Intern assignment

Investigation of the Coffee Grinding Process

-Confidential-

Erik Schakel

20-11-2015

rapport

PCV Group
people creating value

Preface

PCV Group, where PCV stands for People Creating Value, is a design company for end-to-end product development. Their expertise is dispensing and dosing systems and they have strong competences in pre-development, concept development, mechanical engineering, system design and project management. The core team consists out of over 30 experts in multiple fields and PCV Group has over 40 network partners.

In order to strengthen their competences, PCV Group invests time and effort in themes and technologies (matching their competences) that - if developed further - could add value to the business of their customers. Grinding of coffee is one of these themes.

This 10 week internship investigates a presumption of experts in the field of coffee grinding. This report contains the problem definition, approach and results of this investigation. Furthermore it presents two new ideas for coffee grinding in bean-to-cup coffee machines.

I want to thank the employees at PCV group for their contribution and knowledge. Special thanks go to Elias van Hoek and Henk van der Wulp for their guidance during the internship. At last I want to thank PCV Group for the enormous amount of experience I have gained during the internship.

Erik Schakel
November 18, 2015

Summary

Experts in the coffee industry have a strong presumption that the repeatability of the coffee grinding process is negatively affected when multiple cups coffee are made in a short time span. It is believed that the heat that is created during the grinding process influences the repeatability of the process.

A framework is created to identify all important input and performance parameters of the grinding process. The performance (output) consists out of the next three parameters: Particle size distribution shape, position of the peak in the particle size distribution and the volume of the coffee grounds. A particle size analysis is necessary to investigate the repeatability of the first two parameters. Since no feasible method is found within budget to analyse these parameters, only the repeatability of the volume of the coffee grind is investigated.

A first series of tests that is performed with a time interval of 1, 5 and 40 minutes between grinding sessions. Furthermore two more tests were performed to investigate the influence of the amount of beans in the reservoir and the grind size setting of the grinder. The Miele CM 6310 is used for testing.

A regression analysis shows there is a correlation between time and sample weight if the time interval between grinding comes below a certain threshold. An average increase of coffee grounds up to 0,085 gram per grinding session is measured. However, this average increase is less than 1% of the total sample weight and is therefore deemed insignificant. No information is acquired about the change in the particle size distribution and therefore no definite conclusions on the repeatability can be made.

The Miele CM7 is tested to see if the repeatability is similarly affected with a time interval of 1 minute between grinding. The regression analysis shows a clear correlation with an average increase of 0,1412 gram per grinding session. This is significantly higher than the average increase of 0,0651 gram per sample that is measured for the CM 6310 under the same conditions.

In the first series of tests it is concluded that the amount of beans in the reservoir could have an influence on the standard deviation of the grinding process. A new series of tests is conducted and no difference in the standard deviations is found. The maximum difference between average sample weight is 0,4 gram and between standard deviations is 0,02 gram, which is within acceptable range. This invalidates the observation during the first series of tests.

The grind size setting has a significant influence on the volume of the coffee grounds. The reason for this is that the grinding time for all grind sizes is the same. Since a larger grind size requires less grinding, the volume increases. Furthermore the repeatability of the process for a larger grind size is more affected than a fine grind size.

Two new ideas were generated to achieve a noise reduction during grinding. Instead of using friction between two surfaces with a certain profile where the bean is sliced and crushed, the particle size is reduced purely by crushing. The first idea is based on a roller grinder, which is already used on commercial and industrial scale. The second idea is based on a mortar and pestle, of which no known concept exists.

Table of contents

Introduction

Experts in the coffee industry have a strong presumption that the repeatability of the coffee grinding process is negatively affected when multiple cups coffee are made in a short time span. It is believed that the heat that is created during the grinding process influences the repeatability of the process.

Repeatability is a measure of a system's consistency to achieve identical results across multiple tests. The flavours extracted from the coffee grounds depends on the properties of the grind. In order to make a consistent cup of coffee time and time again, it is therefore important to have a highly repeatable grinding process.

It is not known if this presumption holds and what mechanism(s) play an active role. This research is focussed on investigating this presumption, identifying mechanisms that have a negative effect on the repeatability of the grinding process and providing solutions.

This report is structured as follows. First some general information about coffee is presented, followed by an analysis of grinders in current bean-to-cup coffee machines. After this a framework containing all important parameters of the grinding process is presented. The performed tests are explained using this framework and the results are presented and discussed. Finally two ideas of an alternate way to grind coffee are presented.

Objectives

The first objective is to investigate the short term repeatability of the grinding process on a well-known, commercially available bean-to-cup coffee machine and try to identify mechanisms that (may) have a negative effect on the repeatability of the grinding process .

If the repeatability is significantly affected, the second objective is to develop ideas and conceptual solutions to improve or (completely) change the design of coffee grinders in order to guarantee the repeatability of the grinding process (read: significantly improved).

Scope

The scope of the project is the repeatability of the grinding process in a commercial available bean-to-cup coffee machine. Other factors during the grinding of coffee, like the quality of ingredients, are not taken into account and kept constant.

Furthermore it is assumed that wear of grinders does not play an active role in the short term repeatability. An average burr needs to be replaced because of wear after grinding hundreds of kg of coffee. Based on this, the effect of wear on the results when grinding a few grams multiple times is deemed neglectable. Nevertheless a short literature study is performed to be aware of the effects of wear.

1. Making coffee

Coffee is a natural product made from seeds of the coffee plant, the coffee beans. Converting the coffee bean into a cup of coffee can be divided in 3 main processes: Roasting, grinding and brewing. A flowchart of the process can be found in figure 1. Each of these processes has a big influence on the final flavour of the cup of coffee. The roasting and brewing process are shortly treated in this section for information purpose.

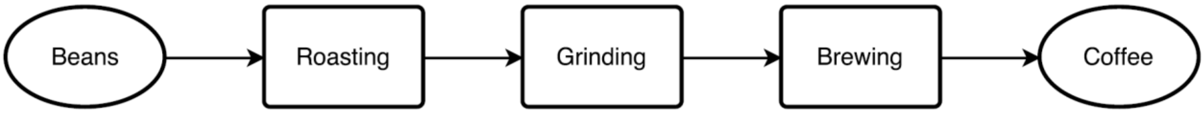


Figure 1: Flowchart of making coffee

1.1 Coffee roasting

The purpose of roasting is to transform green coffee beans into the brown beans used for brewing coffee. Green coffee beans have none of the characteristics of roasted beans. All the characteristics and flavours are ‘locked’ inside the beans, making them unsuitable for making coffee. The roasting causes multiple chemical reactions, changing the chemical and physical properties of the bean and unlocking these flavours. Roasting determines the characteristics of the bean including how it behaves during grinding.

1.1.1 Roasting process

Before the roasting process begins, the beans are destoned to remove as much stones as possible from the beans. This is needed as these stones can later on damage equipment such as the grinder.

The roasting process consists out of heating the beans to a certain temperature over a certain time, after which the beans are quickly cooled down again. The specific combination of time and temperature, also referred to as ‘roast profile’, determines the flavours released during the brewing process. Although flavour profile characteristics are determined by the coffee itself, they are greatly impacted by the roast profile as it highlights certain flavour characteristics. Different beans usually have different profiles and even different roasting equipment.

The most important factor for the quality of roasted coffee is the quality of the beans. Other important factors that have been identified are process temperature, hot air humidity and air-to-bean ratio[1].

1.1.2 Staling

Roasted coffee has a very limited shelf-life. The deterioration of the coffee flavour is called staling. The main sources of staling are identified as the oxygen concentration in storage atmosphere, the impact of temperature and moisture [1]. A two phase model for staling is proposed by Steinhart and Holscher to describe the staling process[2]. Staling of coffee is considerably faster in ground coffee because of the increased surface[1], and it is suggested that roasted coffee is best kept as whole beans in order to minimise changes during storage [3].

1.1.3 Roast types

Roast names and descriptions are not standardised in the coffee industry. In general, the coffee roasts can be categorised in the next four categories; light, medium, medium-dark and dark roasts. The roast characteristics and the internal temperature of the bean at the end of the roasting according to CoffeeCrossroads [4] is given for each roast type in table 1.

Roast	Max internal temperature	Characteristics
Light	180°C - 205°C	Light bodied, high acidity and no obvious roast flavour
Medium	210°C - 220°C	Higher body and some roast flavours
Medium-dark	225°C - 230°C	Bittersweet flavours are prominent and roast becomes clearly evident
Dark	240°C - 250°C	None of the origin character remains and roast is clearly evident

Table 1: Roast types

1.2 Brewing method

There are a lot of different methods to make coffee, each with its own characteristic flavour. The most common brewing methods are:

1. French press
2. Percolator
3. Drip brewing
4. Espresso
5. Turkish coffee

The brewing method used in bean-to-cup coffee machines is that of an espresso. A schematic of the brewing process with important parameters can be found in figure 2. The focus of this report lies within the red circle.

The first step of the brewing process is to grind the beans very fine after which the resulting coffee ground is transported to the brewer. The coffee ground is tamped down and pre infusion wets the top of the grounds. This promotes the even penetration of the grounds with hot water. Following the hot water is forced through the compacted ground under pressure. Usually this pressure is around 9 bar. The result of this brewing process is a beverage with a crema, which does not occur in other brewing methods. The crema is the layer of thickly effervescent foam that is on top of the espresso. An impression of the espresso brewing process can be found in figure 2.

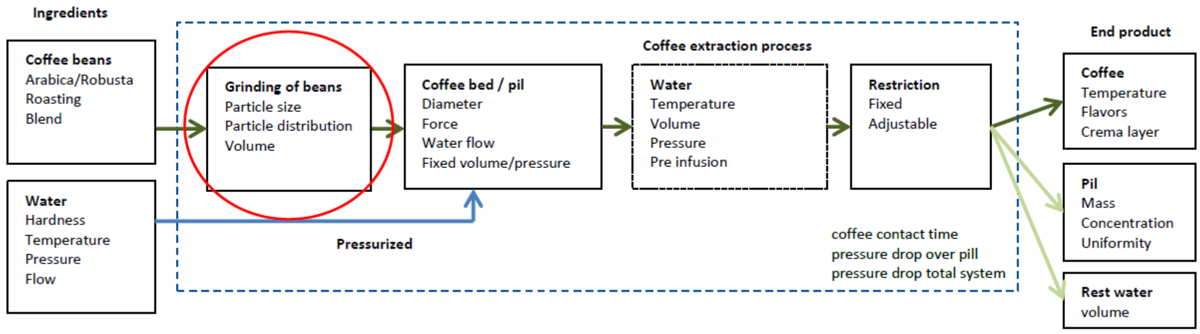


Figure 2: Schematic of the espresso brewing process

2. Grinding

Grinding is the second process in converting the coffee bean into coffee. It is desired to grind the beans just before brewing since coffee is best preserved as a bean [3]. Within 5 minutes after grinding considerable amounts of odorants are lost [1]. Bean-to-cup coffee machines are available with a grinder to let the customer use fresh beans for their coffee, allowing minimal time between grinding and brewing. All available bean-to-cup coffee machines use a burr grinder for grinding.

An explanation of the burr grinder and the most important characteristics is presented in this section. Furthermore the influence of the particle size distribution is described and the guidelines for the particle size per brewing method is given. Finally some effects that are known to change grinding results over time are discussed.

2.1 Burr grinder

A burr grinder uses 2 rings with a profile to crush the bean into smaller particles. There are a lot of different burr grinders, the most important characteristics of a burr grinder are:

- Flat or conical design
- Operating speed
- Material
- Diameter
- Adjusting grind size

Both flat and conical burr grinders are used in home and commercial grinders, as they are both capable of producing consistent and quality grinds. A flat burr grinder uses two flat rings that are placed parallel to each other while a conical burr grinder uses two cone shaped rings that are placed within each other. Both types of grinders keep one ring stationary while the other is rotated by a motor. The crushing process is roughly divided into three stages:

1. The beans are crushed into smaller parts.
2. The smaller parts are crushed into rough particles
3. The rough particles are crushed into fine particles

The operating speed is the speed at which the ring is rotated. There are high and low speeds grinders where the low speed grinders can be divided into gear reduction grinders and direct drive grinders. Burr grinders are capable of adjusting the grind size, which can be achieved in two different manners. This can either be a stepwise adjustment, which is the most common, or the stepless adjustment. An elaboration of all these different characteristics is presented.

2.1.1 Flat burr grinder

A flat burr uses 2 rings with a cutting profile, which are placed parallel to each other, to turn the beans into coffee grind. The coffee beans are fed into the two rings after which the coffee is pushed through the system. This happens because of the design of the cutting profile and the centrifugal force created by the rotating ring. There are two different kinds of flat burr grinders in which the realisation of the first stage of the crushing process differs. The first kind realises all three stages of the crushing process within the rings. The second kind uses a cone shaped part in the centre of the rings to realise the first step, after which the last two steps are again realised within the two rings. An example of both types of flat burrs can be seen in figure 3.

Figure 3: Example of two kinds of flat burrs

A schematic and visualisation of the cutting process for the kind of grinder that realises the three stages within the rings can be found in figure 4. It clearly shows the three different stages of the cutting process.

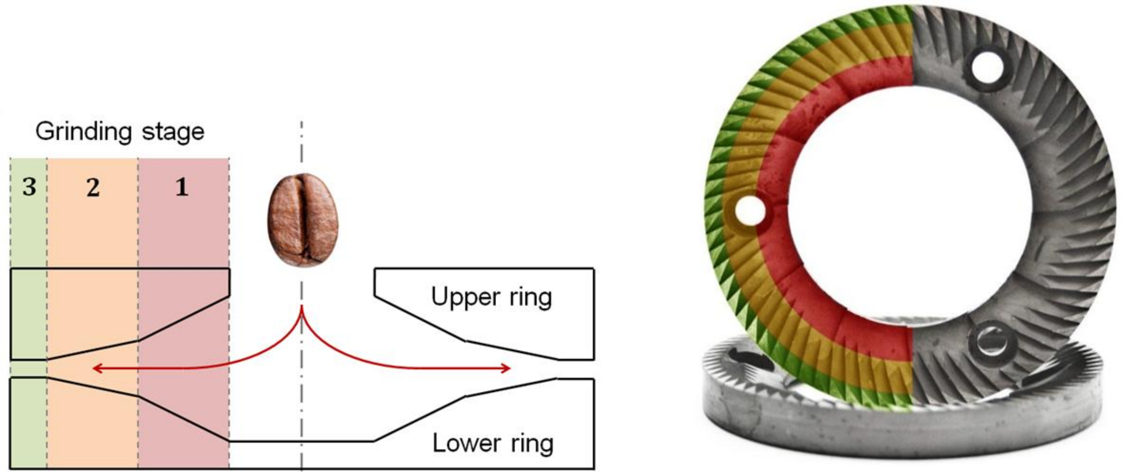


Figure 4: Schematic and visualisation of the flat burr grinding processes

2.1.2 Conical burr grinder

A conical burr uses two conical shaped rings to turn the beans into coffee grind. The beans are fed into the two rings and because of gravity the coffee is pushed through the system. An example of a conical burr can be seen in figure 5.

