuring the distance between the four sides of the aluminum block with the Renishaw spindle probe. The Renishaw spindle probe touched X_1 and the X_2 and measured the length and divided this measurement by two. The probe then did the same thing for the two Y side of the aluminum block. By measuring the exact coordinate positioning and finding the true center of the aluminum block, previous variation caused by positioning error and variation in initial size of the aluminum blocks was eliminated. Along with the integration of the probe, the tool was also monitored before machining each block by measuring the tool wear with a Renishaw tool touch off setter. The researcher used the Renishaw spindle probe to determine the ability to increase final process capability over initial process capability and increase final process capability over the group of aluminum blocks processed in the CIM cell without the use of the probe.

In order to measure and gather the six sets of data used in the study, the researcher used a Mitutoyo caliper to measure the X and Y dimensions. The Mitutoyo caliper measured to one hundredth of a millimeter and was used in conjunction with MeasurLink Real Time Plus. MeasurLink Real Time Plus is a measuring computer software that was directly wired to a Mitutoyo caliper with a communication cable. The software allowed the Mitutoyo caliper to transfer measurements from the caliper to the computer with the push of a foot pedal. The MeasurLink had an integrated foot pedal switch that automatically implemented measurements into the measuring software. By using the MeasurLink software linked with the Mitutoyo caliper, user error by manually writing in the numbers was eliminated.

A gage calibration study was conducted to determine if the Mitutoyo caliper were still operating within their measuring capabilities. Generally when a gage study is conducted, it is carried out as an r&r study that represents repeatability and reproducibility. For this research it was not necessary to ensure reproducibility because there was only one operator using the caliper to measure the components. Repeatability was important in order to validate the true data that was collected. The caliper was calibrated using a set of standard cera gage blocks manufactured by Mitutoyo. The cera blocks were certified on June 15, 2005. This certification data was still valid due to the low amount of time the cera blocks had been used. The cera blocks were used once a year for instructional purposes only. Since the cera blocks were in standard measurement, the researcher used a 1’’ cera block and converted the measurement to

25.4mm. To validate the caliper, the researcher measured the cera block ten times. The data gathered was placed in a table (see Table 1).

Table 1

Gage Repeatability Measurements

Attempt	Length (mm)
1	25.4
2	25.4
3	25.4
4	25.4
5	25.4
6	25.4
7	25.4
8	25.4
9	25.4
10	25.4

The repeatability was measured by placing the data in following formula in order to calculate the accuracy of the Mitutoyo caliper:

$$\text{Accuracy} = Xbar_m - X \qquad (5)$$

$Xbar_m$ = measurement length average

X = actual size of cera block

When the data was plugged into formula (5), the researcher discovered that the accuracy was +/- 0.00mm. This signified that the digital caliper was able to accurately measure within one hundredth of a millimeter. This assured the researcher that the Mitutoyo digital caliper was not introducing unaccounted error into the study (Sahay, 2012).

Once the caliper was determined to be operating within its proper specifications, the researcher used the caliper to measure the blocks in order to gather the data needed to calculate process capability. The data gathered was then placed in a table (see Appendix

B). The initial process capability was calculated by using the measures gathered in regards to the X and Y dimensions of the 100 aluminum blocks. The formula (1) was used to calculate the Cp for the aluminum blocks established by the manufacturer in both the X and Y dimension. A Cpk was also calculated for the aluminum blocks supplied by the manufacturer using formulas (2), (3), and (4) in both the X and Y dimension. The final process capability with the in-process measuring device and the final process capability without the in-process measuring device were calculated using the same formulas (1), (2), (3), and (4). The only difference is how the process capability was measured in regards to the X and Y dimensions used to calculate the process capability. The final capability measure was based on how close the square pocket was milled into the center of the aluminum block in both the X and Y dimension. The researcher took X_1-X_2 and Y_1-Y_2 and these measures were centered on the nominal value of 0mm. The Cp and Cpk was used to determine if the Renishaw spindle probe had a direct effect on process capability in the study when analyzed in regards to: initial process capability X, initial process capability Y, final process capability without in-process measuring device X, final process capability without in-process measuring device Y, final process capability with in-process measuring device X, and final process capability with in-process measuring device Y.

Findings

After all the data was collected using the Measurlink software, the data was transferred to Microsoft Excel to determine the process capability for the various parameters measured in this study. Descriptive statistics were calculated for the six sets of 100 data points (initial process capability X, initial process capability Y, final process capability without in-process measuring device X, final process capability without in-process measuring device Y, final process capability with in-process measuring device X, and final process capability with in-process measuring device Y.). These descriptive statistics were then used to calculate Cp and Cpk using the formulas mentioned in the review of literature:

$$Cp = (USL - LSL)/ 6\sigma \quad (1)$$

$$Cpk = (1 - K) \times Cp \quad (2)$$

$$K = 2\,|\mu - M|\,/(USL - LSL) \quad (3)$$

$$M = (USL + LSL)/2 \quad (4)$$

K = capability index

M = midpoint

μ = *process mean*

σ = *standard deviation*

USL = Upper Specification Limit

LSL = Lower Specification Limit

Collecting descriptive statistics on the data collected was vital to gathering the appropriate information to calculate Cp and Cpk. The numbers gathered were then placed in the formula to calculate the Cp and Cpk (Chen, Lai, & Nien, 2010). The results gathered from the study were organized in a table to easily see the changes in the process capability amongst the six sets of data (see Table 2).

