Optimization of a Floor Grinding Machine for Uniform Grinding Pattern

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Abstract

Husqvarna Construction is one of the leading construction machinery manufacturers in the world. To stay in the forefront, investing in novel methods to model, test & and optimizing machinery is crucial. The most important part of development and testing is to bridge the gap between desired and actual results. Model-based Simulation in testing plays a superior role in visualizing possibilities while cutting down the usage of resources.

Floor Grinders are common in industrial and commercial settings to achieve desired floor results. Like every machinery, optimization towards achieving better results is a necessity. The purpose of this thesis is to develop a methodology to optimize HCE’s floor-grinding machine through its grinding pattern and further study & gather data about the key indicators for an optimum grinding pattern. This is done by setting up a grinding pattern simulation of the PG 690 floor grinder on SIMGRIND (Husqvarna CE’s own simulation application).

A metric was developed to determine whether a grinding pattern is good and by utilizing the metric as an optimization goal, the impact of different machine parameters on the grinding pattern was established. The grinding & travel speeds were viewed as ratios and it was observed that optimized patterns were attained at particular ratios. Another crucial factor that was studied was the impact of oscillations. Further, the impact of grinding head size on the grinding pattern was also studied.

The investigation was limited to a simulation study since physical validation opened up several uncertainties beyond the scope of this work. At the end of this work, a few recommendations for developing physical validation setups are made, to test the results of the simulation.
Acknowledgements

I begin this acknowledgement section by expressing my heartfelt gratitude for the remarkable journey of exploration that both my academic pursuits and life itself have been. None of this would have been possible without the unwavering support and encouragement of numerous individuals and organizations. First and foremost, I extend my gratitude to my parents, Srikantha Dath and Lakshmi, and my dear sister Yashaswini, for their enduring love and support, which has been my anchor throughout. I am thankful to my extended family, including my aunts and uncles for their support.

I owe a significant debt of thanks to Husqvarna Construction and the Floor Grinding division for providing me with the invaluable opportunity and resources necessary to successfully complete this thesis. I extend my deepest appreciation to my supervisors, Casper Christiansen and Linus Ottosson, as well as my manager, Dan Paulsson, for their constant support, guidance, and motivation during this thesis journey. A special mention goes to Daniel Karlsson for his invaluable insights that set my work in motion. I also want to express my gratitude to all my colleagues in the Floor Grinding division for their support during this time.

My heartfelt thanks go to Linköping University and the Department of Product Realization for granting me the opportunity to pursue my master’s course and for imparting invaluable knowledge. I am particularly grateful to Sanjay Nambair and Mehdi Tarkian, my supervisor and examiner, for their continuous support and guidance throughout the thesis process. I’d also like to acknowledge Olle Vidner for his insights into the analysis of my results.

A heartfelt shoutout goes to my friends Sesh and Aish, along with my dear friends at LiU and Göteborg, who made life away from home feel a little closer to heart.

Adithya S Dath
# Nomenclature

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<td>LiU</td>
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<tr>
<td>Husqvarna CE</td>
<td>Husqvarna Construction Equipment</td>
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<tr>
<td>RC</td>
<td>Radio Controlled</td>
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<tr>
<td>CoT</td>
<td>Centre of Tool</td>
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<tr>
<td>CoD</td>
<td>Centre of Disc</td>
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<tr>
<td>CoH</td>
<td>Centre of Head/ Grinding Head</td>
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<tr>
<td>CoM</td>
<td>Centre of Machine</td>
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<tr>
<td>CV</td>
<td>Coefficient of Variance</td>
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<td>DO</td>
<td>Design Optimization</td>
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<td>GA</td>
<td>Genetic Algorithm</td>
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<tr>
<td>CNC</td>
<td>Computerized Numerical Control</td>
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<td>MRR</td>
<td>Material Removal Rate</td>
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1 Introduction

In the pursuit of efficiency, precision and sustainability in modern construction processes, the optimization of floor grinders has emerged as a paramount endeavour. Floor grinders are tasked with the intricate process of refining surface floors to attain refinement and quality while also playing a pivotal role in achieving safety, aesthetics and functionality in diverse industrial contexts [1]. The multifaceted nature of the tasks assigned to floor grinding machines poses an inherent challenge - simultaneous consideration of multiple conflicting objectives such as maximizing material removal rate while minimizing energy consumption and surface roughness, in addition to extending the grinding tool life.

The material-removing processes on CNC machines such as milling, turning and grinding have equations to calculate the theoretical material removal rate. These equations provide a clear understanding of the possible outcome of the processes. Besides, there exist methods to determine MRR even through machining history data [2]. However, unlike these cases, no such numerical equations or empirical data exists for the case of floor grinders. With sustainability taking centre stage in modern construction practices, the optimization of energy consumption and material usage in floor grinding machines has gained prominence. This thesis delves into a novel method of optimizing the grinding pattern of floor grinding machines through model-based methods perhaps also called digital twins.

1.1 Background

The background section will serve as an introduction to what floor grinding machines are, the existing machines in Husqvarna, tool grinding tools and so on.