Figure 5: Example of a conical burr

A schematic and visualisation of the cutting process of a conical burr grinder can be seen in figure 6. it clearly shows the three different stages of the cutting process.

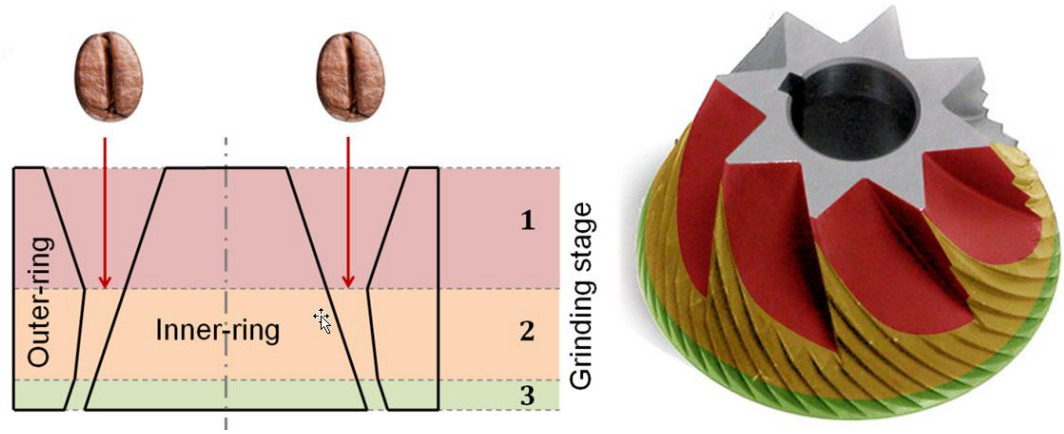


Figure 6: Schematic and visualisation of the conical burr grinding process

2.1.3 Operating speed

High-speed grinders are generally referred to as direct drive grinders because the motor is attached directly to the burrs. This makes high-speed grinders cheaper then low-speed grinders. However, there are some drawbacks when using high-speed grinders. The high operating speed will create more heat during the grinding process. Furthermore the coffee will pick up static electricity which creates chunks in the coffee ground. This in turn can affect the tamping of the coffee grounds. The last drawback is that the high-speed creates quite some noise which is unpleasant.

The low-speed grinder operates at a lower speed and therefore has none of the drawbacks of the high-speed grinders. There is little to no static electricity and very little heat is created during the grinding process. Furthermore the low speed allows for quiet grinding of the coffee. The reduction of the speed can be realised in two manners, direct drive or gear reduction. The drawback is that it is more expensive.

Low-speed direct drive grinders are the best grinders available for home or light commercial use, but also the most expensive. The low-speed motor is connected directly to the burrs, similar to a high-speed grinder. Because of the low operating speeds, a powerful motor is required to not bog down during grinding.

A low-speed gear reduction grinder uses gears to slow down the high speed of the motor. In this way a high speed motor can be used but a low grinding speed is achieved. Gear reduction grinders tend to be noisier than the direct drive grinders.

2.1.4 Material

There are three materials used in burr grinders: ceramic, steel and titanium. The main differences of these materials according to Kyle Anderson, president and co-owner of Baratza, are discussed below.

The life expectancy of steel burrs is the lowest, while ceramic burrs last on average twice as long as steel burrs and titanium burrs can last up to three times as long. However if a stone is encountered the brittle ceramic material will be most prone to be damaged. Steel burrs are in this case more durable and titanium burrs are least prone to damage.

The material of the burr has no influence on the root cause of heat build-up in the grinders, which comes from the crushing and cutting of the beans. However the material has an influence in the dissipation of this heat. Steel and titanium burrs have a higher thermal conductivity than ceramic burrs and can therefore dissipate heat that is created during the grinding process more easily.

Unit costs of ceramic burrs are much lower than comparable steel or titanium burrs, but they require a custom mould or tool to form them. These tools are expensive and therefore steel burrs are preferred.

2.1.5 Adjusting grind size

Burr grinders are capable of adjusting the grind size, which can be achieved stepwise or stepless. With stepwise adjustable grinders the grind size can be adjusted in little steps and the available grind sizes are prescribed by the grinder. Having a stepwise adjustable grinder does not mean there are a very limited number of steps. Some grinders provide more than 50 steps, making it sufficient to satisfy most coffee lovers in terms of grind control. With stepless adjustable grinders an infinite number of settings can be achieved as there are no prescribed grind sizes.

2.1.6 Diameter

If the diameter of the burr increases, the amount of cutting surface increases with it. This influences the speed at which the grinder is able to grind, but also influences the total throughput of beans until the burr needs replacement (replacement throughput). Manufacture data from six grinders from Mazzer are used to show this correlation. It is chosen to use different grinders from only one manufacturer, as multiple manufacturers can have a different view on when a burr set needs replacement. A summary of the specifications can be found in table 2.

Grinder	Type	Diameter *(mm)*	Material	Grinding throughput *(g/s)*	Replacement throughput *(Kg)*
Mazzer Mini	Flat	58	Steel	1	300
Mazzer Super Jolly	Flat	64	Steel	1,6	400
Mazzer Major	Flat	83	Steel	4	590
Mazzer Kony	Conical	63	Steel	3,8	745
Mazzer Robur 110V	Conical	71	Steel	6,7	770
Mazzer Robur 220V	Conical	83	Steel	unknown	815

Table 2: Specifications of six Mazzer grinders

The grinding throughput of the Mazzer Robur 220V is not available. The grinding throughput versus burr diameter and the replacement throughput vs burr diameter is plotted in figure 7. The correlation is clearly visible in these figures. An increase in burr diameter causes a higher grinding throughput and a higher replacement throughput. This can be explained by the increase in surface which makes it possible to crush more beans in the same time, increasing the grinding throughput. In the same time the amount of beans crushed per unit of area decreases, making it possible to crush more beans with the same grinder before it needs a replacement. This explains the increase in replacement throughput.

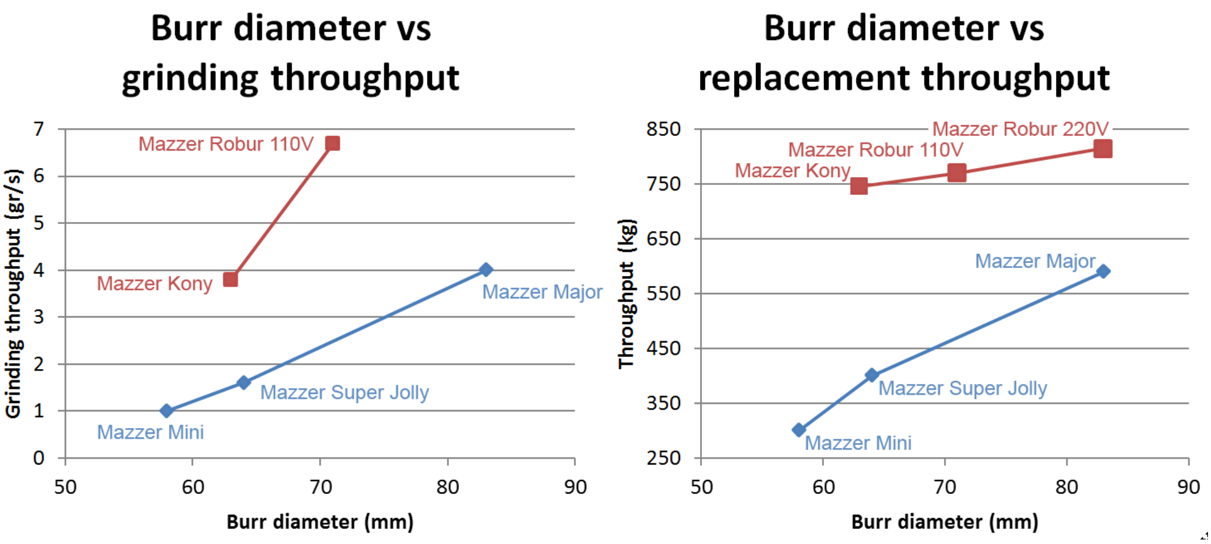


Figure 7: Diameter vs throughput

2.2 Particle size distribution

Coffee grind is achieved by grinding the beans, which means dividing the beans into small particles. The coffee ground that exits the grinder is not an uniform ground with one particle size, but a distribution in which a variation of particle sizes is present. The particle distribution has an influence on the permeability of the coffee grind, which in turn influences the extraction time[5]. An example of the particle size distribution for two different grind settings can be found in figure 8.

The extraction time, the time it takes for the water dosage to get through the coffee grind, determines the flavours that are extracted from the coffee grind. If the extraction time is too short, the pressurised hot water will not have had the opportunity to extract the best flavours from the coffee grinds, according to David Schomer, a pioneer in the specialty coffee industry and author of the barista training book Espresso Coffee: Updated Professional Techniques. If the extraction time is too long, the flavour oils will bum due to over-exposure to heated brewing water. In other words, if the particle size distribution changes over time, the extraction time will also change and thus the flavour of the coffee will be different.

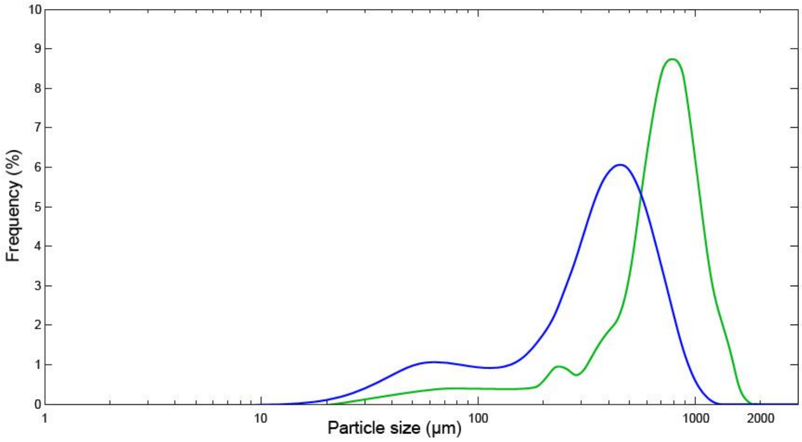


Figure 8: Example of a particle size distribution for two different grind settings

According to Coffee chemistry [6] there are several factors that influence the bean and therefore affect the way coffee behaves during grinding, as the bean is a natural product. These factors include:

Moisture content Typically roasted beans that have been subjected to water quenching tend to be softer than air cooled ones. As a result, water quenched beans tend to distort unevenly during grinding and tend to produce inconsistent grind particles.

Degree of roast Typically beans of lighter roasts will be more pliable and tenacious than darker roasted coffee. It is the greater loss in moisture in dark roasts that makes beans more brittle and as such, produces a greater number of finer particles than lighter roasts.

Bean brittleness The origin of the coffee also affects how the bean behaves during grinding. Natural coffees will grind differently than wet processed coffees - given the same roast level. Also new crop coffees will always produce fewer fine particles than past crop coffees. Altitude also affects the way the bean will grind, since those beans grown at higher altitude tend to be denser than those grown at lower altitude.

It can be concluded that in order to make a good espresso coffee time and time again, constant grind size and particle size distribution are crucial. The coffee grinder has a critical role in the determination of this and therefore has a significant influence on the flavour of the coffee.

2.3 Grind size and brewing methods

Multiple brewing methods were discussed in the previous section. The required grind size differs per brewing process and an overview of which grind size is suitable for which brewing process is presented in table 1. For each grind size an interval of the peak in the particle size distribution is given based on values prescribed by websites specialised in coffee [7][8]. It should be noted that the position of the peak is not limited to the given interval. The interval is merely presented to get a feeling of what particle size roughly correlates with what grind size and type of coffee according to coffee websites.

Grind size	Types of coffee	Peak interval (μm)	Description
Coarse	French press Percolators	900-1200	The grind size can be compared to sea salt.
Medium	Flat-filter drip brew	700-800	The grind size can be compared to sand.
Medium-fine	Cone-filter drip brew	500-700	The grind size can be compared to refined sugar.
Fine	Espresso	200-350	The grind size can be compared to granulated sugar. It should be difficult to see individual grounds
Extra fine	Turkish coffee	100-150	The grind size can be compared to flour. It should be barely possible to distinguish individual grounds.

Table 3: Grind size per brewing method

2.4 Grinding results over time

The result of your grinding process will change over time. The taste of the brewed coffee will change as a result of this. Looking at the grinder, almost all causes of changing results over time can be brought back to two categories: pollution and wear.

2.4.1 pollution

The first category only exists if insufficient maintenance is performed which can already be noticeable within a week. Even when using the best grinder, some coffee fines and oil residue will remain in the grinder after the grinding process. This can cause numerous unwanted effects:

The build-up of oils can clog up the grinder and thus decrease the grinder performance, which will lead to a change in grind results. If oil residue comes in contact with fresh coffee, it will affect their flavour. The result is a grind that will look the same as before, but the flavour will be different. The oil residue will spoil over time which will only worsen this effect.

These effects can all be prevented with sufficient maintenance of the grinder.

2.4.2 Wear

In contrast to pollution, the changes in grinding results because of wear are inevitable. Grinders become dull over time because of the grinding. It is also possible that stone particles are left behind in the roasted beans, especially in home roasted beans, which will accelerate this process. The bean is crushed and cut during the grinding process. The efficiency of the cutting process will decrease if the grinders become dull, resulting in an overall decrease of efficiency of the grinding process. The effect of wear increases over time and it depends on the type of grinder, diameter, material and the amount of coffee that is ground, which was discussed in burr grinder section. Wear could cause numerous unwanted effects:

The particle size distribution changes as a result of wear. This could be because of inefficient cutting of the beans, or because the distance between the grinders changes. As explained, the particle size distribution has a significant influence on the taste of the coffee. Dull blades will cut the beans with less efficiency, resulting in more heat being created during the grinding process. This heat can affect the taste of the coffee ground.

These effects of wear are inevitable and therefore the grinder should be replaced when advised by the manufacturer to guarantee no significant change in taste takes place.

3. Framework

The presumption is that the repeatability of the coffee grinding process is negatively affected when multiple cups coffee are made within a short time span. The goal is to investigate this presumption and identify mechanisms that have a negative effect on the repeatability. A framework is created to systematically map all important factors and parameters of the grinding process. The purpose of the framework is to get a clear view on all parameters of the process, which will act as a base for testing.

First the input and output of the grinding process are determined. The input is divided into two parts, the grinder and the coffee beans. The grinder is a design input and the beans are a scenario input as its parameters change per grinding process. The output consists out of coffee grind and is the performance of the grinding process. A flowchart of this process can be found in figure 9.