Table 2

Process Capability Data for Six Sets of Data

Data Sets	X	Y
Initial Process Capability	Cp = 7.1915 Cpk = 7.1570	Cp = 2.7500 Cpk = 2.6975
Final Process Capability Without Probe	Cp = .61874 Cpk = .56280	Cp = 1.4780 Cpk = .96571
Final Process Capability With Probe	Cp = 3.9399 Cpk = 3.5199	Cp = 3.8446 Cpk = 3.0053

Conclusion

After gathering the results from this study, the researcher was able to come to a conclusion about the previous stated hypotheses. Based on the Cp and Cpk results the researcher was able to accept the first research hypothesis:

$H_1$1: There was a difference between initial process capability and final process capability without the use of the in-process measuring device.

The first research hypothesis was accepted based on the change that occurred in the process capability from the initial capability to the final capability without the use of the in-process measuring device. When the in-process measuring device was not in use, the added variation introduced by the CIM cell caused the process capability of the work piece to decrease (see Table 2).

The data collected also revealed that the researcher could retain the second research hypothesis.

$H_1$2: There was a difference between initial process capability and final process capability with the use of the in-process measuring device.

The study showed that the Renishaw spindle probe was able to measure and account for variation that was introduced by previous steps. This allowed the CNC mini mill to machine the internal pocket in the center of the aluminum block at greater dimensional accuracy (see Table 2).

When the researcher analyzed the results based on the third set of hypotheses, it was more challenging to gather a conclusive result. The set of blocks processed with the Renishaw spindle probe in the X axis showed a decrease in process capability while the Y axis showed an increase in process capability when compared to the initial process capability of the aluminum blocks. This result was linked to the extremely high initial process capability in the X axis (see Table 2). As stated in the methodology, only one of the X axis sides was machined during the initial machining process to create the aluminum blanks. This translated into all of the blocks retaining one factory edge in the X axis resulting in less variation being introduced to the overall width in the X axis. Due to less variation present in the X axis, the initial process capability was substantially higher than the Y axis.

The Renishaw spindle probe showed a difference for the process capability in both the X axis and the Y axis. The process capability for the Y axis improved, while the process capability for the X axis decreased so the researcher was able to retain the second research hypothesis. The ability to improve the process capability over the initial variation established by the raw material was shown with the improvement in the final process capability in the Y axis. The results showed that there was a limit in the amount of variation that the Renishaw spindle probe was able to operate within. This was shown in the decrease of the final process capability in the X axis.

$H_1 3$: There was a difference between final process capability with the in-process measuring device and final process capability without the in-process measuring device. The data collected on the third research hypothesis showed that the Renishaw spindle probe had the capability to eliminate variation and improve the machining capabilities of the CNC machine. The drastic improvement in Cp and Cpk shown in both the X and Y axis allowed the researcher to accept the third research hypothesis.

After the researcher analyzed the data collected and studied the results in regard to the three sets of hypotheses, the researcher was able to conclude that process capability decreased in the CIM cell due to the compounding variation introduced by each piece of linked automation. The researcher discovered that, in order to account for this compounding variation, a Renishaw spindle probe could act as an in-process measuring device. The in-process measuring device allowed the CNC machine to account for the previous variation introduced in the system and adjust accordingly. Individually adjusting the machining process for all of the aluminum blanks allowed the final process capability to improve over the initial process capability. This showed that the process was able to create a part containing less variation than initially present in the raw material.

Suggestions for Further Research

In order to revalidate the information gathered from this research it is important that the research be completed again while focusing on a few areas that could possibly cause unintended variation. Revalidating the data collected will help prove that the Renishaw spindle probe was able to improve the process capability within the CIM cell.