1.1.1 Introduction to Floor Grinding Machines

Floor grinding machines are purpose-built equipments employed for the grinding and polishing of diverse flooring surfaces, which are usually composed of concrete, stone, or other robust materials. They find frequent utilization in construction, renovation, and maintenance endeavours, aiming to ready and improve the condition of the floor’s surface, restore damaged surfaces and level uneven joins. These machines are equipped with either rotating discs or planetary heads that have abrasive elements called tools or pads affixed to them. These abrasive elements effectively grind the uppermost layer of the floor, eliminating imperfections, coatings, adhesives, and other surface materials. The rotating discs or planetary heads are usually driven by a gear or chain drive, based on the application. These machines can be categorized into two primary types based on their power source, electric and gas-driven floor grinders. All of the key players in the floor grinding machine market in the EU including Scan Maskin AB, Klinedex and Husqvarna CE employ a planetary system for grinding. Electric floor grinders are commonly associated with the EU market while the gas-powered grinders are associated outside the EU, due to its regulations. While floor grinding machines are designed to provide precise control over the grinding process, it is essential to note that the results may not always be uniform or consistent.
Various factors can influence the outcome, such as the condition of the floor, the type and hardness of the material being ground, operator technique, and other external variables.

Over time and with advancements in technology, the field of floor grinding has evolved in multiple ways. After the introduction of the first-generation floor grinders in the early 20th century, various advancements such as motorized operation, dust extraction systems, planetary grinding systems, and diamond tools for grinding have been established. The need for increased efficiency, productivity, and operator comfort has driven the constant evolution of floor grinders.

1.1.2 Husqvarna’s Floor Grinding Machines

Husqvarna’s passion towards innovation has played an integral role in shaping the organisation into its current form. It is now an essential component of its efforts towards achieving a sustainable future. Husqvarna’s portfolio also offers a series of floor grinding machines under its construction equipment division[1]. The concrete floor grinders at Husqvarna’s machines use a planetary motion to remove material from industrial floors, such as epoxy coatings and concrete. The grinding head of the machine has a large head that rotates three or four grinding discs. Each disc has between three and six diamond grinding segments on them. The grinding segments generated due to this planetary motion are complex and chaotic yet deterministic.
1.1.3 Floor Grinding Tools at Husqvarna

The reliability, durability, and versatility of Husqvarna’s floor grinding tools are well-known. These tools have been designed to ensure reliable and accurate outcomes by effectively eliminating coatings, adhesives, and other surface materials. Various applications are catered to by offering tools suitable for different floor hardness and material removal rates. The metal-bonded tools are recommended for grinding on concrete surfaces. Coarser finishes are achieved with lower grit sizes, which are more abrasive and remove material at a faster rate. Conversely, finer grit sizes result in a smoother surface finish, albeit with a slower removal rate. For challenging concrete floors, it is recommended to use soft-bonded tools to enable deeper penetration of the diamonds during grinding. In contrast, softer floors benefit from the use of hard-bonded tools.

1.1.4 Concrete Surfaces in the context of Floor Grinding Machines

The condition and characteristics of the concrete surface play a crucial role in determining the approach and effectiveness of a floor grinding process. Factors such as hardness, age, presence of coatings or adhesives, and any existing imperfections impact the grinding process. Moisture content is another important factor during a floor grinding process. Usually what happens is that concrete surfaces are never consistent. A lot of environmental factors determine the consistency of concrete. This hence becomes entirely uncertain during the grinding process. One of the main reasons why the grinding process, material removal rate etc is uncertain is because of this.

1.1.5 The Machine, Tool & Concrete Surface trifecta

Achieving effective and desired results in grinding operations is contingent upon the crucial inter-relationship between three elements: the grinding machine, the grinding tool, and the concrete surface. Consistent results are controlled by floor grinding machines’ design and machine parameters, which come in different sizes and configurations. The crucial aspect in attaining the desired grinding outcome is properly selecting the tool and abrasives. Throughout the tool’s lifespan, the amount of material removal will never be the same, and the material removal rate is also determined by the velocities at which the tools move. The completion of the trifecta is represented by the grinding surface/concrete itself. Factors such as the consistency of the surface, moisture content, hardness of the surface, and flatness before grinding contribute to the outcome of the grinding process.

In summary, the achievement of effective and desired results in grinding operations is dependent on the inter-relationship between the grinding machine, grinding tool, and concrete surface. The consistent results are controlled by the design and machine parameters of floor grinding machines. The proper selection of the grinding tool and abrasives is crucial for attaining the desired grinding outcome.
1.2 Previous Work

The machine under study is the PG 690 RC, shown in figure 3. This particular machine belongs to Husqvarna’s PG machine series, which utilizes dual drive technology and can accommodate up to three discs. While the optimization method can be applied to any machine within the PG generation, the choice to focus on the PG 690 RC stems from its popularity in Husqvarna CE’s product catalogue.
SIMGRIND is an simulation software developed in-house, capable of simulating different grinding processes and approximating a number of floor parameters upon grinding. More theory about SIMGRIND will be shared in the following sections. It is important to note that no previous optimization tests have been conducted using SIMGRIND. SIMGRIND, which is still in the development phase, has primarily been utilized to explore aspects such as tool movement and area coverage with different tools. The ultimate purpose of SIMGRIND’s development is to facilitate optimization in grinding processes. In the absence of optimization tests using SIMGRIND, physical prototypes and purpose-driven tests have been carried out. These tests have aided in identifying parameters that yield visually favorable results, with feedback from product specialists also contributing to the process. However, it is crucial to acknowledge that these findings are not conclusive. The performance of tools in tests has been inconsistent, primarily due to the uncertain nature of concrete and the lack of standardized testing procedures.