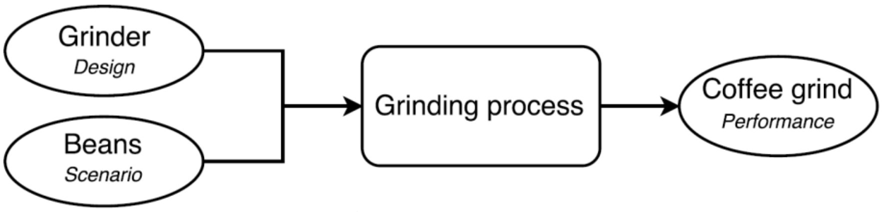


Figure 9: Flowchart of the grinding process

The relevant parameters for each input and output will be determined first. Hereafter a closer look is taken at the grinding process itself.

3.1 Design parameters

The design parameters are the parameters of the grinder that are relevant to the grinding process. These can directly be extracted from the grinder section and are:

- Flat or conical grinder
- Material
- Operating speed
- Diameter
- Grind size setting

3.2 Scenario parameters

The scenario parameters are parameters that are not specified by the bean-to-cup machine. In this case the scenario parameters contain all information about the beans that are fed to the grinder. These parameters are:

- The amount of beans in the hopper
- Brittleness
- Size

The amount of beans in the hopper is important as it determines the pressure on top of the beans that are at the entrance of the grinder. If there are a lot of beans in the hopper, the beans on top apply pressure to the beans at the entrance, pushing these beans harder into the grinder than if few beans are in the hopper.

The brittleness of the beans has influence on the way they behave during grinding and are dependent on the type of bean and roast. The size of the beans has multiple influences. Smaller beans enter the grinder easier than larger beans and need less grinding to achieve the same grind size.

3.3 Performance parameters

Performance parameters say something about the output of the grinding process. In this case this is the coffee grind. The next performance parameters are defined:

- Position of the peak in the particle size distribution
- Shape of the particle size distribution
- Volume

In the brewing methods section it is concluded that each brewing method requires a certain grind size. The grind size is described by the position of the peak in the particle size distribution. For brewing methods that use a fine grind size, a small deviation causes a significant change.

The position of the peak describes the grind size, but the shape defines the proportions in which the particle sizes are present in the grind. A high and narrow peak in the distribution with few fines describes a grind that has a high concentration of particles with a certain size. A wide and low peak describes a grind that has a wider variety of particle sizes and thus a different extraction time, even though the position of the peak may be the same. A visualisation of this can be seen in figure 10.

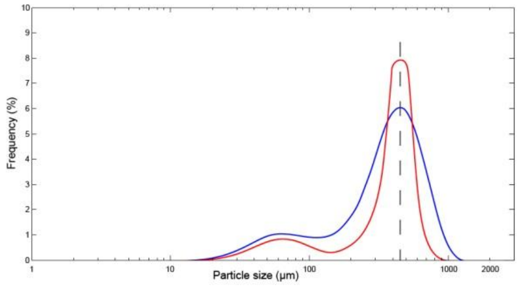


Figure 10: Same position of the peak but a different shape

As described in section 2.2, the particle size determines the extraction time. If the position of the peak or the shape of the peak changes, the extraction time changes with it. Therefore not only the position but also the shape of the peak is very important for the short term repeatability.

The throughput amount is the amount of coffee ground that is eventually used to make coffee since not 100% of the coffee that goes into the grinder eventually reaches the brewer. Some coffee stays behind in the system. The amount of coffee ground determines the amount of flavours that can be extracted.

3.4 Grinding process

Multiple parameters are interesting during the grinding process when considering the repeatability. These are parameters that can influence the output parameters and are:

- Temperature of the grind
- Throughput time

The impact of temperature during grinding is not negligible and can reach over 100°C, probably leading to undesired reactions [9]. This has an influence on the flavours that are later extracted in the brewing process. Therefore the temperature during grinding is an important aspect.

The throughput time is the time it takes from the moment a bean enters the grinder and leaves the grinder as grind. The temperature of the bean increases as it is crushed and sliced in the grinder. The more time the bean spends in the grinder, the longer it is exposed to these conditions.

3.5 The framework

All this information is summarised in the framework and can be found in figure 11. The framework contains all important parameters for the grinding process and will act as a base for testing.

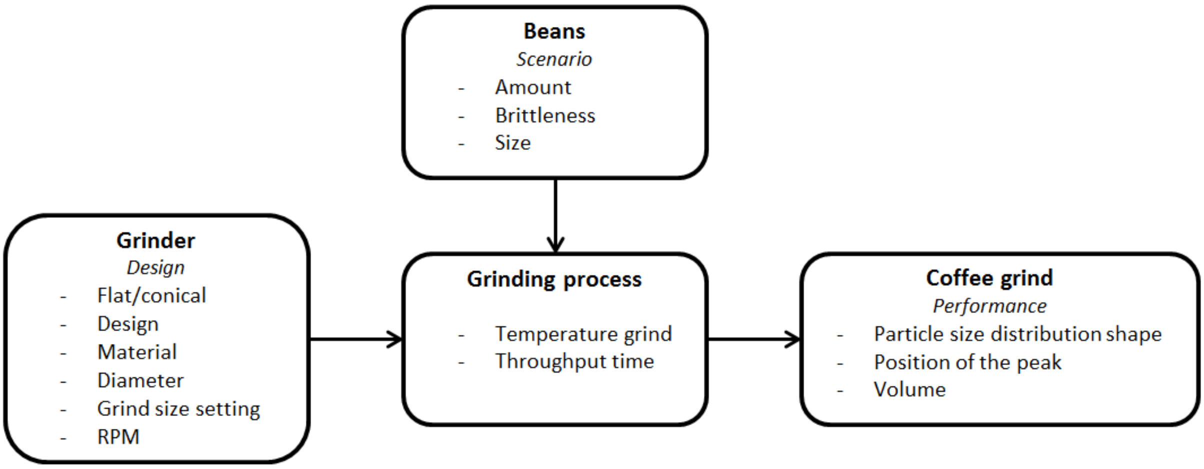


Figure 11: Framework of the grinding process

4 Testing the repeatability

Multiple tests are determined to investigate the repeatability of the grinding process using the parameters of the framework. The first objective of the tests is to identify if the repeatability of the grinding process is negatively affected when multiple cups of coffee are made in a short time span. The second objective is to find mechanisms that influence the repeatability of the grinding process.

First the tests are determined after which the test setup is shortly described. After this the results, conclusion and discussion are presented.

4.1 Tests

The first objective of the tests is to identify if the repeatability of the grinding process is negatively affected if multiple cups of coffee are made in a short time span.

Looking at the framework there are two areas in which the performance can change, the particle size distribution and the volume. From these two areas, the particle size distribution tells something about how the results change and is therefore preferred to analyse. Unfortunately no feasible method within budget is found to analyse the particle size distribution.

However, testing the volume could already give a definite answer about whether or not the presumption holds. If a significant change in volume is measured when multiple cups of coffee are made in a short time span, it can be concluded that the repeatability of the grinding process is affected as is presumed. If not, a particle size distribution analysis is necessary to give a definite answer. A change in volume is measured by measuring the weight of the coffee that is ground.

Tests with multiple time intervals between consecutive grinding processes are performed to investigate if the repeatability of the process changes. Note that the repeatability of the process should change for different time intervals. If the repeatability of the process does not change with different time intervals, it can be concluded that the time interval has no effect on the repeatability and the presumption does not hold.

The time intervals between grinding that are used for testing are 1, 5 and 40 minutes. A 1 minute time interval is the shortest time interval possible between grinding sessions as the whole process of making a cup of coffee with a bean-to-cup coffee machine takes around 1 minute. The 5 minute time interval represents extensive use and the 40 minute acts as a baseline. The repeatability of the 1 and 5 minute intervals is compared to the 40 minute interval. Each test is repeated 3 times and consists out of 10 measurements with the specified time interval between each measurement.

The design and scenario parameters should be kept constant. The design parameters are constant as only one machine is used for testing and the only parameter that can change is the grind size setting. The scenario parameters are kept as constant as possible by using only one type of coffee, assuming that size and brittleness is equal for all beans. Each test uses the finest grind setting and a controlled amount of beans in the reservoir.

Two extra tests are performed to investigate the influence of these parameters. The first test is performed with the coarsest grind setting to investigate if these results differ with the finest grind setting. This is performed with the 1 minute interval since the biggest influence is expected here. The second test is performed with 'normal' conditions for the amount of beans. The bean reservoir is filled before each test after which all 10 measurements are performed without adding or removing beans from the reservoir.

A summary on the performed tests can be found in table 4.

Test	Δt (min)	Grind size setting	Beans in reservoir	Measurements	Repetitions
1	1	Finest	Constant	10	3
2	5	Finest	Constant	10	3
3	40	Finest	Constant	10	3
4	1	***Coarsest***	Constant	10	3
5	5	Finest	***Normal***	10	3

Table 4: Summary of the performed tests

4.2 Test setup

In this section the test setup and procedure are shortly described. The Miele CM 6310 bean-to-cup coffee machine is used together with Illy espresso beans during testing. More information about the used equipment can be found in appendix A.

The Miele CM 6310 is adjusted in order to obtain all the coffee grounds that otherwise would enter the brewer. The brewer unit is removed and all safeguards are disabled. A detailed explanation of all alterations can be found in appendix B.

The Miele CM6310 uses a conical burr after which the coffee grounds is transported to the brewer through a horizontal transportation shaft. A schematic of the process can be seen in figure 12. Since the horizontal transportation shaft is integrated in the grinder design, it is not possible to remove this part and catch the coffee grounds directly from the burr grinder.

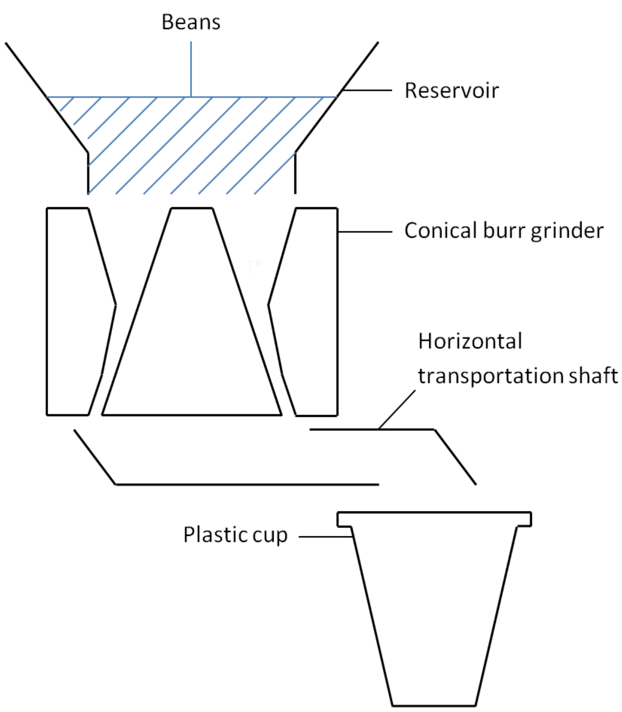


Figure 12: Schematic of the test setup

A plastic cup is used to catch all the coffee grounds, after which the weight can be determined. A standard procedure is made to ensure all tests are performed under the same conditions. This procedure includes several steps before and during testing and is presented in appendix C.

4.3 Results

The results of the tests are analysed to investigate if the presumption that the repeatability of the coffee grinding process is negatively affected when multiple cups coffee are made in a short time span holds. To do so a regression analysis is performed to see if there is a correlation between the time interval between grinding and sample weight.

Hereafter the influence of the design and scenario parameters that could change are evaluated. All results of each separate repetition and test can be found in appendix D.

4.3.1 Repeatability of the grinding process

The repeatability of the grinding process is evaluated by looking at the correlation between sample number and sample weight. It is expected that the test with a 40 minute time interval shows no correlation between sample number and sample weight, while there is a correlation expected between sample number and sample weight for the 1 minute time interval. If this is the case, the repeatability of the grinding process is affected by the time interval. If for both short and long time intervals there is a similar correlation or no correlation, the repeatability of the sample weight is not affected by the time interval.

A linear regression analysis is performed to test if there is a statistical correlation between sample number and sample weight. The average sample weight of all three repetitions is used in the regression analysis. The average sample weight is taken to damp the effect of individual measurements and the effect of the horizontal shaft connecting the grinder and the brewer, and to look for a common correlation between time and sample weight.

The regression analysis gives a p-value. The p-value tests the null hypothesis that there is no correlation. A low p-value ($p < \alpha$) indicates that the null hypothesis can be rejected and that a correlation is present.

The alpha level is the probability of rejecting the null hypothesis when the null hypothesis is true. A commonly accepted confidence level of 95% ($\alpha = 0{,}05$) is used in this rapport to accept or reject the null hypothesis (no correlation). In other words, the lower the p-value, the smaller the chance that the sample data falsely suggests a correlation. The results of the regression analysis can be found in table 5.

	Test 1	Test 2	Test 3	Test 4	Test 5
Δt (min)	1	5	40	1	5
P-value	0,007	0,071	0,373	0,002	0,091
Slope fitted line (g/sample)	0,0651	0,0241	-	0,0845	0,0351

Table 5: Results of the regression analysis

The p-value's for each time interval are similar, suggesting that time is the main reason for the correlation. If the p-value's differed a lot per time interval it would suggest that another mechanism than time has a significant influence on the correlation, which is not the case here. The p-value of test 1 and 4 (Δt = 1 min) are very low, from which can be concluded that there is a correlation between time and sample weight.

The p-value of test 2 and 5 (Δt = 5 min) are just above the alpha level, accepting the null hypothesis that there is no correlation. However, since it is very close to the alpha level it strongly implies that time does has an influence. The p-value of test 3 (Δt = 40 min) is high, suggesting that there is no correlation between time and sample weight. This means that the average sample weight is constant.

From this data is concluded that if the time interval decreases below a certain threshold, there is a correlation between time and sample weight. This strongly suggests that the repeatability of the grinding process is negatively affected if the time between making multiple cups of coffee becomes below a certain threshold.

A linear approximation of this correlation is obtained with Minitab, which is a statistics package developed at the Pennsylvania State University. This approximation is a straight line that describes the correlation with the formula $y = ax + b$. The slope a of this line describes the average increase in sample weight of each grinding session. This approximation is obtained for all tests with a 1 and 5 minute time interval and the slope of the line can be found in table 5. For example, each cup of coffee that is made with the coarsest grind size setting and with one minute between grinding sessions, has on average 0,0845 gram extra coffee grounds in it.

What stands out is the difference between grind size. Test 1 and 4 are performed both with only 1 minute between grinding but a different grind size. A correlation between interval time and average sample weight is clearly present in both cases, but the effect is significantly higher for the coarsest grind size.

4.3.2 Possible causes

The regression analysis shows that the time interval has an influence on the sample weight below a certain threshold. The only parameter that is identified in the process that fades over time is temperature. Multiple possible effects of temperature can be identified.

Motor winding resistance is the main cause of heat generation within the motor [10]. As the motor temperature increases, winding resistance will increase based on the temperature coefficient of copper. The flux density of the permanent magnets will also decrease as a function of temperature. The change in these 2 key elements will change the motor performance, which in turn can result in a change in sample weight.