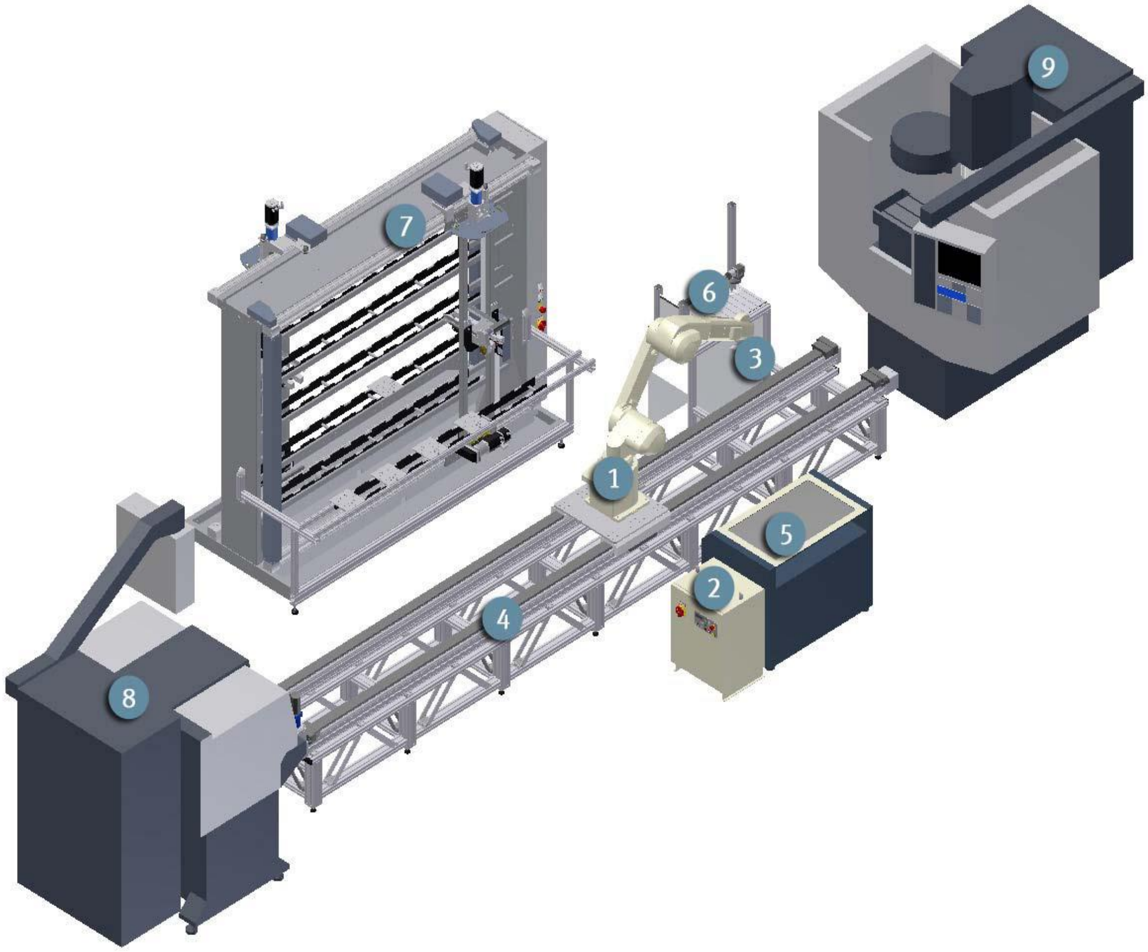
The first area that could be adjusted in future studies is the way that tool wear was monitored. An issue occurred with tool breakage while machining the 100 aluminum blocks without the use of the Renishaw spindle probe. Tools breaking caused the amount of tool wear that each block experienced without the probe to vary. In order to eliminate the varying tool wear experienced during the machining process, the tool touch off setter could be used the same way it was used on the blocks processed with the Renishaw spindle probe. Before each block was machined, the tool could be measured with the tool touch off probe. This would eliminate the issue of varying tool wear between the sets of blocks processed with and without the probe, while still determining if the Renishaw spindle probe had the capability to eliminate compound process variation.

Another area of variation that could be more closely monitored in future studies is the means used to measure the aluminum blocks. Instead of using an individual to measure all of the data with a digital caliper, a jig could be used to eliminate human variation that was introduced into the study. If the caliper was held incorrectly during a measurement, the measurement was retaken by the operator, but there is still the potential to introduce an incorrect measurement into the study. If a jig was used that would prevent the operator from introducing human measuring error into the study, the data would increase in validity.

Along with these issues there was also a problem with the vice that prevented the robot from consistently loading the aluminum blocks in the cell. Over time, the vibrations present in the CNC milling machine prevented the jaws on the vice from opening to their full reach. This restriction on the opening of the jaws caused the robot to incorrectly load the aluminum blocks. When the blocks were incorrectly loaded, the CIM cell had to be shut down and restarted. Since the CIM cell had to be restarted each time the robot incorrectly loaded the part, this prevented the CIM cell from running the desired batch size without restarting the cell. Constantly restarting the cell could have introduced unexpected variation into the data that could be eliminated in future studies now that the vice has been repaired.

The last revision that could be made in future studies deals with the X side retaining one of the factor edges. The researcher attributed the high initial process capability in the X axis to the fewer number of steps that were present when processing the aluminum blocks on the X axis. If both sides of the X axis were processed on the manual milling machine then the process capability would more closely resemble the initial process capability of the Y axis. In future studies, the same steps used to process the Y axis should be used to process the X axis to ensure a more consistent initial process capability for the work piece.

Appendix A: CIM Cell


9
7
6
3
1
5
2
4
8

Appendix B: Part Data

Initial Process Capability (mm)

Part Number	X Dimension	Y Dimension	USL	LSL	Nominal Dimension
1	129.96	129.99	131	129	130
2	129.97	129.97	131	129	130
3	130.01	130.00	131	129	130
4	130.02	130.08	131	129	130
5	130.00	129.94	131	129	130
6	130.01	130.07	131	129	130
7	130.01	129.93	131	129	130
8	130.00	130.07	131	129	130
9	130.07	130.02	131	129	130
10	129.98	129.99	131	129	130
11	130.05	129.96	131	129	130
12	129.93	129.98	131	129	130
13	129.99	130.01	131	129	130
14	130.04	129.96	131	129	130
15	129.81	130.06	131	129	130
16	130.05	129.99	131	129	130
17	129.95	129.96	131	129	130
18	129.92	130.04	131	129	130
19	130.04	129.98	131	129	130
20	130.02	129.94	131	129	130
21	130.07	129.95	131	129	130
22	130.14	130.00	131	129	130
23	130.00	130.03	131	129	130
24	130.03	129.95	131	129	130
25	130.08	130.07	131	129	130
26	130.13	129.99	131	129	130
27	130.11	130.03	131	129	130
28	129.92	130.00	131	129	130
29	129.97	129.97	131	129	130
30	130.10	129.93	131	129	130
31	130.03	129.93	131	129	130
32	130.06	129.97	131	129	130
33	130.03	130.01	131	129	130
34	129.81	130.02	131	129	130
35	130.03	129.89	131	129	130
36	130.02	129.98	131	129	130
37	130.01	130.00	131	129	130
38	129.92	129.98	131	129	130
39	130.01	130.02	131	129	130
40	130.00	129.94	131	129	130