The current knowledge available through literature and interviews can be summarized as follows:

- Husqvarna has not conducted any tests to optimize the grinding pattern of their floor grinding machine. Similarly, no valuable information has been obtained from other manufacturers
- It is widely believed that achieving a uniform grinding pattern results in uniform material removal or a flat surface after grinding. This is the primary motivation behind the thesis work
- Attempts to understand material removal through physical testing have yielded
unsatisfactory results. Similar parameters tested at different times have led to inconsistent outcomes

- At Husqvarna, lower drum speed has been observed to be advantageous in achieving a good grinding process. However, it has also been noted that some manufacturers run their machines with a higher drum speed than Husqvarna’s
- It is often difficult to find information about how tools behave under different machine parameters. Frequently, undesired patterns and insufficient material removal are blamed on the tools
- It seems that the machines are not performing to their fullest potential due to limitations in their tools. Further exploration is needed to fully realize their capabilities
- Optimization process with more tool data would prove to be helpful and applicable

1.3 Problem Formulation

In the realm of grinding technology advancements, the primary objective of optimization is to enhance the efficiency and productivity of grinding machines. In line with this goal, the aim here is to optimize the current floor grinding machine to achieve a uniform grinding pattern. Considering the limited knowledge available about the behaviour of the machine itself, this thesis serves as a starting point to comprehend the optimization of the grinding process from the perspective of grinding machines. A significant challenge with the current machines is the lack of understanding regarding when the machine produces satisfactory results.

All planetary grinding machines have the capability to operate at ten different levels of travel speeds. However, it is recommended to use level 3 and level 4, corresponding to 3m/min and 4m/min, respectively. These speeds ensure that the tools are not damaged and enable the maintenance of optimal performance. Currently, the machine’s performance is greatly influenced by the other two elements in the trifecta, namely the tools and the concrete surface. There is a lack of information available regarding the ideal machine settings for the tools. Furthermore, the concrete surface is naturally irregular and is likely to have a lower level of predictability.

Furthermore, the objective is to comprehend the impact of various machine parameters on the grinding process. A uniform grinding pattern is believed to result in uniform material removal. The goal is to enhance the material removal process to the extent that a single pass of the machine is sufficient to achieve a basic or standard level of material removal. This implies that material removal should be uniform across the ground area. Additionally, it necessitates fully exploiting the capabilities of the existing machines. All of these objectives constitute the focal points of this optimization endeavor.

Most industrial machinery applications at Husqvarna have traditionally been managed by iterative design solutions with purpose-built prototype approaches.
However, following the growing trend towards data-driven design in the industrial sector, an in-house simulation tool, SIMGRIND, has been developed that can output simulated grinding results based on a digital twin of the physical grinder. The result from the simulation will be used as a target metric in an optimization driven design approach. A data driven optimization leverages the large amount of data that can be generated through the simulations. The results of such an optimization can improve decision making substantially leading to a clear understanding of the impact of different factors while making way for optimized designs for the future, at lower investment costs.

1.4 Aims and Objectives

The goal of the thesis is to optimize the grinding performance of a floor grinding machine, between Husqvarna CE’s PG690 RC and PG 830RC. Although multiple iterative design methods have been developed to improve the performance, a data driven optimization methodology does not exist. The thesis aims to explore this further and develop a methodology to arrive at optimized dimensions, speeds, ratios that can be used in an enhanced design.

The key objectives are listed below:

- To develop a method to optimize the performance of floor grinders using the existing mathematical models on SIMGRIND
- To establish relevant metrics for floor grinders for an optimized grinding head
- To derive optimized dimensions, speeds and ratios, to be used in an enhanced design via simulations

1.5 Research Questions

The thesis aims to address the research questions put forth by Husqvarna and Linköping University to achieve its purpose and objectives. These research questions will be examined and analyzed in the thesis:

1. What is an appropriate metric for evaluating and grading a grinding pattern?

2. What is the effect of varying input parameters such as radius and speed of the discs and drum, moving speed of the machine, number of tools, and oscillations in the machine on the grinding pattern?

3. How does the grind pattern affect the material removal rate?

1.6 Delimitations

The delimitations of the thesis are listed below:

- The thesis is limited to the simulations and will not include any testing as such. The validations must be conducted for the already known cases or as future work.
• The primary focus of the simulation-based optimization is to establish a methodology.

• The thesis will utilize the mathematical models already integrated into SIMGRIND, and develop additional models only if required.

• The developed metric for evaluating grinding patterns will serve as objective functions for current and future optimizations.

• The thesis work will be conducted with the PG 690 machine, however the optimization methodology can be extended to any floor grinder in Husqvarna’s portfolio.
2 Theory

This section of the report deals with the background framework and the theoretical framework behind this thesis work. It serves as a foundation for comprehending and analyzing the methodology and findings, enabling one to make informed conclusions about the subject matter.

2.1 Floor grinding machines

Floor grinders or Concrete grinders are purpose-built machines for grinding and polishing marble, granite, concrete, and even wood. Floor grinding machines can be rated or graded based on their grinding output, which is usually measured in terms of the amount of concrete surface they can grind per hour. This rating can vary depending on the size and power of the machine, as well as the type of grinding tool and the hardness of the surface being ground.