It is known that heat is created during grinding [9]. If the time interval between grinding is too short, the remaining heat from the previous grinding session could influence the performance of the new grinding session.

4.3.3 Influence design and scenario parameters

Influence amount of beans

An extra test (test 5) is performed to identify the influence of the amount of beans in the reservoir. The difference between test 2 and 5 is that test 2 uses a constant amount of 20 gram of beans in the reservoir, while in test 5 the bean reservoir is completely filled at the beginning of the test and no beans are added during testing. The average sample weight and standard deviation is compared using Minitab. The results can be found in table 6.

Results		
	Test 2	Test 5
Sample mean (g)	11,75	11,61
Std. Dev. (g)	0,124	0,190
Mean and variance analysis		
	Mean analysis	Variance anlaysis
Null hypothesis	$\mu1=\mu2$	$\sigma1=\sigma2$
P-value	0,082	0,105

Table 6: Comparison mean and variance

The p-value for both the mean and the variance analysis is just above the alpha level. This means that there is no statistical difference between the two tests. However, the p-values are just above the alpha level, which means that there is no strong evidence for this.

A closer look is taken by plotting the results, which can be seen in figure 13 and 14. Since each repetition is performed with a different can of beans, bean characteristics differ slightly between repetitions. This causes different average weights per sample. The average repetition weight is subtracted to compare results.

The controlled amount of beans (Test 2) visually shows a more precise process. Together with the p-values it suggests that the amount of beans could have a negative impact on the grinding process.

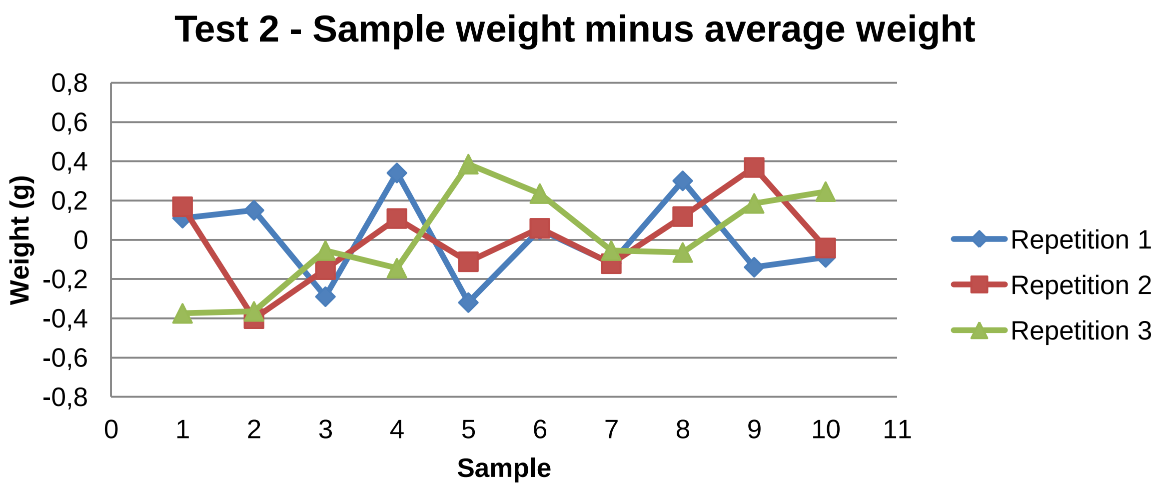


Figure 13: Results test 2

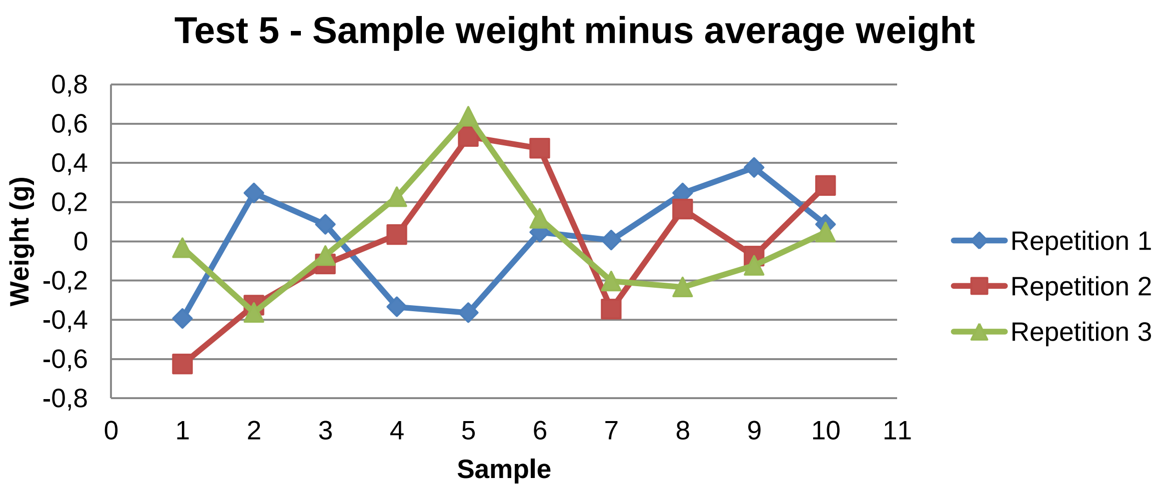


Figure 14: Results test 5

Differences between batches of beans

A large difference in average sample weight is observed during test 5. The only explanation that is found for this is that a different batch of coffee was used compared to the other two repetitions. The difference in average sample weight is only evaluated per test as different tests may have different average sample weight due to changing testing conditions.

The maximum difference in average sample weight between repetitions with the same batch is 0,29 gram, while the maximum difference in average sample weight between repetitions with a different batch is 0,86 gram. Only in one test different batches of coffee are used in different repetitions, so no conclusions can be made from this observation.

It can be explained by the fact that coffee beans are a product of nature and therefore prone to environmental influences. This causes each bean to be different. This difference is larger between each harvest of beans as the environmental influence differs with the previous batch.

Beans from only one Illy can are used per repetition to minimise this effect during testing. The average sample weight per repetition and the corresponding coffee batch can be found in table 7.

Repetition		Test 1	Test 2	Test 3	Test 4	Test 5
1	*Avg weight (g)*	10,75	11,64	10,53	12,33	11,49
	Coffee batch	08/2017 25-16:14	06/2016 24-08:42	08/2017 25-16:14	08/2017 25-16:14	06/2016 24-08:42
2	*Avg weight (g)*	11,04	11,77	10,61	12,49	11,25
	Coffee batch	08/2017 25-16:14	06/2016 24-08:39	08/2017 25-16:14	08/2017 25-16:14	06/2016 24-08:39
3	*Avg weight (g)*	10,99	11,83	10,71	12,64	12,10
	Coffee batch	08/2017 25-16:14	06/2016 24-08:39	08/2017 25-16:13	08/2017 25-16:14	08/2017 26-08:20
	Max difference	0,29	0,20	0,18	0,31	0,86

Table 7: Average sample weight with corresponding coffee batch

Influence grind size

An extra test (test 4) is performed to identify the influence of the grind size setting. The difference between test 1 and 4 is that test 1 uses a fine grind size setting and test 4 uses a coarse grind size setting. The average sample weight and standard deviation is compared using Minitab. The results can be found in table 8.

Results		
	Test 1	Test 4
Sample mean (g)	10,93	12,48
Std. Dev. (g)	0,250	0,299
Mean and variance analysis		
	Mean analysis	Variance anlaysis
Null hypothesis	μ1=μ2	σ1=σ2
P-value	0	0,269

Table 8: Results comparison test 1 and 4

The p-value of the mean analysis is 0,000, rejecting the null hypothesis that the average sample weight is the same. The average sample weight is significantly higher for the coarser grind size setting with an increase of 1,5 gram. The p-value of the variance analysis 0,269 which accepts the null hypothesis that the variance is the same for both tests. From this can be concluded that the grind size setting has a significant influence on the average sample weight, but not on the standard deviation of the grinding process.

The grinding time is measured for both settings to see if a difference is found. No difference in grinding time is found so the increase is not caused by longer grinding. Another cause could be that the beans have to be reduced to a smaller particle size for the fine grind size. Because of this the grinding process takes longer and thus less coffee is ground.

4.4 Conclusion

The first objective of the test is to see if the repeatability of the grinding process is affected when multiple cups of coffee are made within a short time span. A regression analysis shows there is a correlation between time and sample weight if the time interval between grinding comes below a certain threshold. An average increase of ground coffee up to 0,085 gram per grinding session is measured with a one minute time interval between grinding sessions. However, this average increase is less than 1% of the total sample weight and is therefore deemed insignificant.

Therefore the conclusions can be made that the repeatability of the volume of the coffee grounds is not significantly affected when multiple cups of coffee are made within a short time span. No definite conclusions about the repeatability can be made as it is unknown what happens with the particle size distribution.

The mechanism that is identified to influence the repeatability is heat generation. There are two possible reasons that heat generation influences the performance. The heat either influences the performance of the grinding session itself or it influences the performance of the electric motor.
During testing the influence of the next design and scenario parameters were evaluated:

- The amount of beans in the reservoir
- Grind size

A mean and variance analysis for different conditions of the amount of beans gave a p-value just above the alpha level, accepting the null hypothesis that the mean and variance are the same for both conditions. However, since they are just above the alpha level it is strongly suggested that the performance could be influenced by the amount of beans in the reservoir. This is confirmed when looking at a plot of the results.

A mean and variance analysis for different grind size settings concluded that the average sample weight significantly increases for a coarser grind size. However, no change in the variance between both settings is found. The same grinding time for both settings is adduced as cause for this.

Differences in average sample weight up to 0,85 gram were measured for different batches of beans. This is explained by the fact that coffee beans are a product of nature and differences in bean characteristics are inevitable.

4.5 Discussion

Between the grinder and the brewer is a short horizontal transportation shaft. The effect of this shaft on the sample weight is not taken into account. This could explain the fluctuation in the sample weights. To dampen this effect the average sample weight of all 3 repetitions is taken when determining the correlations.

The difference in average sample weight per can is only once evaluated. Therefore the results don’t have to represent the average difference between cans.

The results and conclusions are based on tests with only 1 grinder. Therefore the results don’t have to represent the results of all grinders.

5. Repeatability Miele CM7

In the first series of tests the repeatability of the grinding process was tested and it is concluded that an (insignificant) increase in volume is present when multiple cups of coffee were made within a short time span. However, only one grinder was tested and the Miele CM 6310 has a horizontal transportation shaft connecting the grinder and the brewer, of which the effect is unknown.

At this point a Miele CM7 bean-to-cup coffee machine became available for testing. The CM7 uses a different grinder and grinding setup where there is no horizontal transportation shaft. The CM7 is used to see if the repeatability is similarly affected if a time interval of 1 minute between grinding is used. Since the CM7 uses a different grinder than the CM 6310, the properties as mean and standard deviation of the grinding process can't be compared. A regression analysis is performed to see if a correlation is present. The results are compared to the results the first series of tests.

The same test parameters and procedures are used as before to be able to compare the repeatability. This means that the test is performed 3 times with 10 samples, with a time interval of 1 minute between grinding sessions. The fine grind size setting is used and the amount of beans in the reservoir is constant. The used procedure can be found in appendix C.1 and C.2.

The Miele CM7 uses the same safeguards as the Miele CM 6310 and is prepared the same way for testing. An overview of the test setup for the Miele CM 6310 can be found in section 4,2 and appendix B.

5.1 Results and discussion

A linear regression analysis is performed to teste if there is a statistical correlation between sample number and sample weight. This analysis is performed in the same manner as in the previous series of test in order to compare both results. This means that the average sample weight of all three repetitions is used in the regression analysis. The results of the regression analysis can be found in table 9. All results of each separate repetition can be found in appendix E.

	Miele CM 6310	Miele CM7
Δt (min)	1	1
P-value	0,007	0,000
Slope fitted line (g/sample)	0,0651	0,1412

Table 9: Results regression analysis

The p-value of the regression analysis is 0,000, which means that there is a correlation present. The slope of the linear approximation is 0,1412 gram per sample. This means that there is on average an increase of 0,1412 gram each sample, which is significantly higher than the average increase of 0,0651 gram per sample of the CM 6310. No explanation is found during testing for this. A possible cause of this increase could be that the grinder, grinding setup or electric motor of the CM7 is more prone to heat build-up.

Conclusion

The Miele CM7 is tested to see if the repeatability is similarly affected with a time interval of 1 minute between grinding. The regression analysis shows a clear correlation with an average increase of 0,1412 gram per grinding session. This is significantly higher than the average increase of 0,0651 gram per sample that was measured for the CM 6310 under the same conditions.

6. Testing the amount of beans in the reservoir

In the first series of tests is concluded that the amount of beans in the reservoir could have an influence on the standard deviation of the grinding process. Three tests are performed to validate this conclusion. The objective of these tests is to get an indication of the influence of the amount of beans in the reservoir on the standard deviation of the process.

Three new tests are performed. Since only the standard deviation of the process is investigate, a time interval of 10 minutes between grinding sessions is used. This because a time interval of 5 minutes still shows an influence on the repeatability of the process. It is assumed that this influence is negligible after 10 minutes. A regression analysis will be performed to confirm this. A summary of the performed tests can be found in table 10.

Two of the test are performed with a constant amount of beans in the reservoir. The first has a constant amount of 25 gram beans in the reservoir and the second a constant amount of 250 gram beans. The third test is started with 250 gram beans in the reservoir and no new beans are added during the test.

The test equipment is the same as in the first series of tests, thus the Miele CM 6310 is used. The test procedure is equal to the procedure used in test 2 and 5 in the first series and can be found in appendix C. Only one part changes, the total amount of beans used for the 250 gram starting amount test exceeds the amount of beans in a single can. In the first tests is a difference of average sample weight between cans observed, to minimise this effect beans from 2 cans are mixed before testing.

Test	Δt (min)	Nr. of Samples	Starting condition	Starting amount (g)
1	10	20	Constant	25
2	10	20	Constant	250
3	10	20	Normal	250

Table 10: Performed tests

6.1 Results and discussion

A summary of the results and analyses can be found in table 11. All results of each separate repetition and test can be found in appendix F. It is assumed that a time interval of 10 minutes is sufficient to ensure no increase in sample weight during testing. A regression analysis is performed to see if this assumption holds. In the tests with a constant amount of beans (test 1 and test 2), no correlation is present and the assumption holds. However, in with a decreasing amount of beans there is a correlation present. No explanation is found for this correlation as all other parameters are kept constant throughout the tests.