41	129.96	129.99	131	129	130
42	130.04	130.00	131	129	130
43	129.99	129.97	131	129	130
44	130.05	130.05	131	129	130
45	129.99	129.98	131	129	130
46	129.92	130.00	131	129	130
47	129.99	130.04	131	129	130
48	130.03	130.10	131	129	130
49	129.98	130.09	131	129	130
50	130.05	130.03	131	129	130
51	129.92	129.90	131	129	130
52	129.99	129.97	131	129	130
53	129.97	130.00	131	129	130
54	130.00	130.00	131	129	130
55	130.20	130.02	131	129	130
56	129.99	130.02	131	129	130
57	129.90	129.98	131	129	130
58	129.97	130.08	131	129	130
59	129.96	130.04	131	129	130
60	130.04	129.99	131	129	130
61	129.90	130.04	131	129	130
62	129.96	129.96	131	129	130
63	130.04	130.00	131	129	130
64	129.02	129.95	131	129	130
65	129.97	129.98	131	129	130
66	129.96	130.02	131	129	130
67	129.87	130.01	131	129	130
68	129.89	129.99	131	129	130
69	129.99	130.08	131	129	130
70	129.98	129.97	131	129	130
71	130.00	129.91	131	129	130
72	129.95	129.98	131	129	130
73	129.94	130.01	131	129	130
74	129.96	129.99	131	129	130
75	130.10	129.98	131	129	130
76	129.93	130.03	131	129	130
77	129.99	129.99	131	129	130
78	129.87	129.96	131	129	130
79	129.99	129.98	131	129	130
80	130.03	129.95	131	129	130
81	130.04	130.02	131	129	130
82	129.96	130.03	131	129	130
83	129.92	130.04	131	129	130

84	130.02	129.93	131	129	130
85	130.04	129.97	131	129	130
86	129.94	129.97	131	129	130
87	129.87	129.99	131	129	130
88	130.11	130.16	131	129	130
89	130.00	129.97	131	129	130
90	130.02	129.99	131	129	130
91	129.98	129.95	131	129	130
92	129.96	130.01	131	129	130
93	130.03	129.92	131	129	130
94	130.02	130.08	131	129	130
95	130.10	130.01	131	129	130
96	129.97	129.92	131	129	130
97	129.90	129.99	131	129	130
98	130.02	129.96	131	129	130
99	129.92	129.99	131	129	130
100	129.69	129.99	131	129	130

Final Process Capability Y Dimension Without the Probe
(mm)

Part Number	Y_1 Dimension	Y_2 Dimension	Y_1-Y_2	USL	LSL	Nominal Dimension
1	52.17	52.83	-0.66	1	-1	0.00
2	53.39	51.66	1.73	1	-1	0.00
3	52.55	52.53	0.02	1	-1	0.00
4	52.37	52.66	-0.29	1	-1	0.00
5	51.95	53.07	-1.12	1	-1	0.00
6	52.72	52.27	0.45	1	-1	0.00
7	52.36	52.72	-0.36	1	-1	0.00
8	52.50	52.39	0.11	1	-1	0.00
9	52.70	52.40	0.30	1	-1	0.00
10	52.66	52.41	0.25	1	-1	0.00
11	52.84	52.26	0.58	1	-1	0.00
12	52.72	52.26	0.46	1	-1	0.00
13	52.74	52.34	0.40	1	-1	0.00
14	52.60	52.60	0.00	1	-1	0.00
15	52.64	52.34	0.30	1	-1	0.00
16	52.45	52.66	-0.21	1	-1	0.00
17	52.55	52.51	0.04	1	-1	0.00
18	52.65	52.35	0.30	1	-1	0.00
19	52.57	52.47	0.10	1	-1	0.00
20	52.58	52.45	0.13	1	-1	0.00
21	53.07	51.89	1.18	1	-1	0.00
22	52.84	52.15	0.69	1	-1	0.00
23	52.81	52.04	0.77	1	-1	0.00
24	52.71	52.32	0.39	1	-1	0.00
25	53.12	51.97	1.15	1	-1	0.00
26	52.44	52.54	-0.10	1	-1	0.00
27	52.61	52.50	0.11	1	-1	0.00
28	52.65	52.37	0.28	1	-1	0.00
29	52.91	52.09	0.82	1	-1	0.00
30	52.61	52.46	0.15	1	-1	0.00
31	52.50	52.57	-0.07	1	-1	0.00
32	51.95	53.05	-1.10	1	-1	0.00
33	52.71	52.41	0.30	1	-1	0.00
34	52.81	52.38	0.43	1	-1	0.00
35	52.49	52.50	-0.01	1	-1	0.00
36	52.70	52.33	0.37	1	-1	0.00
37	52.61	52.21	0.40	1	-1	0.00
38	52.54	52.56	-0.02	1	-1	0.00
39	52.28	52.75	-0.47	1	-1	0.00