2.1.1 Floor grinders from Husqvarna CE

Husqvarna provides an extensive range of floor preparation solutions, including concrete floor grinding and polishing machines, as well as scarifiers, to meet diverse needs. Following the acquisition of HTC, Husqvarna CE expanded its product line with additional machines that use different driving technology. These adaptable machines can handle various applications, such as surface preparation, coating removal, surface flattening, honing, and polishing of concrete and natural stone surfaces. The company’s planetary floor grinders collection consists of a broad selection of concrete grinders and polishing machines, with sizes ranging from 450 mm to 830 mm footprints. Additionally, the larger models are available in self-propelled or remote-controlled versions. Moreover, machines with Dual Drive Technology, providing full control over the speed and direction of rotation of the grinding heads, are also available. The machines from HTC’s lineage come with the Duratiq technology that uses a single motor to control the drum and disc rotation. The machines are versatile to support applications related to overlay removal, surface preparation, concrete floor grinding, and polishing. Figure 4 shows the largest floor grinder at Husqvarna CE, the PG 830 RC (RC stands for Radio Controlled).
2.1.2 Construction and Operation

This thesis intends to implement optimization techniques between the models’ PG 830 & PG 690. The models function similarly, with the only difference being their drum sizes, as indicated by their model numbers. These two models are also reputed as some of the highest-selling ones, which is among the reasons behind their selection for this optimization work.

Figure 5: Components of the Floor Grinder

Figure 5 depicts the components of a typical floor grinder in the PG series. The
machine can be controlled in one of two ways, manually with the console on the machine or with a radio controller. The machine is fully electric and is supported by two traction wheels. The wheels operate using a differential drive, allowing independent forward and backward movement to steer. Underneath the drum cover, there are grinding tools and a grinding head. The drum cover is sealed to prevent concrete dust from spreading and to ensure a safe and clean work environment. The centre of the grinding head or drum is denoted by $CoH$ (Centre of Head), centre of the discs by $CoD$ (Centre of Disc) and the centre of the tools by $CoT$ (Centre of Tool). Additionally, the seal is connected to a vacuum pipe to efficiently remove any concrete dust that is produced during the grinding process. Figure 6 shows the vacuum pipe routed from the back of the machine. Since the machine is supported by two wheels, it causes the machine to tilt forward and keep the tools on the head in constant contact with the floor.

![Figure 6: Back View of the Floor Grinder](image)
The point of interest in the machine is the grinding head and elements associated with it such as the grinding discs and the grinding tools. Figure 7 shows the construction of the grinding head, which is located beneath the machine. All the current generation grinding machines from Husqvarna consist of three discs mounted onto the drum. The discs house between three to six grinding tools. The drum is coupled to the primary motor, and the discs are coupled to the secondary motor through a belt drive system. This independent coupling between the drum and discs allows various driving speed ratios and rotations between the two. Although the drum and discs rotate independently, the discs rotate in unison at the same speed and direction. A different range of floor grinders, from the HTC acquisition, which has four grinding discs, has a unique feature where one pair of discs rotate in the opposite direction to the other pair.

2.2 SIMGRIND

SIMGRIND is an in-house simulation software developed by the floor grinding division at Husqvarna CE. Using SIMGRIND, it is possible to simulate several floor grinding process and approximate certain floor properties upon grinding. Currently, the software is being utilized to comprehend and assess the influence of specific theoretical characteristics of the machine in comparison to its practical implementation. In this thesis, the before-mentioned objectives will be achieved through the utilization of SIMGRIND and its features, whereby optimization algorithms and data-driven methods will be implemented. The software is built on Python utilizing libraries such as numpy, matplotlib, customtkinter and pyinstaller.
2.2.1 Simulation Functions

The software has several functions to control the different machine and grinding head parameters such as travel or moving speed of the machine, rotational speeds of the drum and disc, size of the drum and disc, number of discs and tools, and the type of tool. Various outputs can be approximated and visualized, including the pattern of the grinding tools, the grinding density of the tools, the floor cross-section after grinding, the velocity plots of the diamond tools, and other related visual representations.

Several SIMGRIND outputs that are relevant to this thesis work include the following:

- **Pattern Plot**: The pattern plot is a visualization function that displays the travel and pattern of the CoT, CoD, and CoH from a top-view perspective. In Figure 9, a sample pattern plot of a machine with a single disc is shown with the travel pattern of the drum (blue), discs (yellow) and tools (green).
• **Surface Plot**: The surface plot is a visualization function that displays the surface upon grinding from a top-view perspective. The surface plot is a contour plot that represents the density of the grind in different regions by assigning colours. The number of times a tool passes on a particular mesh is calculated and this is visualized as a contour plot. The colour gradient ranges from red, indicating the highest density or the most number of tool passes, to blue, indicating the lowest density. Figure 10 is a sample surface plot.
• **Cross section Plot**: The cross-sectional plot is a visualization function that displays the surface cross-section upon grinding. The cross-section plot displays two plots - one depicting the number of passes against the width of the machine across the grinding area and the other approximating the floor against the width of the machine. This cross-section plot is generated between the two horizontal red lines at \( y = 400\text{mm} \) & \( y = 700\text{mm} \) shown in Figure 10.

Figure 10: Surface Density Plot

Figure 11: Cross Section Plot

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2.3 Statistical methods

As this thesis focuses on data-driven optimization, several statistical inferences have been made for data analysis. The field of statistics involves collecting, arranging, examining, deciphering, and showing information for various purposes. The statistical methods used in this thesis have been explained below.