Results						
	Test 1		Test 2		Test 3	
Sample mean (g)	10,92		11,13		11,33	
Std. Dev. (g)	0,275		0,268		0,283	
Regression analysis						
	Test 1		Test 2		Test 3	
p-value	0,311		0,286		0,001	
Fitted line	-		-		0,032*sample + 11	
Mean and variance analysis						
	Mean comparison			Variance comparison		
Null hypothesis	μ1=μ2	μ1=μ3	μ2=μ3	σ1=σ2	σ1=σ3	σ2=σ3
P-value	0,017	0	0,029	0,922	0,9	0,789

Table 11: Results of the regression analysis and mean and variance comparison

Using Minitab, the mean and variance of each test is compared to see if these are equal. Note that the regression analysis shows that an increase in sample weight is present in the third test, making the results less suitable to compare with the other two tests where no regression is present.

The analysis shows that the means are not equal as the p-value is below the alpha level of 0,05 for all comparisons. This means that the amount of beans do have an influence on the average sample weight. The difference in average sample weight is at most 0,4 gram, even with the increasing sample weight of test 3. This difference is below 5% of the total weight, which is deemed acceptable.

The standard deviation is equal for all tests, which means that the amount of beans had no influence on the precision of the grinding process during these tests. This invalidates the observation during earlier tests that the amount of beans could have an influence on the standard deviation of the grinding process. This can be explained by the fact that the new tests have more samples and a longer time interval is used which reduces the effect of heat.

6.2 Conclusion

There is no statistical difference in standard deviation of the grinding process measured when testing with 3 different amount of beans conditions. This invalidates the observation during earlier tests. The maximum average sample weight between tests is 0,4 gram and between standard deviation is 0,02 gram, which is within acceptable range.

7. Redesign of the grinder

The second objective of this report was to redesign the grinder such that the repeatability is significantly improved. During testing was concluded that the repeatability isn't significantly affected and a redesign on this topic is therefore not necessary.

However, expert knowledge within the company states that the noise that bean-to-cup coffee machines make is experienced as too loud and annoying and a reduction in noise would be a big improvement. Since the repeatability of is not significantly affected, the redesign of the grinder will be based on noise reduction. A brainstorm sessions was performed with multiple employees from PCV Group to identify sources of noise and to develop ideas that would generate less noise during grinding. First the sources of noise that were determined with a short study and during the brainstorm session are presented. Hereafter two ideas in which a noise reduction is feasible are discussed.

Note that testing took longer than planned and at this point only a few days of the internship were left. It was therefore not possible to fully develop and test both ideas. Instead a short introduction of both ideas is presented.

7.1 Sources of noise

Multiple sources of noise can be identified. It can be the grinder itself, the electric motor or the coffee machine. An overview of sources of noise can be found in table 12. The research of James R. Hendershot [11] was used to identify the sources of noise in electric motors.

Part	Source	Description
Grinder	Friction	The friction between the rotating en fixed parts
	Beans	The beans are crushed and sliced under high speed which causes noise
Electric motor	Magnetostriction	The increase/decrease of material dimensions due to a chaning magnetic field
	Radial deflection	The distortion of the rotor due to unbalanced forces causes noise
	Mechanical noise	Loose parts that cause noise
	Balance of rotor	Causes a significant amount of vibration noise
	Bearing noise	Noise created in bearings
Housing	Resonance	Noise created by resonating parts
	Loose parts	Noise created by loose parts

Table 12: Sources of noise

As can be seen there are different aspects that add to the noise. The focus of this report lies on the noise reduction of the grinding process itself and noise reduction in the electric motor or housing is not taken into account.

7.2 Roller grinder concept

Roller grinders are already widely used by commercial and industrial scale coffee producers. A roller grinder uses cylindrical rollers to crush or grind the coffee beans. This can either be at once or in multiple stages. An example of a multiple stage roller grinder can be seen in figure 15[12].

Roller grinders produce an even grind size distribution and heats the ground coffee less than other grinding methods. However, due to their size and cost, roller grinders are used exclusively by commercial and industrial scale coffee producers. The challenge is therefore to keep the costs low enough to make it feasible for home bean-to-cup coffee machines.

Friction between the rotating and non-rotating ring of a burr grinder is a source of noise in current bean-to-cup coffee machines. If the rollers of a roller grinder rotate at the same velocity, no friction between the rollers will exist. The only noise that is generated will be the crushing of the beans, which is inevitable, and the noise of the motor/housing. To reduce these noises would be the next step in noise reduction.

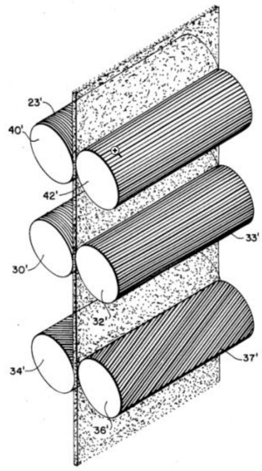


Figure 15: Multiple stage roller grinder

Another advantage of roller grinding is the little generation of fines. The fines are very hard to contain and contaminate the coffee machine. Less fines are therefore very desirable. The advantages and disadvantages of roller grinders in general are presented in table 13.

Advantages	Disadvantages
Energy efficient	High initial costs
Uniform particle size reduction	Maintenance can be expensive
Exact control of particle size	
Little noise generation	
Little fines generation	

Table 13: Advantages and disadvantages of a roller grinder

Important parameters and a possible configuration will be presented based on existing designs. After this recommendations on the continuation of this concept are presented.

7.2.1 Roller parameters

The amount of rollers is the first parameter that has to be defined as it has a great impact on the design of the concept. Each roller has to be powered and manufactured, adding extra complexity and costs to the concept. A minimum amount of rollers is therefore desired.

However, if the amount of rollers are reduced, the particle size reduction per set of rollers increases. With only one set of rollers the reduction from bean to the desired grind size has to be achieved at once. Since a fine profile is needed to achieve the desired grind size, the profile could be insufficient to grab and pull the bean through the grinder. In this case the bean would bounce on top of the grinder and nothing would happen.

Taking this into account a two-step grinding process seems the best solution. A first step where the beans are crushed into smaller particles and a second step where it is ground into the desired grind size.

The roller profile of these two steps should fit their task. The task of first set of rollers is to pull the beans in the rollers and crush them into smaller particles. A profile with teeth should be able to fulfil this task. The task of the second set of rollers is to create the desired uniform particle size and therefore should have a fine profile.

The dimensions partly determine the torque needed to crush the beans. Furthermore it influences the compactness and costs of the concept and therefore it is a trade-off that should carefully be made. An example of the discussed configuration can be found in figure 16.

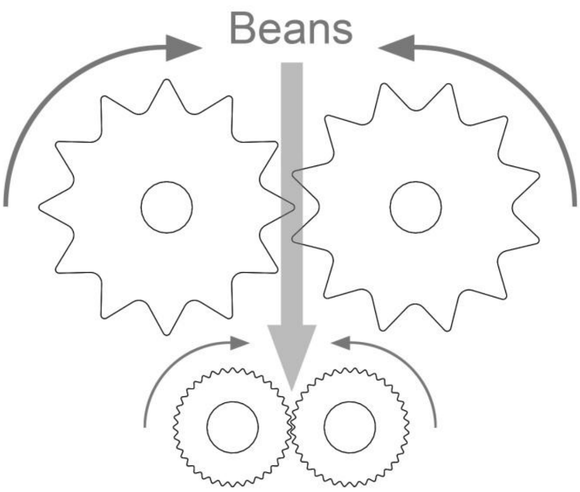


Figure 16: Example of the discussed configuration

7.2.2 Housing

The first parameter is the transmission. The electric motor has to power all rollers such that all rollers rotate at the same angular velocity. The easiest way to achieve this is by using gears. The power is transmitted directly transmitted to 1 roller of each pair. The power is then transmitted to the other roller trough gears at the other end of the shaft. A visualisation of this can be found in figure 17.

The bearings should withstand the radial forces that are created during grinding. Furthermore the distance between the lower set of rollers should be adjustable with 0,5mm to achieve the required different grind sizes.

Lastly the housing should provide a constant supply of beans to the rollers. This can be achieved in a similar way as is used in current bean-to-cup coffee machines by using a hopper design at the bottom of the reservoir to channel the beans into the grinder.

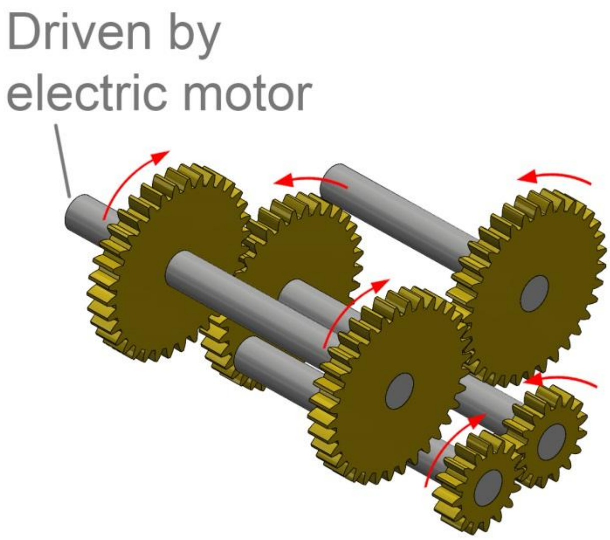


Figure 17: Example of the power transmission

7.2.3 Recommendations

The next recommendations should be executed to test the feasibility of the roller grinder.

- The principle of grinding beans with rollers is already used on commercial and industrial scale, but those rollers have a large diameter. The first step would be to verify that this process is feasible with rollers with a small diameter. Roller grinders with a small roller diameter used for grinding grain are available at www.monsterbrewinghardware.com and are a good starting point.
- If the smaller diameter proves feasible, the noise generation should be compared to a burr grinder. This could be tested by comparing the noise level of the roller grinder used in the above recommendation and a manual burr grinder.
- It should be examined if a roller could design could be achieved that requires only one set of rollers. This would greatly simplify the system, increase compactness and reduce costs. Furthermore less gears are required and therefore less noise will be generated.
- The required torque to crush the beans should be compared to a burr grinder. A higher torque requires a more powerful electric motor, resulting in an increase of noise, dimensions and costs.
- A cost price estimation should give an indication if the concept is feasible for commercial bean-to-cup coffee machines.

7.3 Mortar and pestle concept

The mortar and pestle concept is unlike the roller grinder concept not based on an existing commercial and industrial scale grinding technique. Grinding with a mortar and pestle is normally performed manually, not fast and hasn't a uniform particle size. However, it is a very silent way of grinding the beans. The idea behind the concept is to automate and speed up this process and to achieve a uniform particle size. In this section a proposal for such a design will be presented.

First a possible configuration is presented to explain the idea behind the concept. After this recommendations on the continuation of this concept are presented. Not that the important parameters and configuration will be less developed than the roller grinder concept as it is not based on an existing principle.

7.3.1 Explanation of the idea

A schematic of the idea can be found in figure 18. Instead of crushing the beans underneath the pestle they are crushed between the wall (mortar) and the cylinder (pestle). The lower hinge should only allow a rotation around the r_x and r_z axis. By doing so, the cylinder will not rotate relative of the wall and the beans will be crushed by force instead of friction. This hinge could be realised with a universal joint. The upper hinge should allow all rotation, for which a ball and socket joint can be used. The lower gap between the pestle and mortar is constant and determines the grind size.

It works as follows. The electric motor rotates the upper hinge eccentric, causing the pestle to make a wagging motion in the mortar. If the pestle rotates, the beans falls down as the gap between the wall and the pestle increases. If the pestle than rotates back, the gap between the wall and the pestle decreases and the beans are crushed. This process is repeated until the particles are small enough to fit through the gap between the wall and the pestle.

A profile on the cylinder and wall should prevent that beans are pushed upwards or that the beans are pushed away of the cylinder instead of being crushed. A downwards spiral shape similar to current conical burr grinds could fulfil this.

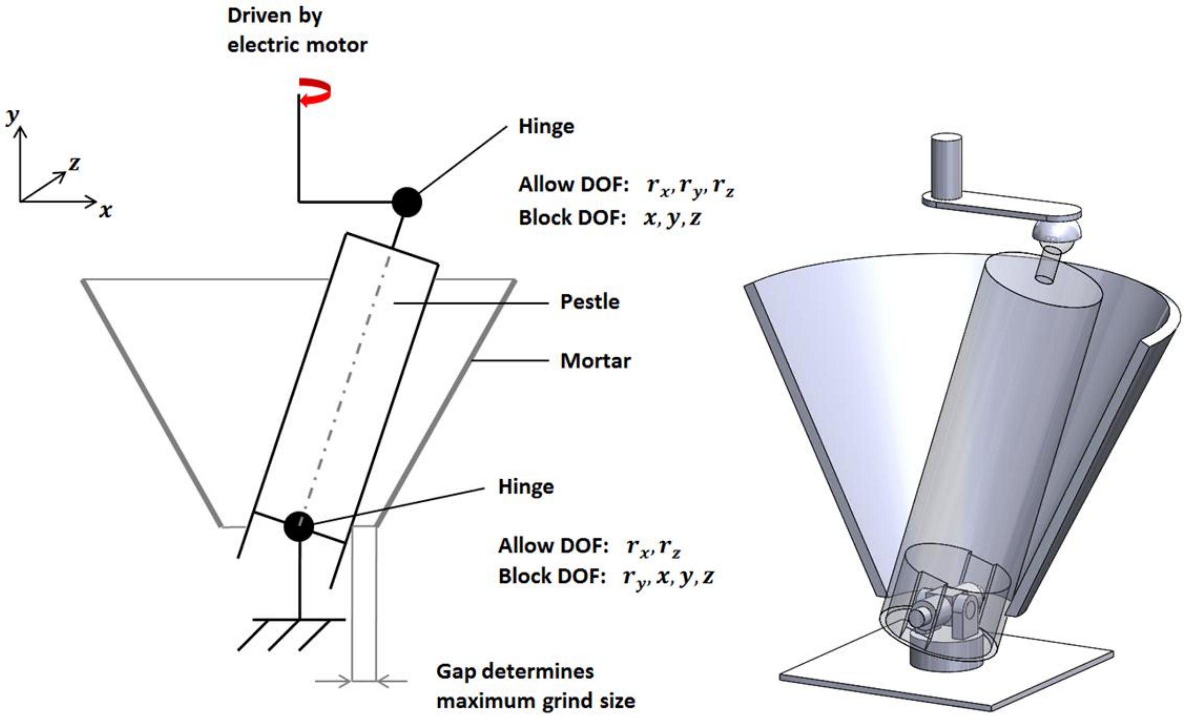


Figure 18: Schematic and visualisation of the mortar and pestle concept

7.3.2 Recommendations

The next recommendations should be executed to test the feasibility of the mortar and pestle concept.

- The principle of crushing beans in this manner should be tested to see if the grinding principle proves feasible. A key element here is the design of the profile.
- If the principle proves feasible, the noise generation should be compared to a burr grinder. This could be tested by comparing the noise level of the setup used in the above recommendation and a manual burr grinder.
- The required torque to crush the beans should be compared to a burr grinder. A higher torque requires a more powerful electric motor, resulting in an increase of noise, dimensions and costs.
- A cost price estimation should give an indication if the concept is feasible for commercial bean-to-cup coffee machines.