40	52.54	52.50	0.04	1	-1	0.00
41	52.43	52.59	-0.16	1	-1	0.00
42	52.65	52.36	0.29	1	-1	0.00
43	52.54	52.45	0.09	1	-1	0.00
44	52.65	52.54	0.11	1	-1	0.00
45	52.58	52.50	0.08	1	-1	0.00
46	52.64	52.44	0.20	1	-1	0.00
47	52.54	52.40	0.14	1	-1	0.00
48	52.82	52.34	0.48	1	-1	0.00
49	52.71	52.33	0.38	1	-1	0.00
50	52.28	52.70	-0.42	1	-1	0.00
51	52.17	52.99	-0.82	1	-1	0.00
52	52.73	52.35	0.38	1	-1	0.00
53	52.63	52.41	0.22	1	-1	0.00
54	52.34	52.64	-0.30	1	-1	0.00
55	52.63	52.45	0.18	1	-1	0.00
56	52.52	52.58	-0.06	1	-1	0.00
57	52.67	52.49	0.18	1	-1	0.00
58	52.55	52.50	0.05	1	-1	0.00
59	51.87	53.24	-1.37	1	-1	0.00
60	52.72	52.37	0.35	1	-1	0.00
61	52.43	52.76	-0.33	1	-1	0.00
62	52.71	52.37	0.34	1	-1	0.00
63	52.55	52.49	0.06	1	-1	0.00
64	52.73	52.26	0.47	1	-1	0.00
65	52.29	52.75	-0.46	1	-1	0.00
66	52.41	52.66	-0.25	1	-1	0.00
67	53.17	51.89	1.28	1	-1	0.00
68	52.60	52.50	0.10	1	-1	0.00
69	52.17	52.80	-0.63	1	-1	0.00
70	52.73	52.30	0.43	1	-1	0.00
71	52.83	52.27	0.56	1	-1	0.00
72	52.43	52.65	-0.22	1	-1	0.00
73	52.65	52.44	0.21	1	-1	0.00
74	52.49	52.62	-0.13	1	-1	0.00
75	52.48	52.70	-0.22	1	-1	0.00
76	53.18	51.84	1.34	1	-1	0.00
77	52.94	52.09	0.85	1	-1	0.00
78	52.47	52.62	-0.15	1	-1	0.00
79	52.16	52.92	-0.76	1	-1	0.00
80	52.30	52.77	-0.47	1	-1	0.00
81	52.78	52.31	0.47	1	-1	0.00
82	52.22	52.82	-0.60	1	-1	0.00

83	52.20	52.92	-0.72	1	-1	0.00
84	52.54	52.46	0.08	1	-1	0.00
85	52.68	52.40	0.28	1	-1	0.00
86	52.61	52.49	0.12	1	-1	0.00
87	52.70	52.32	0.38	1	-1	0.00
88	52.43	52.63	-0.20	1	-1	0.00
89	52.21	52.77	-0.56	1	-1	0.00
90	52.54	52.54	0.00	1	-1	0.00
91	52.80	52.29	0.51	1	-1	0.00
92	52.16	53.03	-0.87	1	-1	0.00
93	52.44	52.73	-0.29	1	-1	0.00
94	52.06	52.97	-0.91	1	-1	0.00
95	52.54	52.41	0.13	1	-1	0.00
96	52.51	52.47	0.04	1	-1	0.00
97	53.31	51.78	1.53	1	-1	0.00
98	52.50	52.53	-0.03	1	-1	0.00
99	52.56	52.50	0.06	1	-1	0.00
100	52.42	52.66	-0.24	1	-1	0.00

Final Process Capability X Dimension Without the Probe
(mm)

Part Number	X_1 Dimension	X_2 Dimension	X_1-X_2	USL	LSL	Nominal Dimension
1	52.76	52.25	0.51	1	-1	0.00
2	52.84	52.26	0.58	1	-1	0.00
3	52.75	52.45	0.30	1	-1	0.00
4	52.57	52.52	0.05	1	-1	0.00
5	52.68	52.53	0.15	1	-1	0.00
6	52.84	52.24	0.60	1	-1	0.00
7	52.55	52.57	-0.02	1	-1	0.00
8	52.72	52.36	0.36	1	-1	0.00
9	52.85	52.32	0.53	1	-1	0.00
10	52.79	52.50	0.29	1	-1	0.00
11	52.51	52.47	0.04	1	-1	0.00
12	52.54	52.52	0.02	1	-1	0.00
13	52.50	52.58	-0.08	1	-1	0.00
14	52.83	52.29	0.54	1	-1	0.00
15	52.54	52.62	-0.08	1	-1	0.00
16	52.52	52.48	0.04	1	-1	0.00
17	52.60	52.39	0.21	1	-1	0.00
18	52.58	52.45	0.13	1	-1	0.00
19	52.71	52.37	0.34	1	-1	0.00
20	52.72	52.17	0.55	1	-1	0.00
21	52.65	52.43	0.22	1	-1	0.00
22	52.84	52.26	0.58	1	-1	0.00
23	52.59	52.50	0.09	1	-1	0.00
24	52.72	52.18	0.54	1	-1	0.00
25	52.81	52.33	0.48	1	-1	0.00
26	52.73	52.30	0.43	1	-1	0.00
27	52.99	52.14	0.85	1	-1	0.00
28	52.59	52.22	0.37	1	-1	0.00
29	52.76	52.33	0.43	1	-1	0.00
30	52.61	52.37	0.24	1	-1	0.00
31	52.60	52.46	0.14	1	-1	0.00
32	52.59	52.40	0.19	1	-1	0.00
33	52.75	52.24	0.51	1	-1	0.00
34	52.61	52.53	0.08	1	-1	0.00
35	52.77	52.40	0.37	1	-1	0.00
36	52.63	52.35	0.28	1	-1	0.00
37	52.77	52.11	0.66	1	-1	0.00
38	52.76	52.28	0.48	1	-1	0.00
39	52.60	52.43	0.17	1	-1	0.00