1. **Mean:** The statistical mean or mean is a numerical value that indicates the central tendency or mathematical average of all the terms of a dataset. It is calculated by adding up all the values in the dataset and then dividing the sum by the number of values in the dataset. The mean is a commonly used measure of central tendency because it provides a summary of the data that is sensitive to all the values in the dataset, rather than just a few extreme values.

   \[
   \text{Mean} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (1)
   \]

2. **Median:** The median is a measure of central tendency in a dataset that represents the middle value when the data is arranged in order. The median is useful in situations where extreme values or outliers may skew the results obtained from the mean.

   \[
   \text{Median} = \begin{cases} 
   \text{Element at } \frac{n+1}{2} \text{th position,} & \text{if } n \text{ is odd} \\
   \frac{1}{2} \left( \text{Element at } \frac{n}{2} \text{th position} + \text{Element at } \frac{n}{2} + 1 \text{th position} \right), & \text{if } n \text{ is even}
   \end{cases} \quad (2)
   \]

3. **Variance:** Variance is a statistical measure that quantifies the amount of variability or dispersion in a dataset. It is calculated by taking the average of the squared differences between each data point and the mean of the dataset. The resulting value is a measure of how much the individual data points deviate from the mean. A low variance indicates that the data points tend to be close to the mean, while a high variance indicates that the data points are more spread out and have a wider range of values.

   \[
   \text{Variance} = \frac{1}{n} \sum_{i=1}^{n} (x_i - \text{Mean})^2 \quad (3)
   \]

4. **Standard Deviation:** The standard deviation is a statistical measure that indicates how much variation or dispersion there is in a dataset. It is a measure of the amount of deviation or dispersion of individual data points from the mean of the dataset. Mathematically, the standard deviation is the square root of the variance. The standard deviation is a commonly used measure of the spread of a dataset and is useful in understanding the variability and distribution of the data. It is typically expressed in the same units as the data itself and is often used in statistical analyses to assess the significance of differences between groups or the variability within a group. In summary,
variance is a measure of the amount of variation in the data, while standard deviation is a measure of how spread out the data is.

\[
\text{Standard Deviation} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \text{Mean})^2}
\]  

(4)

5. **Coefficient of Variance:** The coefficient of variance (CV) is a statistical measure used to compare the variability of data relative to its mean. It is calculated by dividing the standard deviation of a dataset by its mean, and is expressed as a percentage. The CV is particularly useful when comparing datasets with different units of measurement or different scales, as it provides a normalized measure of the variability relative to the mean.

\[
\text{Coefficient of Variation (\%)} = \left( \frac{\text{Standard Deviation}}{\text{Mean}} \right) \times 100
\]  

(5)

### 2.4 Model Based Optimization

Traditional design approaches rely on prototypes and physical testing, which can be time-consuming, expensive, and impractical for complex systems. As traditional design methods pose such challenges, model-based design (MBD) techniques are gaining popularity. It is an approach to engineering and product development that emphasizes the use of mathematical models and simulations to guide the design process. In MBD, mathematical models are used to represent the behaviour of the system or the product being designed, and simulations to predict the behaviour under different conditions. By simulating the system’s behaviour before implementation, designers can identify and correct design flaws and performance issues before they become expensive and time-consuming to fix. Optimization techniques can be used within the model-based design process to find the best design parameters that meet specified performance criteria. MBD and optimization can be combined to create an efficient and effective design process. The proposed process of Model based Optimization with SIMGRIND is shown in the image 12. In this approach, a mathematical model of the system that is created can be used to test and optimize different designs before physically building and testing them. This can help to reduce the number of physical prototypes needed, saving time and money in the design process. Additionally, the use of MBD and optimization can help to identify trade-offs between different design objectives, such as weight, cost, and performance. By considering these trade-offs during the design process, designers can create designs that better balance different requirements and meet the needs of the end-user.
2.5 Design Optimization

Optimization is a fundamental aspect of human nature [6]. Numerous laws of physics are linked to optimization, such as the principle of minimum energy. As noted by Leonhard Euler [7], nothing at all takes place in the universe in which some rule of maximum or minimum does not appear.

The process of engineering design involves a series of iterations that engineers go through to create a product that fulfils a specific task. For complex products, this process requires the involvement of teams of engineers and multiple stages with many iterations, some of which may be nested. Optimization is commonly used to indicate improvement. However, in mathematical terms, it refers to finding the most optimal solution by changing controlled variables, usually subject to certain constraints. The universality of optimization lies in its broad applicability in various domains, as well as the human drive to enhance things. Any problem that requires a decision-making process can be framed as an optimization problem. While some simple optimization problems can be solved analytically, most real-world problems are too intricate to be resolved in this way. Fortunately, the advent of numerical computing and optimization algorithms has enabled the resolution of problems of growing complexity [6].

Design optimization (DO) in engineering design, refers to the process of systematically improving the performance or other desirable characteristics of a product, system, or process through the use of mathematical algorithms and computational tools. The goal of design optimization is to find the optimal solution that meets a set of specified design requirements and constraints while minimizing cost, weight, or other objective functions. The optimization process involves the use of models to simulate the behavior of the system under different conditions and the application of optimization algorithms to search for the best design parameters. Figure 13 explains the overall optimization approach in design.