Conclusion

The repeatability of the grinding process in a bean-to-cup coffee machine is investigated when multiple cups of coffee are made within a short time span.

- The Miele CM 6310 shows an average increase of 0,0845 gram coffee per cup if a time interval of one minute between grinding and a coarse grind size setting is used.
- The Miele CM7 shows an average increase of 0,1412 gram coffee per cup under the same conditions.
- The repeatability of the volume of coffee grounds is not significantly affected as all average increases are under 1,5% of the total volume. This is within acceptable range.
- There is no information acquired about the change in the particle size distribution and therefore no definite conclusions about the repeatability of the whole process can be made.

A test is performed to investigate the influence of the grind size setting.

- The average amount of coffee per grinding session differs significantly for the fine and coarse grind size setting. The reason for this is that the grinding time for all grind sizes are the same and since a larger grind size requires less grinding, the volume increases.
- The repeatability of the process for a larger grind size is more affected than a fine grind size.

A series of tests is performed to test the influence of the amount of beans in the reservoir.

- The amount of beans in the reservoir has no influence on the average sample weight or the standard deviation of the grinding process.
- The maximum difference between average sample weight is 0,4 gram and between standard deviations is 0,02 gram, which is within acceptable range.
- The repeatability of the grinding process isn't significantly affected and therefore no redesign on this topic is necessary. However, expert knowledge within the company states that the noise that bean-to-cup coffee machines make is experienced as too loud and annoying and a reduction in noise would be a big improvement. Future research should therefore be focussed on reducing noise.

Recommendations

The recommendations can be divided into three parts. The recommendations after testing and the recommendations of the continuation of both concepts.

Testing

- It is determined that the repeatability of the volume of the ground coffee is not significantly affected if the time span between grinding is below a certain threshold. The effect on the particle size distribution is not evaluated and should be tested to see if a significant change is present.
- Heat generation is presented as the main mechanism that influences the repeatability of the grinding process. It is not known where it affects the process. More tests should be performed to identify at what part (grinder/ motor performance) the heat affects the repeatability.
- A design of experiment could be conducted to systematically map in what way all factors influence the grinding process.

Concept roller grinder

- The principle of grinding beans with rollers is already used on commercial and industrial scale, but those rollers have a large diameter. The first step would be to verify that this process is feasible with rollers with a small diameter. Roller grinders with a small roller diameter used for grinding grain are available at www.monsterbrewinghardware.com and are a good starting point.
- If the smaller diameter proves feasible, the noise generation should be compared to a burr grinder. This could be tested by comparing the noise level of the roller grinder used in the above recommendation and a manual burr grinder.
- It should be examined if a roller could design could be achieved that requires only one set of rollers. This would greatly simplify the system, increase compactness and reduce costs. Furthermore less gears are required and therefore less noise will be generated.
- The required torque to crush the beans should be compared to a burr grinder. A higher torque requires a more powerful electric motor, resulting in an increase of noise, dimensions and costs.
- A cost price estimation should give an indication if the concept is feasible for commercial bean-to-cup coffee machines.

Concept mortar and pestle

- The principle of crushing beans in this manner should be tested to see if the grinding principle proves feasible. A key element here is the design of the profile.
- If the principle proves feasible, the noise generation should be compared to a burr grinder. This could be tested by comparing the noise level of the setup used in the above recommendation and a manual burr grinder.
- The required torque to crush the beans should be compared to a burr grinder. A higher torque requires a more powerful electric motor, resulting in an increase of noise, dimensions and costs.
- A cost price estimation should give an indication if the concept is feasible for commercial bean-to-cup coffee machines.

Bibliography

1. *Baggenstoss, J. (2008). Coffee roasting and quencing technology - formation and stability. Zurich: ETH Zürich.*
2. *Czerny, M.; Schieberle, P. Changes in roasted coffee aroma during storage – influences of the packaging. In 19th International Scientific Colloquium on Coffee, Trieste, Italy, 2001; Association Scientifique Internationale pour le Café: Paris, France.*
3. *C. Yeretzian, E. P. (2012). Effect of roasting conditions and grinding on free radical contents of coffee beans stored in air. Food Chemistry Volume 131, Issue 3, 811–816.*
4. *CoffeeCrossroads*. (sd). http://www.coffeecrossroads.com/coffee-101/coffee-roasts-from-light-to-dark
5. B.R. Corrochano, J. M. (2015). A new methodology to estimate the steady-state permeability of roast. *Journal of Food Engineering*, 106-116.
6. *Coffee chemistry*. (sd). Opgehaald van http://www.coffeechemistry.com/quality/grinding/grinding-fundamentals
7. *DoddCoffee*. (sd). Opgehaald van https://www.doddcoffee.com/visual-guide-to-coffee-grinds/
8. *KonaCoffeeBeans*. (sd). Opgehaald van http://www.konacoffeebeans.org/how-to/how-to-grind-coffee-the-only-guide-youll-ever-need
9. Illy, A.; Viani, R. Espresso coffee: The chemistry of quality. Academic Press Limited: London, 1995.
10. Dan Montone, H. K. (sd). *Temperature effects on motor performance.* HARLEYSVILLE, PA: Pittman Motors.
11. Hendershot, J. R. (sd). *Causes and sources of audible noise in electric motors.* Hillsboro, OH 45133: Tridelta Industries INC.
12. Corporation, G. F. (1987). *Patentnr. US4655400 A.* New York.
13. *Illy*. (n.d.). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Illy
14. *Italian Espresso and Coffee Machines*. (n.d.). Retrieved from Illy: www.Illy.com

Appendix A: Test equipment

A.1 Miele CM 6310 bean-to-cup coffee machine

The Miele CM 6310 bean-to-cup countertop coffee machine is used for testing. Miele is a German-based manufacturer of high-end domestic appliances, commercial equipment and fitted kitchens. The Miele CM 6310 is a bean-to-cup coffee machine, which means it makes coffee by grinding beans which are stored in a container at top of the machine. The CM 6310 contains ten portion sizes- single and double servings of espresso, coffee, cappuccino, latte macchiato and cafe latte. Additional features include a heated cup rest and dedicated hot water spout. The specifications can be found in table 14.

Contruction type	
Freestanding bean-to-cup coffee machine	
Design	
Display	DirectSensor
Beverage specialities	
Espresso	
Coffee	
Cappuccino	
Long coffee	
Latte macchiato	
Caffè latte	
Hot water	
Hot milk	
Milk froth	
Consumer benefits	
OneTouch preparation	
One Touch and One Touch for Two	
Flavour preserving conical grinding unit	
Second type of coffee possible using coffee ground	
User profiles programmable	
Grinding grade selectable	
Ground quantity programmable	
Water quantity programmable	
Water temperature programmable	
Amount of milk can be programmed	
Amount of milk froth can be programmed	
Pre-brewing programmable	
User convenience	
Individual language selection	
Height adjustment of infinitely adjustable central spout (cm)	8,0-14,0
Heated cup storage area	
BrilliantLight	
Easily accessible containers	
User convenience	
Capacity of coffee bean container (g)	300
Capacity of water container (l)	1,8
Capacity of waste container (capsules)	dec-14
Programmable switch-on time	
Programmable switch-off time	
Programmable stand-by time	

Cleaning convenience	
Convenient cleaning programmes	
Automatic rinsing of the milk pipework from the water container	
Automatic rinse function	
ComfortClean	
Removable milk pipework	
Removable brew unit	
Efficiency and sustainability	
Energy-saving Eco mode option	
Safety	
System lock	
Technical data	
Niche width (mm)	450
Niche height (mm)	508
Niche depth (mm)	555
Appliance width (mm)	251
Appliance height (mm)	359
Appliance depth (mm)	427
Total connected load kW	1,5
Voltage in (V)	220-240
Fuse rating (A)	10
Number of phases	1
Length of electrical cable (m)	1,4
Accessories supplied	
Descaling agent	
Cleaning tablets	
Stainless steel thermal milk flask	
Coffee spoon for ground coffee	

Table 14: Specifications of the Miele CM 6310

A.2 Miele CM7 bean-to-cup coffee machine

The CM7 is used to see if the repeatability is similarly affected if a time interval of 1 minute between grinding is used. The specifications of the CM7 can be found in table 15

Contruction type	
Freestanding bean-to-cup coffee machine	
Design	
Display	C touch
Beverage specialities	
Espresso	
Coffee	
Cappuccino	
Long coffee	
Ristretto	
Latte macchiato	
Caffè latte	
Hot water	
Hot milk	
Milk froth	

Consumer benefits	
OneTouch preparation	
One Touch and One Touch for Two	
Flavour preserving conical grinding unit	
Second type of coffee possible using coffee ground	
User profiles programmable	
Grinding grade selectable	
Ground quantity programmable	
Water quantity programmable	
Water temperature programmable	
Amount of milk can be programmed	
Amount of milk froth can be programmed	
Pre-brewing programmable	
Coffeepot function	
User convenience	
Individual language selection	
Cup sensor	
Height adjustment of infinitely adjustable central spout (cm)	8,0-16,0
Heated cup storage area	
BrilliantLight	
Easily accessible containers	
User convenience	
Capacity of coffee bean container (g)	500
Capacity of water container (l)	2,2
Capacity of waste container (capsules)	14-16
Programmable switch-on time	
Programmable switch-off time	
Programmable stand-by time	
Time storage in hours	200
Cleaning convenience	
Convenient cleaning programmes	
Automatic rinsing of the milk pipework from the water container	
Automatic rinse function	
ComfortClean	
Removable milk pipework	
Removable brew unit	

Efficiency and sustainability	
Energy-saving Eco mode option	
Safety	
System lock	
Technical data	
Niche width (mm)	510
Niche height (mm)	550
Niche depth (mm)	575
Appliance width (mm)	311
Appliance height (mm)	397
Appliance depth (mm)	445
Total connected load kW	1,5
Voltage in (V)	220-240
Fuse rating (A)	10
Number of phases	1
Length of electrical cable (m)	1,2
Accessories supplied	
Cleaning tablets	
Can of Illy coffee (250g)	
Stainless steel thermal milk flask	

Table 15: Specifications Miele CM7

A.3 Illy espresso beans

Illy is an Italian coffee company that was founded by Francesco Illy in 1933. The company has more than 800 employees and has reached a gross revenue of 361 million euro in 2012 [13]. Illy espresso beans is a medium roast and consists out of 100% Arabica beans, directly purchased from farms spanning four continents. The espresso bean is described by Illy as a quintessential balance of strength and smoothness, with distinct aromas of chocolate, toast, caramel and a light flowers.[14] The beans are packaged in steel canisters and pressurised with an inert gas, which decreases the degradation of the beans.

It was desired to have minimal differences between multiple cans of beans. Illy is a lead in the premium coffee segment and produces a lot of coffee in large batches. Because of this it is assumed that differences between the beans per batch is minimal. For this test beans from two batches are used.

A.4 Other equipment

The Kern KB 240-3N Precision balance is used for measuring the samples. It can weigh samples up to 240 g with a precision of 1 mg. Plastic cups are used to catch and weigh the samples.

Appendix B: Test setup

A picture of the used test setup can be found in figure 19.

Figure 19: Test setup

The test setup should provide a way to catch the coffee ground that otherwise would fall into the brewer. To do so the brewer is taken out and the Miele CM 6310 is adjusted as it has several safeguards to ensure no coffee is made without it in place. The adjustments can be found on the left in figure 20 (left) and are:

1. A mechanical switch is located here to inform the software if the door is open or close. A small part was machined and fixed with tape to bypass this safeguard.
2. A mechanical switch is located here to inform the software if the brewer is in place. A small part was machined and fixed with tape to bypass this safeguard.
3. At this place the brewer connects with the supply of heated water through a nozzle on the brewer. A safeguard within the connection of the nozzle makes sure no hot water flows through the connection without the nozzle in place. The nozzle was disassembled from the brewer and fixed in place with tape.
4. A tube is attached to the nozzle to divert the water from the coffee machine to the sink.

At this point it is possible to make coffee without the brewer and door in place. When the button for coffee is pressed, the machine will follow normal procedure. It will first grind the beans after which the coffee ground is tunnelled through the short horizontal shaft and falls into the place where normally the brewer is. A picture of the end of this shaft can be found in figure 20 (right). During testing the coffee ground is caught when exiting this shaft.

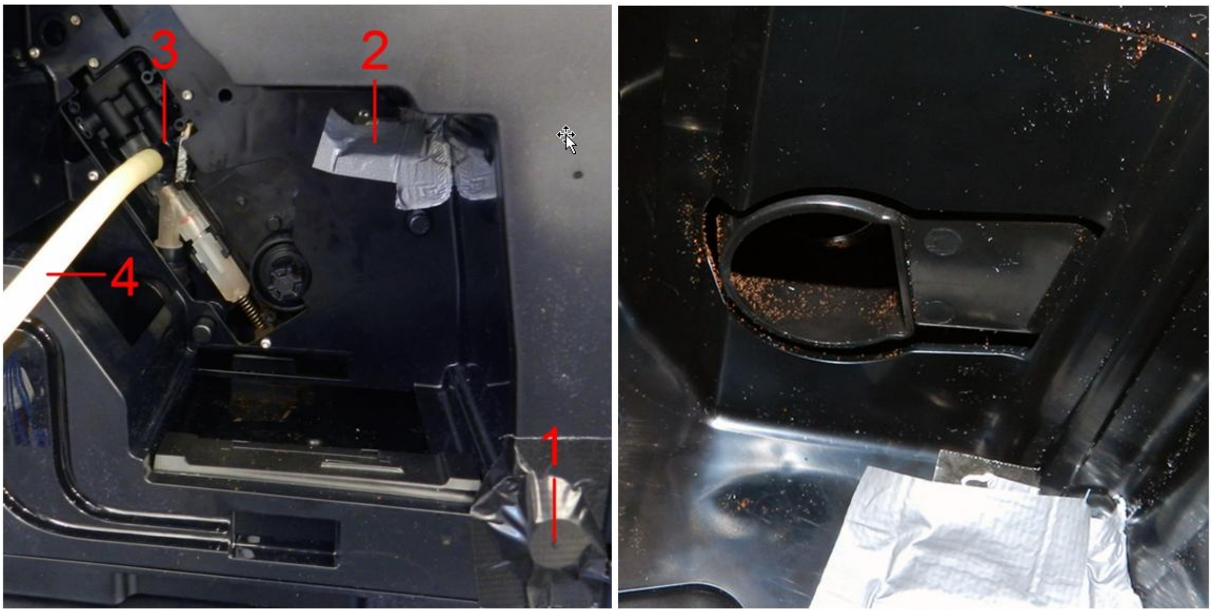


Figure 20: Alterations (left) and the end of the horizontal shaft (right)

Appendix C: Procedures

A standard procedure is created for each test. The procedure consists out of two parts, the procedure before and during testing. Minor variations on the procedure during testing are present due to the conditions of the test. The procedures for each test will be presented in this section.