40	52.58	52.41	0.17	1	-1	0.00
41	52.53	52.46	0.07	1	-1	0.00
42	52.80	52.26	0.54	1	-1	0.00
43	52.52	52.31	0.21	1	-1	0.00
44	52.70	52.21	0.49	1	-1	0.00
45	52.84	52.13	0.71	1	-1	0.00
46	52.55	52.44	0.11	1	-1	0.00
47	52.80	52.37	0.43	1	-1	0.00
48	53.00	52.11	0.89	1	-1	0.00
49	52.65	52.45	0.20	1	-1	0.00
50	52.79	52.17	0.62	1	-1	0.00
51	52.65	52.27	0.38	1	-1	0.00
52	52.56	52.52	0.04	1	-1	0.00
53	52.81	52.32	0.49	1	-1	0.00
54	52.56	52.55	0.01	1	-1	0.00
55	52.55	52.46	0.09	1	-1	0.00
56	52.52	52.45	0.07	1	-1	0.00
57	52.85	52.16	0.69	1	-1	0.00
58	52.61	52.49	0.12	1	-1	0.00
59	52.81	52.48	0.33	1	-1	0.00
60	52.48	52.45	0.03	1	-1	0.00
61	52.66	52.31	0.35	1	-1	0.00
62	52.87	52.35	0.52	1	-1	0.00
63	52.55	52.41	0.14	1	-1	0.00
64	52.76	52.29	0.47	1	-1	0.00
65	52.65	52.47	0.18	1	-1	0.00
66	52.59	52.41	0.18	1	-1	0.00
67	52.68	52.43	0.25	1	-1	0.00
68	52.71	52.38	0.33	1	-1	0.00
69	52.87	52.26	0.61	1	-1	0.00
70	52.75	52.29	0.46	1	-1	0.00
71	52.87	52.24	0.63	1	-1	0.00
72	52.85	52.25	0.60	1	-1	0.00
73	52.75	52.23	0.52	1	-1	0.00
74	52.68	52.49	0.19	1	-1	0.00
75	52.64	52.37	0.27	1	-1	0.00
76	52.61	52.48	0.13	1	-1	0.00
77	52.87	52.20	0.67	1	-1	0.00
78	52.64	52.43	0.21	1	-1	0.00
79	52.82	52.24	0.58	1	-1	0.00
80	52.67	52.42	0.25	1	-1	0.00
81	52.84	52.18	0.66	1	-1	0.00
82	52.76	52.25	0.51	1	-1	0.00

83	52.51	52.43	0.08	1	-1	0.00
84	52.64	52.38	0.26	1	-1	0.00
85	52.79	52.18	0.61	1	-1	0.00
86	52.65	52.38	0.27	1	-1	0.00
87	52.37	51.88	0.49	1	-1	0.00
88	52.77	52.14	0.63	1	-1	0.00
89	52.62	52.41	0.21	1	-1	0.00
90	52.70	52.26	0.44	1	-1	0.00
91	52.56	52.41	0.15	1	-1	0.00
92	52.59	52.38	0.21	1	-1	0.00
93	52.85	52.28	0.57	1	-1	0.00
94	52.79	52.19	0.60	1	-1	0.00
95	52.83	52.16	0.67	1	-1	0.00
96	52.78	52.25	0.53	1	-1	0.00
97	52.66	52.50	0.16	1	-1	0.00
98	52.90	52.18	0.72	1	-1	0.00
99	52.65	52.38	0.27	1	-1	0.00
100	52.67	52.45	0.22	1	-1	0.00

Final Process Capability Y Dimension With the Probe (mm)

Part Number	Y_1 Dimension	Y_2 Dimension	Y_1-Y_2	USL	LSL	Nominal Dimension
1	52.52	52.54	-0.02	1	-1	0.00
2	52.42	52.57	-0.15	1	-1	0.00
3	52.43	52.60	-0.17	1	-1	0.00
4	52.52	52.56	-0.04	1	-1	0.00
5	52.43	52.58	-0.15	1	-1	0.00
6	52.39	52.62	-0.23	1	-1	0.00
7	52.40	52.53	-0.13	1	-1	0.00
8	52.40	52.60	-0.20	1	-1	0.00
9	52.47	52.55	-0.08	1	-1	0.00
10	52.66	52.49	0.17	1	-1	0.00
11	52.52	52.67	-0.15	1	-1	0.00
12	52.48	52.60	-0.12	1	-1	0.00
13	52.42	52.62	-0.20	1	-1	0.00
14	52.39	52.67	-0.28	1	-1	0.00
15	52.46	52.64	-0.18	1	-1	0.00
16	52.37	52.67	-0.30	1	-1	0.00
17	52.50	52.51	-0.01	1	-1	0.00
18	52.50	52.55	-0.05	1	-1	0.00
19	52.40	52.51	-0.11	1	-1	0.00
20	52.42	52.52	-0.10	1	-1	0.00
21	52.42	52.56	-0.14	1	-1	0.00
22	52.42	52.52	-0.10	1	-1	0.00
23	52.38	52.51	-0.13	1	-1	0.00
24	52.42	52.59	-0.17	1	-1	0.00
25	52.43	52.49	-0.06	1	-1	0.00
26	52.44	52.52	-0.08	1	-1	0.00
27	52.42	52.69	-0.27	1	-1	0.00
28	52.52	52.63	-0.11	1	-1	0.00
29	52.41	52.54	-0.13	1	-1	0.00
30	52.45	52.50	-0.05	1	-1	0.00
31	52.44	52.64	-0.20	1	-1	0.00
32	52.47	52.56	-0.09	1	-1	0.00
33	52.41	52.55	-0.14	1	-1	0.00
34	52.50	52.50	0.00	1	-1	0.00
35	52.45	52.55	-0.10	1	-1	0.00
36	52.40	52.61	-0.21	1	-1	0.00
37	52.48	52.56	-0.08	1	-1	0.00
38	52.52	52.56	-0.04	1	-1	0.00
39	52.51	52.50	0.01	1	-1	0.00