As a background study, a few cases pertaining to multi-objective optimization of machining equipment were studied. In the study conducted by Heo et.al, titled "Numerical Control Machine Optimization Technologies through Analysis of Machining History Data Using Digital Twin" [2], the authors explore the use of digital twins in multi-objective optimizations in the domain of manufacturing. This study also gives a perspective on an attempt to bridge real-time data and data from digital
twins to attain optimized data with minimal errors. Another similar study titled "Multi-objective optimization of cutting parameters to minimize power consumption in dry turning of stainless steel 316" conducted by Salem et.al explored testing the simulation results through physical methods. A common conclusion from both these studies was that digital twins alone cannot serve efficient results, however, a lot of understanding of machine parameters can be attained through optimization. The latter also touches upon optimization residual study, which should also be explored as an extension of this thesis work.

![Design Optimization process](image)

**Figure 13: Design Optimization process**

### 2.5.1 Framework for Optimization - Pymoo

Python is becoming the programming language of choice for research and industry projects. Optimization being an integral part of most projects, a number of multi-objective optimization frameworks exist. Julian Blank et.al compares Pymoo with other MOO frameworks in Python such as PyGMO, PyOMO & jMetalPy. Given the advantages of Pymoo in the category of visualisation and support available, PyMOO was a decisive choice of framework for this thesis.

The benefits offered by Pymoo encompass comprehensive functionality, flexibility, customization options, seamless integration with the Python ecosystem, practical
application, and the availability of support. These features contribute to the effectiveness and value of Pymoo as a framework employed in the thesis project. In a design optimization process, the feasible solutions are determined by all possible values of the design variables, and the objective is to find the optimal design within these solutions. In mechanical design, the objectives may include strength, deflection, weight, and cost, among others. Optimization can help achieve a stronger, cheaper, or more environmentally friendly end product, even with traditional deterministic design optimization models. However, as the objective function becomes more complicated, with a large number of design variables or complex constraints, finding the optimum design becomes more challenging. Moreover, conflicting constraints can also add to the complexity of the problem.

Although analytic or numerical methods have shown good performance in many practical design cases, they may not be suitable for more complex design situations where the objective function may have many local optima, but the global optimum is desired. Optimization algorithms can be categorized into two types: local optimization algorithms and global optimization algorithms. Local optimization algorithms, such as gradient-based methods, can solve design problems with a large number of design variables. However, they may only find local optima and are not able to find global optima. In such cases, different start points can be used to help the algorithm find better results. Safavi [9] explains that gradient-based methods are used when the gradient of the function is easily accessible and calculable, whereas non-gradient methods are common in non-differentiable, discrete, non-smooth and non-linear engineering problems. Global optimization algorithms, that handle non-gradient methods are hence effective for handling mechanical design problems as they are capable of finding the global optima in the design space. These algorithms can be categorized into two types: nature-inspired heuristic and deterministic methods. Among these, nature-inspired methods are found to be more efficient than deterministic methods and are widely used. Popular nature-inspired optimization algorithms include Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Harmony Search (HS), the Grenade Explosion Method (GEM) [10].

The most crucial stage in the optimization process is to develop the computational model. In order to define the optimization problem, one or more objective functions can be set. For instance, a weight equation can be used as an objective function that needs to be minimized. Additionally, constraints can be imposed on the design space to ensure that certain requirements are met. The entire optimization is built on design variables and these are essentially evaluated during the optimization process to obtain the optimal values[11].

Mathematically, it is possible to write most optimization problems in the generic form

\[
\begin{align*}
\text{minimize} & \quad f_i(x), & (i = 1, 2, \ldots, M), \\
\text{subject to} & \quad h_j(x) = 0, (j = 1, 2, \ldots, J), \\
& \quad g_k(x) \leq 0, (k = 1, 2, \ldots, K),
\end{align*}
\]
where \( f_i(x), h_j(x) \) and \( g_k(x) \) are functions of the design vector
\[
\mathbf{x} = (x_1, x_2, \ldots, x_n)^T
\]

### 2.5.2 The Genetic Algorithm

Over the years, several algorithms have been developed to solve optimization problems. Optimization algorithms can be categorized into several types based on their characteristics and the specific problems they aim to solve, as explained in the previous sections. In the optimization conducted in this thesis work, the Genetic algorithm is used to generate possible design solutions and evaluate them in terms of the objective function.

Genetic algorithms, which belong to the larger class of evolutionary algorithms, were first introduced by Z. Michalewicz in 1960 [12]. These algorithms simulate natural evolution through computation, with multiple individuals living in a population, where each individual represents a solution to a given problem. The population undergoes evolution over generations, where individuals that showcase superior solutions survive through reproduction, while the others get replaced by their offspring. Random mutations of individuals contribute to stochastic progress towards better solutions.

Due to their reliance on information about the search space and solution performance, genetic algorithms serve as search algorithms that are particularly suitable for scenarios where limited prior knowledge about a problem exists. Although they cannot guarantee a global optimum, genetic algorithms frequently produce satisfactory solutions, particularly when they effectively avoid becoming trapped in early local optima [13]. Consequently, genetic algorithms have demonstrated their effectiveness across a wide range of engineering design problems, making them a viable choice due to their adaptability and ability to handle various types of optimization challenges [14]. A flowchart of a classical genetic algorithm is shown in Figure 14

\[\text{Figure 14: Genetic Algorithm process}\]
In genetic algorithms, operators are used to modify the genetic material of the individuals in the population to produce new offspring that may have better fitness than their parents. The three main operators used in genetic algorithms are Selection, Crossover and Mutation. Kutoch et al. [15] provides a comprehensive analysis of genetic algorithms and their operators along with their probabilities. The most common selection techniques are the Roulette wheel, Tournament, and Boltzmann. The most common crossover techniques include Single point, Two point/k-point, Uniform, and Partially matched crossover. The most common mutation techniques include Displacement, Inversion, and Scramble.