C.1 Before testing

The next steps are taken before a test is performed:

1. Record the batch of coffee that is used
2. Empty the bean reservoir
3. Add 20 grams of beans to the reservoir
4. Perform the grinding process
5. Add the amount off coffee that is ground back to the reservoir as beans
6. Fill the water reservoir and empty the drip trey

Beans from only one can of Illy espresso beans are used for a test. This is to minimise influence of differences in bean characteristics during testing. The batch coffee that is used is identified by the expiration date on the can, which is written down as it may explain differences between tests later on.

The bean reservoir is emptied by manually collecting all beans still present in the reservoir. Beans that are present at the entrance of the grinder and can't be collected manually are removed using a vacuum cleaner.

Between 10 and 12 grams of beans is ground each session. By maintaining a constant 20 grams of beans in the reservoir there is a sufficient amount of beans present while the influence is kept to a minimum. At this point the beans in the reservoir are all replaced, but the beans/ground that are still in the grinder/transportation tube not yet. This coffee is replaced with the new coffee by performing the grinding session one time before the test. The weight of coffee that is ground during this step is measured. A cup is then filled with the same amount of beans using the scale and added back to the grinder. This way the amount of beans in the grinder is 20 grams again.

These steps are taken to ensure that all coffee during a test comes from the same batch. At last the water reservoir is filled and the drip trey is emptied to ensure the test can be performed with no interruptions.

C.2 Procedure during test 1 and 4

The next steps are taken during test 1 and 4.

1. Weigh 10 sample cups
2. Weigh 9 cups with an average amount of beans
3. Grind 10 times with a 1 minute interval and add 1 cup with beans to the reservoir between each grinding session
4. Weigh the 10 samples

The interval of 1 minute between each grinding session makes it impossible to weigh the sample and add the corresponding amount of beans to the reservoir between measurements. Therefore all cups used to weigh samples are weighed in advance. A significant deviation in the weight of the plastic cups is present and therefore each cup is separately weighed and corresponds with a specified sample. Thus cup 1 has weight x1 and is used for sample 1, cup 2 has weight x2 and is used for sample 2 etc.

Since no measurements are performed between grinding sessions, the amount of beans that have to be added back to the reservoir is unknown. There was already a grind session performed during the procedure before testing. This sample was weighed and is a good indication of how many beans have to be added. 9 Cups are filled with this amount of beans.

The grind session is performed 10 times. The cup is used to catch all coffee grounds that otherwise would reach the brewer. A digital clock is used to make sure that every 60 seconds a new grinding session is started. Between each grinding session a cup with beans is added to the reservoir.

Each sample is weighed after the grinding sessions. This is the weight of the coffee grounds and the cup together. Since the weight of the cup was determined beforehand, it can be subtracted leaving only the weight of the coffee grounds in the cup.

C.3 Procedure test 2 and 3

The next steps are taken during test 2 and 3. These steps are performed 10 times with the specified time interval between grinding sessions.

1. A cup is placed on the scale and the scale is calibrated to 0
2. The grinding session is performed and the coffee ground is caught using the cup
3. The sample is weighed
4. A new cup is placed on the scale, and the scale is calibrated to 0
5. The weight of the sample is added in beans to the new cup
6. The beans are added to the reservoir

The larger interval times makes it possible to weigh the samples and beans between each measurement. A cup is placed on the scale after which the scale is calibrated to 0 before each grinding session. Hereafter the grinding session is performed and the cup is used to catch the coffee grounds. The cup with coffee grounds is then put on the scale. Since the scale is already calibrated with the weight of the cup, the scale gives the weight of the coffee grounds. A new cup is placed on the scale after which the scale is calibrated to 0. The amount of beans equal to the weight of the sample is then added to the cup after which these beans are added to the reservoir.

C.4 Test 5

The procedure of test 3 is very similar to that of test 2 and 3, except for the last 3 steps. As no new beans are added between grinding sessions, only the first three steps are performed.

Appendix D: Testing the repeatability - results

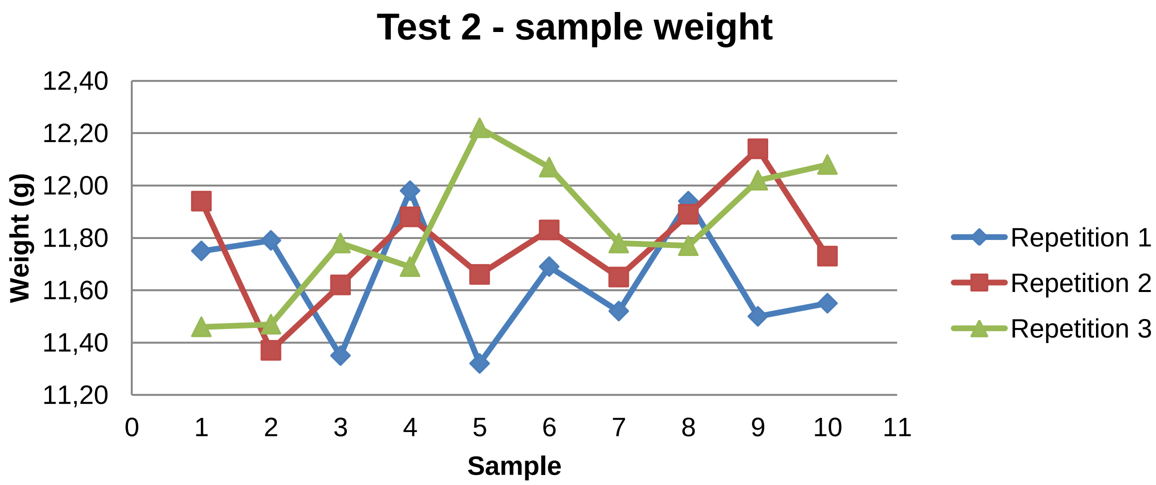
The results of the test that were performed can be found in this appendix. First the results as recorded during tested will be presented, after which a visualisation of the results will be shown.

D.1 Test 1

Test 1 - Δt = 1 min										
Grind size setting	Finest			Beans in reservoir			Constant			
Repetition 1										
Date	13-10-2015			Std. Dev. Samples			0,35			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,25			
Avg. Weight samples (g)	10,75			Trendline (a*sample + b) (g)			0,0831*sample + 10,292			
Sample	1	2	3	4	5	6	7	8	9	10
Time	8:47	8:48	8:49	8:50	8:51	8:52	8:53	8:54	8:55	8:56
Weight cup (g)	3,20	3,20	3,08	3,17	3,16	3,05	3,15	3,19	3,06	3,17
Weight measurement (g)	13,77	13,36	13,74	13,57	13,96	14,23	14,02	13,80	13,92	14,54
Weight sample (g)	10,56	10,16	10,66	10,40	10,80	11,18	10,88	10,61	10,86	11,37
Repetition 2										
Date	13-10-2015			Std. Dev. Samples			0,20			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,18			
Avg. Weight samples (g)	11,04			Trendline (a*sample + b) (g)			0,0297*sample + 10,877			
Sample	1	2	3	4	5	6	7	8	9	10
Time	9:55	9:56	9:57	9:58	9:59	10:00	10:01	10:02	10:03	10:04
Weight cup (g)	3,20	3,20	3,08	3,17	3,16	3,05	3,15	3,19	3,07	3,17
Weight measurement (g)	14,25	13,87	13,97	14,20	14,07	14,40	14,42	14,29	14,25	14,12
Weight sample (g)	11,05	10,68	10,89	11,03	10,91	11,35	11,27	11,10	11,19	10,95
Repetition 3										
Date	13-10-2015			Std. Dev. Samples			0,40			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,32			
Avg. Weight samples (g)	10,99			Trendline (a*sample + b) (g)			0,0824*sample + 10,539			
Sample	1	2	3	4	5	6	7	8	9	10
Time	11:05	11:06	11:07	11:08	11:09	11:10	11:11	11:12	11:13	11:14
Weight cup (g)	3,23	3,23	3,11	3,19	3,18	3,07	3,17	3,21	3,09	3,18
Weight measurement (g)	14,40	13,68	13,73	13,84	14,26	13,88	13,89	14,91	14,41	14,57
Weight sample (g)	11,16	10,45	10,62	10,64	11,09	10,81	10,72	11,70	11,33	11,39

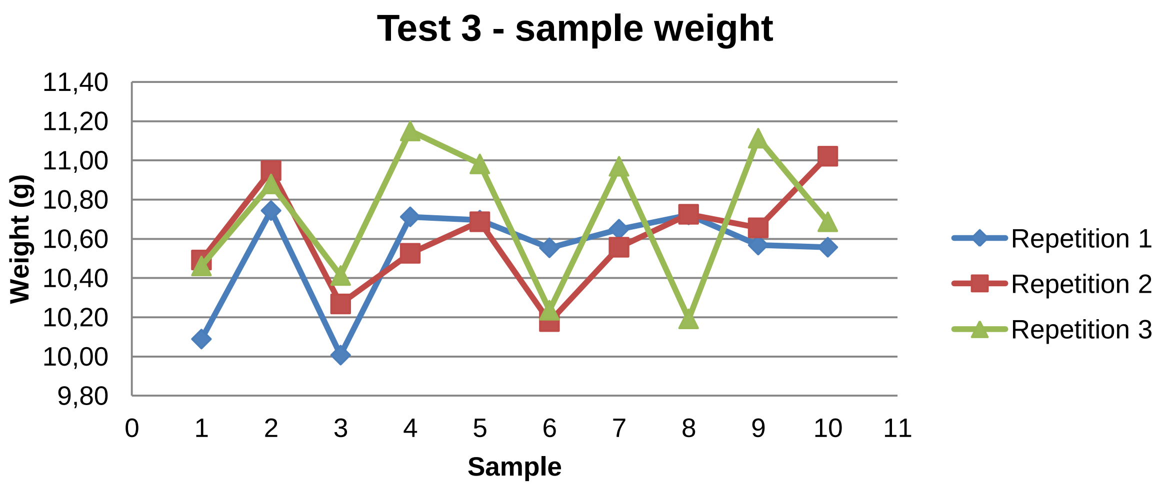
D.2 Test 2

Test 2 - Δt = 5 min										
Grind size setting	Finest			Beans in reservoir			Constant			
Repetition 1										
Date	5-10-2015			Std. Dev. Samples			0,23			
Coffee batch	06/2016 - 24-08:42			Std. Dev. Without trend			0,23			
Avg. Weight samples (g)	11,64			Trendline (a*sample + b) (g)			-0,0115*sample + 11,702			
Sample	1	2	3	4	5	6	7	8	9	10
Time	12:50	12:55	13:00	13:05	13:10	13:15	13:20	13:25	13:30	13:35
Weight sample (g)	11,75	11,79	11,35	11,98	11,32	11,69	11,52	11,94	11,50	11,55
Repetition 2										
Date	6-10-2015			Std. Dev. Samples			0,21			
Coffee batch	06/2016 - 24-08:39			Std. Dev. Without trend			0,20			
Avg. Weight samples (g)	11,77			Trendline (a*sample + b) (g)			0,0262*sample + 11,702			
Sample	1	2	3	4	5	6	7	8	9	10
Time	8:45	8:50	8:55	9:00	9:05	9:10	9:15	9:20	9:25	9:30
Weight sample (g)	11,94	11,37	11,62	11,88	11,66	11,83	11,65	11,89	12,14	11,73
Repetition 3										
Date	6-10-2015			Std. Dev. Samples			0,26			
Coffee batch	06/2016 - 24-08:39			Std. Dev. Without trend			0,19			
Avg. Weight samples (g)	11,83			Trendline (a*sample + b) (g)			0,0576*sample + 11,517			
Sample	1	2	3	4	5	6	7	8	9	10
Time	10:30	10:35	10:40	10:45	10:50	10:55	11:00	11:05	11:10	11:15
Weight sample (g)	11,46	11,47	11,78	11,69	12,22	12,07	11,78	11,77	12,02	12,08



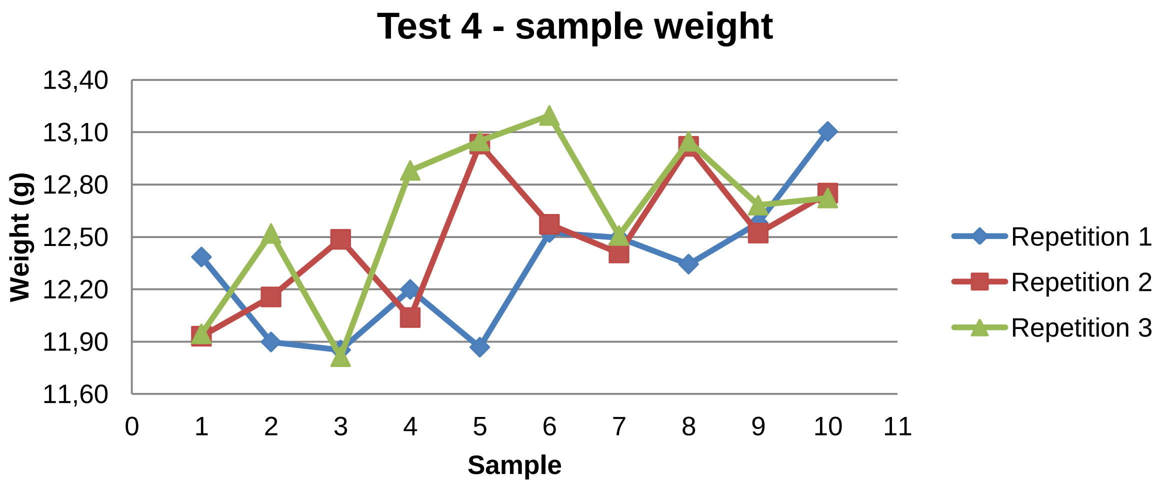
D.3 Test 3

Test 3 - Δt = 40 min										
Repetition 1										
Date	14-10-2015			Std. Dev. Samples			0,26			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,24			
Avg. Weight samples (g)	10,53			Trendline (a*sample + b) (g)			0,0377*sample + 10,322			
Sample	1	2	3	4	5	6	7	8	9	10
Time	8:30	9:10	9:50	10:30	11:10	11:50	12:30	13:10	13:50	14:30
Weight sample (g)	10,09	10,74	10,01	10,71	10,70	10,55	10,65	10,72	10,57	10,56
Repetition 2										
Date	15-10-2015			Std. Dev. Samples			0,26			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,25			
Avg. Weight samples (g)	10,61			Trendline (a*sample + b) (g)			0,0278*sample + 10,453			
Sample	1	2	3	4	5	6	7	8	9	10
Time	8:30	9:10	9:50	10:30	11:10	11:50	12:30	13:10	13:50	14:30
Weight sample (g)	10,49	10,95	10,27	10,53	10,69	10,18	10,56	10,73	10,66	11,02
Repetition 3										
Date	16-10-2015			Std. Dev. Samples			0,36			
Coffee batch	08/2017 - 25-16:13			Std. Dev. Without trend			0,36			
Avg. Weight samples (g)	10,71			Trendline (a*sample + b) (g)			0,0077*sample + 10,666			
Sample	1	2	3	4	5	6	7	8	9	10
Time	8:30	9:10	9:50	10:30	11:10	11:50	12:30	13:10	13:50	14:30
Weight sample (g)	10,46	10,88	10,41	11,15	10,98	10,24	10,97	10,19	11,11	10,69