40	52.47	52.53	-0.06	1	-1	0.00
41	52.45	52.56	-0.11	1	-1	0.00
42	52.56	52.49	0.07	1	-1	0.00
43	52.45	52.52	-0.07	1	-1	0.00
44	52.43	52.58	-0.15	1	-1	0.00
45	52.40	52.56	-0.16	1	-1	0.00
46	52.42	52.58	-0.16	1	-1	0.00
47	52.44	52.60	-0.16	1	-1	0.00
48	52.48	52.52	-0.04	1	-1	0.00
49	52.42	52.57	-0.15	1	-1	0.00
50	52.43	52.53	-0.10	1	-1	0.00
51	52.46	52.50	-0.04	1	-1	0.00
52	52.43	52.61	-0.18	1	-1	0.00
53	52.41	52.63	-0.22	1	-1	0.00
54	52.45	52.67	-0.22	1	-1	0.00
55	52.42	52.54	-0.12	1	-1	0.00
56	52.42	52.61	-0.19	1	-1	0.00
57	52.37	52.50	-0.13	1	-1	0.00
58	52.40	52.40	0.00	1	-1	0.00
59	52.40	52.48	-0.08	1	-1	0.00
60	52.40	52.60	-0.20	1	-1	0.00
61	52.48	52.63	-0.15	1	-1	0.00
62	52.41	52.61	-0.20	1	-1	0.00
63	52.40	52.53	-0.13	1	-1	0.00
64	52.45	52.59	-0.14	1	-1	0.00
65	52.47	52.71	-0.24	1	-1	0.00
66	52.44	52.68	-0.24	1	-1	0.00
67	52.43	52.48	-0.05	1	-1	0.00
68	52.49	52.45	0.04	1	-1	0.00
69	52.42	52.58	-0.16	1	-1	0.00
70	52.56	52.62	-0.06	1	-1	0.00
71	52.58	52.51	0.07	1	-1	0.00
72	52.47	52.59	-0.12	1	-1	0.00
73	52.64	52.54	0.10	1	-1	0.00
74	52.44	52.63	-0.19	1	-1	0.00
75	52.47	52.62	-0.15	1	-1	0.00
76	52.54	52.64	-0.10	1	-1	0.00
77	52.61	52.65	-0.04	1	-1	0.00
78	52.38	52.64	-0.26	1	-1	0.00
79	52.45	52.58	-0.13	1	-1	0.00
80	52.49	52.59	-0.10	1	-1	0.00
81	52.60	52.55	0.05	1	-1	0.00
82	52.48	52.54	-0.06	1	-1	0.00

83	52.50	52.55	-0.05	1	-1	0.00
84	52.48	52.63	-0.15	1	-1	0.00
85	52.51	52.60	-0.09	1	-1	0.00
86	52.46	52.53	-0.07	1	-1	0.00
87	52.57	52.55	0.02	1	-1	0.00
88	52.42	52.46	-0.04	1	-1	0.00
89	52.54	52.60	-0.06	1	-1	0.00
90	52.45	52.53	-0.08	1	-1	0.00
91	52.41	52.54	-0.13	1	-1	0.00
92	52.41	52.56	-0.15	1	-1	0.00
93	52.48	52.58	-0.10	1	-1	0.00
94	52.63	52.61	0.02	1	-1	0.00
95	52.45	52.61	-0.16	1	-1	0.00
96	52.54	52.57	-0.03	1	-1	0.00
97	52.53	52.55	-0.02	1	-1	0.00
98	52.42	52.51	-0.09	1	-1	0.00
99	52.53	52.57	-0.04	1	-1	0.00
100	52.44	52.56	-0.12	1	-1	0.00

Final Process Capability X Dimension With the Probe
(mm)