2.5.3 GA & Multivariable GA in Pymoo

Genetic Algorithm is an optimization technique for unconstrained optimization problems. Regarding their application diversity, genetic algorithms rank among the most popular evolutionary algorithms. A wide range of engineering optimization problems have been successfully addressed using genetic algorithms [16]. Furthermore, genetic algorithms, being population-based, serve as the foundation for many contemporary evolutionary algorithms, with several of these algorithms sharing strong resemblances or direct inspirations from genetic algorithms [17]. GA implementation in Pymoo offers a powerful tool for solving optimization problems with a single objective. The multivariable GA is a variant of the GA for discrete variables and variables of different types. In this thesis work, the multivariable GA employed Random Sampling, Simulated Binary Crossover, and Polynomial Mutation as its default operators to facilitate exploration and exploitation [8]. The default settings of these operators were utilized for all single-objective optimizations conducted in this study.

2.5.4 NSGA - II in Pymoo

The NSGA-II implementation in Pymoo provides a powerful tool for conducting multi-objective optimization tasks. It follows the principles of NSGA-II, which involves using non-dominated sorting, elitism, and shared genetic operators such as crossover and mutation. The difference between NSGA - II and the traditional single objective GA lies in how the Objective Functions, Fitness Evaluation and Selection Mechanism are defined. NSGA - II are recommended for multi-objective optimizations sought to find a set of solutions that are not dominated by any other solution, forming the Pareto front, which represents the trade-off between different objectives. The Fitness Evaluation in a single objective GA relies only on the objective function. However, the NSGA - II involves comparing the solutions based on multiple objectives and categorizing them as non-dominated, dominated, or partially dominated. In a single objective GA, the selection is typically based on proportionate fitness selection, where individuals with higher fitness have a higher probability of being selected. In NSGA-II, the selection is performed based on the concept of non-domination.
2.5.5 Operators in Pymoo

Pymoo offers a wide range of operators for optimization problems. The different type of operators used in this work is described as follows:

Sampling:
1. Latin Hypercube Sampling
2. Random Sampling

Selection:
1. Random Selection
2. Tournament Selection

Crossover:
1. Simulated Binary Crossover

Mutation:
1. Polynomial Mutation

The above-mentioned operators have been used in different combinations during the simulation studies. The combinations were not very flexible because of how Pymoo handles multi-variable parameters & discrete parameters.
3 Methodology

This section of the report focuses on the methods implemented in attaining the results. The theory presented in the previous section will be used to build and implement different methodologies suitably to solve the objectives.

3.1 Overall Approach

This thesis work introduces an optimization framework for floor grinders making it a comprehensive study that primarily examines the feasibility of implementing optimization techniques. Consequently, following a single method becomes challenging due to the nature of the research. The methodology was initially divided into a Field Study and a Simulation Study, which collectively contribute to establishing the goals and requirements of the optimization framework[18]. Figure 15 describes the method framework followed in this thesis.

![Method Framework](image_url)

Figure 15: Thesis Method

3.2 Statistical Methods for Data-driven Optimization

Ott and Longnecker’s book [19], explains the practical implementation of statistical methods in real-world scenarios, particularly in optimization and data-driven designs. Statistical methods can be utilized to optimize various processes and systems. By collecting and analyzing relevant data, statistical techniques such as regression analysis, design of experiments, and algorithm-based optimization can be employed to identify optimal settings and conditions for maximizing desired outcomes. These methods help in fine-tuning parameters and making data-driven decisions to achieve
the best possible results. Furthermore, this enables the generation of reliable conclusions and informed recommendations based on the statistical analysis of the collected data.

3.3 Simulation Settings

SIMGRIND, like most other MBS tools, is built as a discrete event simulation. A discrete event system models the operation of a system as a function of time. As in, each event occurs at a particular event of time. In such simulations, achieving convergence is of utmost importance as it signifies the stability and reliability of the obtained results. Convergence in simulation refers to the state where the numerical solution reaches a steady state, and further iterations have minimal impact on the solution. This aspect holds significance as it ensures the consistency of the simulation outcomes, thereby instilling confidence in the decisions and predictions based on them. The absence of convergence can lead to unpredictable and unreliable simulation results, potentially leading to incorrect conclusions or decisions. Moreover, the lack of convergence can result in unnecessary computational expenses as the simulation continues to run despite the absence of improvement or stabilization in the results. Consequently, attaining convergence is critical for ensuring the validity and efficiency of simulation results.

In this simulation case, convergence is governed in two aspects, in terms of mesh grid size and time step (dt) itself.

3.3.1 Mesh Grid

The surface density plot, a contour plot, is built on a mesh grid of a certain size. The default size used during normal operations on SIMGRIND is 2mm x 2mm. However, a higher mesh grid of 4mm x 4mm was chosen to keep the computational time per simulation low. This reduces the number of data points to a quarter while leaving a negligible impact on the output.