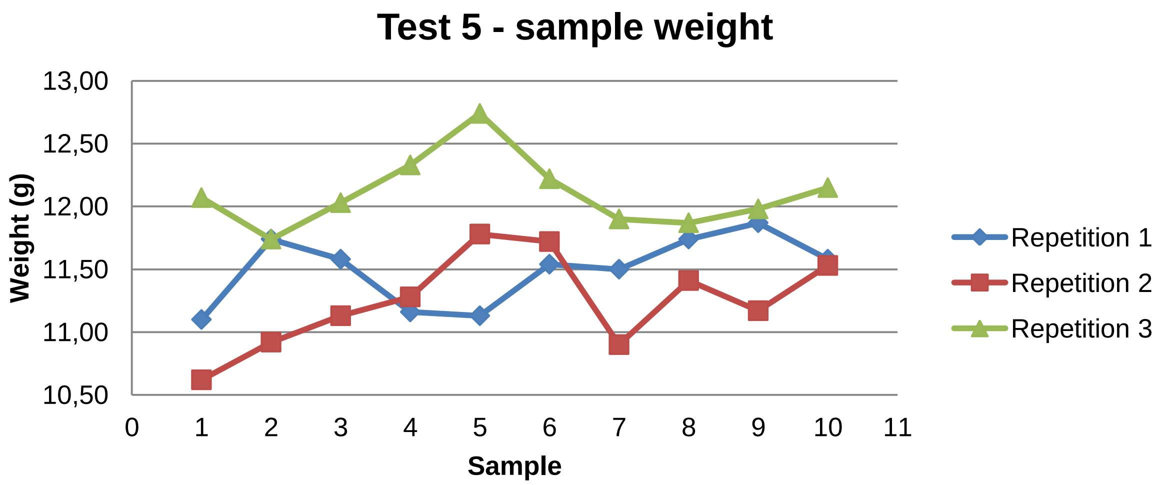
D.4 Test 4

Test 4 - Δt = 1 min										
Grind size setting	Coarsest			Beans in reservoir			Constant			
Repetition 1										
Date	13-10-2015			Std. Dev. Samples			0,39			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,27			
Avg. Weight samples (g)	12,33			Trendline (a*sample + b) (g)			0,0924*sample+11,817			
Sample	1	2	3	4	5	6	7	8	9	10
Time	13:21	13:22	13:23	13:24	13:25	13:26	13:27	13:28	13:29	13:30
Weight cup (g)	3,21	3,21	3,10	3,19	3,17	3,07	3,17	3,21	3,08	3,19
Weight measurement (g)	15,60	15,11	14,95	15,38	15,04	15,59	15,66	15,55	15,66	16,30
Weight sample (g)	12,39	11,90	11,85	12,20	11,87	12,53	12,50	12,34	12,58	13,10
Repetition 2										
Date	13-10-2015			Std. Dev. Samples			0,38			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,29			
Avg. Weight samples (g)	12,49			Trendline (a*sample + b) (g)			0,0803*sample + 12,05			
Sample	1	2	3	4	5	6	7	8	9	10
Time	14:35	14:36	14:37	14:38	14:39	14:40	14:41	14:42	14:43	14:44
Weight cup (g)	3,21	3,20	3,09	3,18	3,16	3,06	3,16	3,20	3,07	3,18
Weight measurement (g)	15,14	15,36	15,57	15,21	16,19	15,63	15,56	16,22	15,59	15,93
Weight sample (g)	11,93	12,16	12,49	12,04	13,03	12,57	12,41	13,02	12,52	12,75
Repetition 3										
Date	13-10-2015			Std. Dev. Samples			0,46			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,39			
Avg. Weight samples (g)	12,64			Trendline (a*sample + b) (g)			0,0808*sample + 12,192			
Sample	1	2	3	4	5	6	7	8	9	10
Time	15:45	15:46	15:47	15:48	15:49	15:50	15:51	15:52	15:53	15:54
Weight cup (g)	3,21	3,20	3,09	3,17	3,18	3,07	3,17	3,21	3,07	3,17
Weight measurement (g)	15,16	15,72	14,91	16,06	16,23	16,26	15,67	16,26	15,75	15,90
Weight sample (g)	11,95	12,52	11,81	12,88	13,05	13,20	12,51	13,05	12,68	12,72



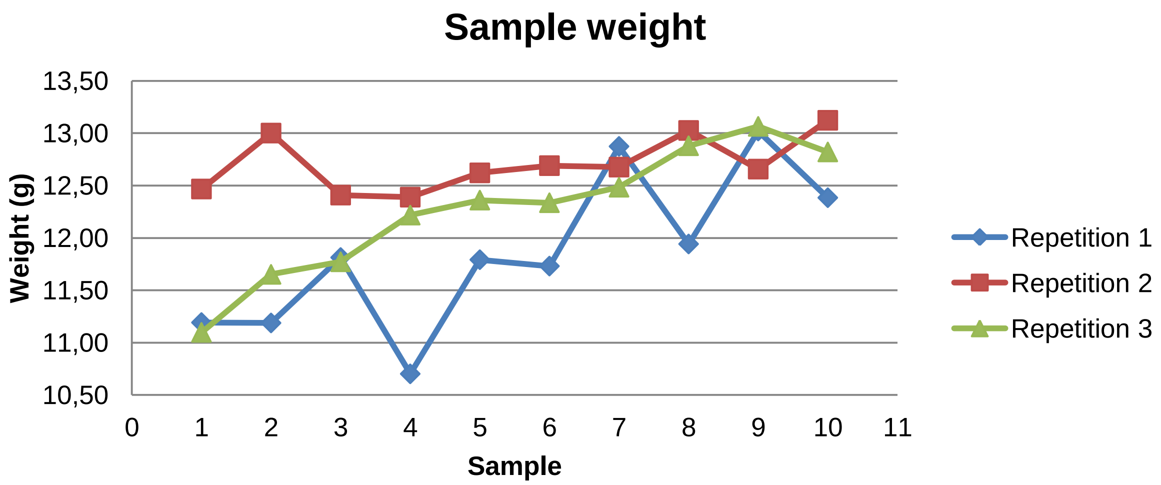
D.5 Test 5

Test 5 - Δt = 5 min										
Grind size setting	Finest			Beans in reservoir			Normal			
Repetition 1										
Date	5-10-2015			Std. Dev. Samples			0,27			
Coffee batch	06/2016 - 24-08:42			Std. Dev. Without trend			0,24			
Avg. Weight samples (g)	11,49			Trendline (a*sample + b) (g)			0,0452*sample + 11,245			
Sample	1	2	3	4	5	6	7	8	9	10
Time	15:00	15:05	15:10	15:15	15:20	15:25	15:30	15:35	15:40	15:45
Weight sample (g)	11,10	11,74	11,58	11,16	11,13	11,54	11,50	11,74	11,87	11,58
Repetition 2										
Date	6-10-2015			Std. Dev. Samples			0,37			
Coffee batch	06/2016 - 24-08:39			Std. Dev. Without trend			0,32			
Avg. Weight samples (g)	11,25			Trendline (a*sample + b) (g)			0,0615*sample + 10,908			
Sample	1	2	3	4	5	6	7	8	9	10
Time	12:30	12:35	12:40	12:45	12:50	12:55	13:00	13:05	13:10	13:15
Weight sample (g)	10,62	10,92	11,13	11,28	11,78	11,72	10,90	11,41	11,17	11,53
Repetition 3										
Date	6-10-2015			Std. Dev. Samples			0,28			
Coffee batch	06/2016 - 24-08:39			Std. Dev. Without trend			0,28			
Avg. Weight samples (g)	12,10			Trendline (a*sample + b) (g)			-0,0013*sample + 12,11			
Sample	1	2	3	4	5	6	7	8	9	10
Time	14:15	14:20	14:25	14:30	14:35	14:40	14:45	14:50	14:55	15:00
Weight sample (g)	12,07	11,74	12,03	12,33	12,74	12,22	11,90	11,87	11,98	12,15



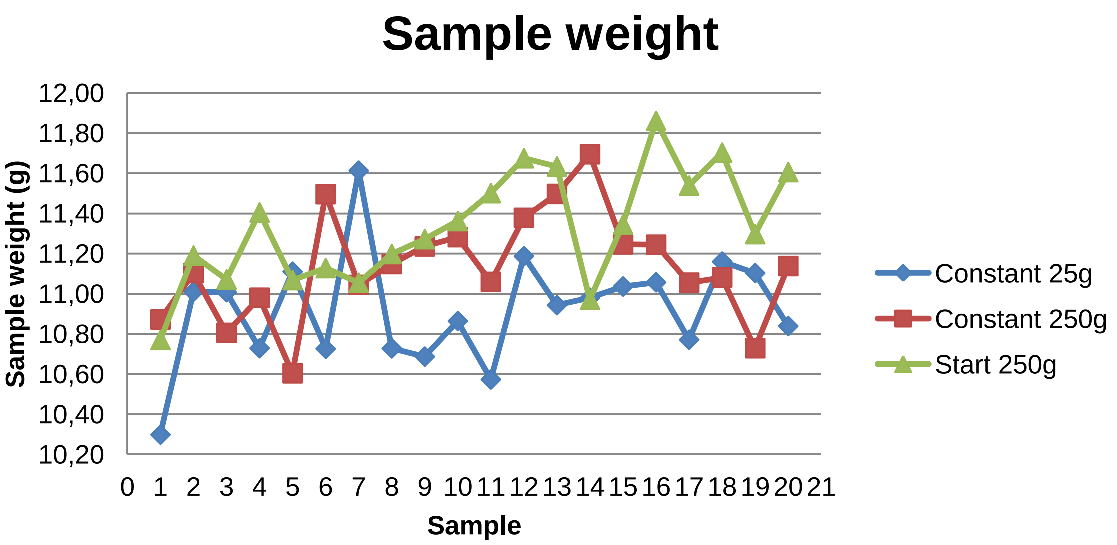
Appendix E: Repeatability Miele CM7 – results

Test CM7 - Δt = 1 min										
Grind size setting	Finest			Beans in reservoir			Constant			
Repetition 1										
Date	4-11-2015			Std. Dev. Samples			0,74			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,48			
Avg. Weight samples (g)	11,86			Trendline (a*sample + b) (g)			0,1858*sample + 10,842			
Sample	1	2	3	4	5	6	7	8	9	10
Time	12:00	12:01	12:02	12:03	12:04	12:05	12:06	12:07	12:08	12:09
Weight cup (g)	3,363	3,262	3,314	3,356	3,240	3,290	3,330	3,239	3,298	3,254
Weight measurement (g)	14,555	14,450	15,127	14,058	15,032	15,021	16,204	15,181	16,319	15,638
Weight sample (g)	11,19	11,19	11,81	10,70	11,79	11,73	12,87	11,94	13,02	12,38
Repetition 2										
Date	4-11-2015			Std. Dev. Samples			0,26			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,22			
Avg. Weight samples (g)	12,71			Trendline (a*sample + b) (g)			0,0455*sample + 12,456			
Sample	1	2	3	4	5	6	7	8	9	10
Time	13:00	13:01	13:02	13:03	13:04	13:05	13:06	13:07	13:08	13:09
Weight cup (g)	3,368	3,267	3,319	3,361	3,245	3,295	3,335	3,244	3,303	3,259
Weight measurement (g)	15,835	16,268	15,728	15,750	15,866	15,985	16,011	16,270	15,960	16,382
Weight sample (g)	12,47	13,00	12,41	12,39	12,62	12,69	12,68	13,03	12,66	13,12
Repetition 3										
Date	4-11-2015			Std. Dev. Samples			0,61			
Coffee batch	08/2017 - 25-16:14			Std. Dev. Without trend			0,19			
Avg. Weight samples (g)	12,27			Trendline (a*sample + b) (g)			0,1922*sample + 11,212			
Sample	1	2	3	4	5	6	7	8	9	10
Time	15:40	15:41	15:42	15:43	15:44	15:45	15:46	15:47	15:48	15:49
Weight cup (g)	3,386	3,288	3,340	3,386	3,271	3,323	3,368	3,273	3,335	3,291
Weight measurement (g)	14,484	14,940	15,112	15,604	15,632	15,659	15,852	16,153	16,400	16,112
Weight sample (g)	11,10	11,65	11,77	12,22	12,36	12,34	12,48	12,88	13,07	12,82



Appendix F: Testing the amount of beans in the reservoir – results

		Constant 25 gram		Constant 250 gram		Start 250 gram	
		28-10-2015		29-10-2015		29-10-2015	
		08/2017 - 25-16:13		08/2017 - 25-16:13		08/2017 - 25-16:13	
	Sample	Time	Weight	Time	Weight	Time	Weight
	1	11:50	10,298	9:10	10,872	13:40	10,770
	2	12:00	11,010	9:20	11,103	13:50	11,190
	3	12:10	11,008	9:30	10,805	14:00	11,071
	4	12:20	10,729	9:40	10,980	14:10	11,405
	5	12:30	11,110	9:50	10,604	14:20	11,068
	6	12:40	10,726	10:00	11,496	14:30	11,128
	7	12:50	11,613	10:10	11,044	14:40	11,055
	8	13:00	10,728	10:20	11,148	14:50	11,198
	9	13:10	10,687	10:30	11,236	15:00	11,272
	10	13:20	10,864	10:40	11,282	15:10	11,362
	11	13:30	10,573	10:50	11,059	15:20	11,501
	12	13:40	11,187	11:00	11,378	15:30	11,675
	13	13:50	10,943	11:10	11,497	15:40	11,634
	14	14:00	10,980	11:20	11,695	15:50	10,970
	15	14:10	11,036	11:30	11,246	16:00	11,345
	16	14:20	11,057	11:40	11,244	16:10	11,861
	17	14:30	10,771	11:50	11,055	16:20	11,539
	18	14:40	11,160	12:00	11,081	16:30	11,703
	19	14:50	11,103	12:10	10,729	16:40	11,297
	20	15:00	10,839	12:20	11,138	16:50	11,606
Sample mean (g)			10,921		11,135		11,333
Sample std. Dev. (g)			0,275		0,268		0,283



PCV Group
people creating value

Enschede office
Oldenzaalsestraat 125
7514 DP Enschede
The Netherlands
+31 (0)53 434 26 24
info@pcvgroup.com

Odenthal office
Altenberger-Dom-Strasse 20
51519 Odenthal
Deutschland
+49 (0)220 297 125
info@pcvgroup.com

Mailing address
Oldenzaalsestraat 125
7514 DP Enschede
The Netherlands

People Creating Value BV
KvK 01163001
IBAN NL 10 RABO 0 123456789
BTW NL8212 53 591 B01