Part Number	X_1 Dimension	X_2 Dimension	X_1-X_2	USL	LSL	Nominal Dimension
1	52.55	52.31	0.24	1	-1	0.00
2	52.67	52.43	0.24	1	-1	0.00
3	52.69	52.46	0.23	1	-1	0.00
4	52.73	52.57	0.16	1	-1	0.00
5	52.68	52.42	0.26	1	-1	0.00
6	52.59	52.43	0.16	1	-1	0.00
7	52.78	52.39	0.39	1	-1	0.00
8	52.61	52.61	0.00	1	-1	0.00
9	52.68	52.46	0.22	1	-1	0.00
10	52.74	52.46	0.28	1	-1	0.00
11	52.65	52.38	0.27	1	-1	0.00
12	52.65	52.43	0.22	1	-1	0.00
13	52.68	52.39	0.29	1	-1	0.00
14	52.65	52.34	0.31	1	-1	0.00
15	52.71	52.47	0.24	1	-1	0.00
16	52.64	52.36	0.28	1	-1	0.00
17	52.77	52.24	0.53	1	-1	0.00
18	52.73	52.45	0.28	1	-1	0.00
19	52.61	52.49	0.12	1	-1	0.00
20	52.62	52.34	0.28	1	-1	0.00
21	52.64	52.64	0.00	1	-1	0.00
22	52.63	52.43	0.20	1	-1	0.00
23	52.72	52.50	0.22	1	-1	0.00
24	52.61	52.40	0.21	1	-1	0.00
25	52.61	52.42	0.19	1	-1	0.00
26	52.59	52.42	0.17	1	-1	0.00
27	52.57	52.50	0.07	1	-1	0.00
28	52.67	52.42	0.25	1	-1	0.00
29	52.55	52.35	0.20	1	-1	0.00
30	52.57	52.47	0.10	1	-1	0.00
31	52.63	52.44	0.19	1	-1	0.00
32	52.57	52.43	0.14	1	-1	0.00
33	52.62	52.47	0.15	1	-1	0.00
34	52.55	52.34	0.21	1	-1	0.00
35	52.56	52.35	0.21	1	-1	0.00
36	52.57	52.39	0.18	1	-1	0.00
37	52.61	52.41	0.20	1	-1	0.00
38	52.60	52.39	0.21	1	-1	0.00
39	52.64	52.36	0.28	1	-1	0.00

40	52.64	52.34	0.30	1	-1	0.00
41	52.66	52.39	0.27	1	-1	0.00
42	52.65	52.43	0.22	1	-1	0.00
43	52.60	52.38	0.22	1	-1	0.00
44	52.71	52.40	0.31	1	-1	0.00
45	52.61	52.41	0.20	1	-1	0.00
46	52.59	52.32	0.27	1	-1	0.00
47	52.58	52.38	0.20	1	-1	0.00
48	52.57	52.44	0.13	1	-1	0.00
49	52.51	52.34	0.17	1	-1	0.00
50	52.58	52.51	0.07	1	-1	0.00
51	52.63	52.34	0.29	1	-1	0.00
52	52.57	52.35	0.22	1	-1	0.00
53	52.59	52.40	0.19	1	-1	0.00
54	52.61	52.40	0.21	1	-1	0.00
55	52.53	52.40	0.13	1	-1	0.00
56	52.57	52.40	0.17	1	-1	0.00
57	52.71	52.35	0.36	1	-1	0.00
58	52.63	52.42	0.21	1	-1	0.00
59	52.73	52.43	0.30	1	-1	0.00
60	52.32	52.03	0.29	1	-1	0.00
61	52.78	52.47	0.31	1	-1	0.00
62	52.54	52.28	0.26	1	-1	0.00
63	52.67	52.45	0.22	1	-1	0.00
64	52.75	52.52	0.23	1	-1	0.00
65	52.55	52.34	0.21	1	-1	0.00
66	52.58	52.51	0.07	1	-1	0.00
67	52.63	52.39	0.24	1	-1	0.00
68	52.75	52.39	0.36	1	-1	0.00
69	52.64	52.41	0.23	1	-1	0.00
70	52.58	52.42	0.16	1	-1	0.00
71	52.61	52.43	0.18	1	-1	0.00
72	52.59	52.45	0.14	1	-1	0.00
73	52.61	52.37	0.24	1	-1	0.00
74	52.60	52.45	0.15	1	-1	0.00
75	52.61	52.51	0.10	1	-1	0.00
76	52.65	52.40	0.25	1	-1	0.00
77	52.62	52.44	0.18	1	-1	0.00
78	52.60	52.37	0.23	1	-1	0.00
79	52.61	52.40	0.21	1	-1	0.00
80	52.75	52.43	0.32	1	-1	0.00
81	52.79	52.43	0.36	1	-1	0.00
82	52.78	52.43	0.35	1	-1	0.00

83	52.61	52.34	0.27	1	-1	0.00
84	52.84	52.39	0.45	1	-1	0.00
85	52.62	52.50	0.12	1	-1	0.00
86	52.49	52.45	0.04	1	-1	0.00
87	52.53	52.50	0.03	1	-1	0.00
88	52.54	52.45	0.09	1	-1	0.00
89	52.68	52.53	0.15	1	-1	0.00
90	52.65	52.43	0.22	1	-1	0.00
91	52.62	52.42	0.20	1	-1	0.00
92	52.57	52.37	0.20	1	-1	0.00
93	52.63	52.35	0.28	1	-1	0.00
94	52.56	52.35	0.21	1	-1	0.00
95	52.67	52.43	0.24	1	-1	0.00
96	52.62	52.35	0.27	1	-1	0.00
97	52.57	52.32	0.25	1	-1	0.00
98	52.55	52.36	0.19	1	-1	0.00
99	52.59	52.41	0.18	1	-1	0.00
100	52.67	52.34	0.33	1	-1	0.00

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