3.3.2 Time Step

Achieving convergence in the mesh grid size was relatively straightforward compared to achieving convergence in the time step for the simulation. In the simulation, the tool strikes the floor once per each time step (dt), meaning that a smaller dt would result in more strikes over the grinding floor, and vice versa. However, in order to obtain consistent and reliable grinding density values for different machine parameters, it was necessary to normalize the number of strikes on the floor. Otherwise, the values would exhibit erratic behaviour, making it challenging to conduct meaningful statistical analysis. However, a study was conducted to investigate the extent of variation in the objective function when altering the time step (dt) for a specific parameter value, shown in the image [16].
In addressing the convergence of the time step (dt), a similar approach was adopted based on the sampling theorem [20]. This theorem states that a signal must be sampled at least twice the frequency of the original signal in order to represent it accurately. Drawing upon this principle, a formula was developed to establish a relationship between the rotational speeds of the drums and discs, the travel speed of the machine, and the mesh grid size. The objective was to ensure that, similar to the sampling theory, the tool would strike each mesh grid in its trajectory at least once. By doing so, the grinding pattern plot on SIMGRIND would be characterized by minimal bias, allowing for reliable and meaningful analysis.

The modified sampling theorem is described below:

$$\frac{\text{surf.res}}{\text{rpm}_L(r_L+r_S)+\text{rpm}_S(r_S)+\text{movSpd}}$$

where:

- \(\text{surf.res}\) = mesh grid size
- \(\text{rpm}_L\) = rpm of drum (rad/s)
- \(\text{rpm}_S\) = rpm of disc (rad/s)
- \(\text{movSpd}\) = Movement speed of machine (rad/s)
- \(r_S\) = radius of disc (mm)
- \(r_L\) = radius of drum (mm)

### 3.4 PG 690 Construction

#### 3.4.1 Grinding Assembly

The focus of this thesis is on the PG 690 model, which serves as the floor grinder under examination. An accompanying image illustrates the components involved in the grinding process. The grinding setup encompasses the entire assembly where the grinding discs are affixed.
Within the grinding drum, the belt drive mechanism facilitates the rotation of the grinding discs. It is worth noting that the mounting arrangement for the discs varies between the Duratiq and the Dual Drive Technology. In the Duratiq system, two rigid pivot pins are employed to confine the disc’s movement along two perpendicular axes. However, the specific degree of tilt and stiffness these pins provide remains unspecified. Conversely, the Dual Drive system does not incorporate such an assembly; rather, the discs are directly mounted onto the shaft. In this configuration, a spring steel plate acts as a suspension element, offering a certain level of flexibility. Although the behaviour of this steel plate under different loads has been quantified, there is a need for a comparative analysis to determine which concept better supports a consistent grinding pattern.

Engineers at Husqvarna assert that the mounting assembly used in the Duratiq system surpasses the other configuration by providing adjustable tilt as an additional feature over uneven surfaces, thereby facilitating a more uniform grinding pattern. The specifications of the PG 690 machine are detailed in table 1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Speed of Drum (rpm)</td>
<td>48</td>
</tr>
<tr>
<td>Top Speed of Disc (rpm)</td>
<td>1500</td>
</tr>
<tr>
<td>Max. No. of Discs</td>
<td>3</td>
</tr>
<tr>
<td>Max. No. of Tools per Disc</td>
<td>6</td>
</tr>
<tr>
<td>Disc diameter (mm)</td>
<td>270</td>
</tr>
<tr>
<td>Drum diameter (mm)</td>
<td>610</td>
</tr>
<tr>
<td>Rated Power of Drum Motor (kW)</td>
<td>11</td>
</tr>
<tr>
<td>Rated Power of Disc Motor (kW)</td>
<td>1.5</td>
</tr>
<tr>
<td>Drive Mechanism</td>
<td>Belt Drive</td>
</tr>
</tbody>
</table>

Table 1: PG 690 Grinding Drum Specifications
3.4.2 Traction Assembly

All the current PG machines in Husqvarna runs with a differential traction control system that uses two independent traction motors, one for each wheel. It is worth noting that it is this system that supports oscillations of the machines, which is seen to be a possible method to attain a uniform grinding pattern in this study. The specifications related to the traction module of the PG 690 machine are detailed in Table 2.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Traction Motors</td>
<td>2</td>
</tr>
<tr>
<td>Top Speed (m/min)</td>
<td>10</td>
</tr>
<tr>
<td>Max Oscillations amplitude (rad)</td>
<td>0.438</td>
</tr>
<tr>
<td>Max Oscillations frequency (rad)</td>
<td>0.274</td>
</tr>
<tr>
<td>Wheel Diameter (mm)</td>
<td>330</td>
</tr>
<tr>
<td>Track Width (mm)</td>
<td>606</td>
</tr>
</tbody>
</table>

Table 2: PG 690 Traction Specifications

3.5 Field Study & Data Gathering

The first leg of the thesis work involved a comprehensive field study aimed at understanding the current grinding methods and their limitations. This phase allowed for interactions with field experts to evaluate various grinding processes and machines, which subsequently informed the limitations and delimitations of the thesis. A notable achievement during this stage was the finalization of an optimization for the grinding pattern, which has the potential to revolutionize grinding methods.
3.5.1 Previous Work

A number of documented and undocumented tests have been carried out to quantify the MRR and a number of methods to attain uniform material removal have been carried out. These have been done independently with the tool as well as the machine as a whole as mentioned in Appendix B. For instance, during a test to quantify MRR with the XX2 tool, the data turned out to be highly eccentric. During a similar test to quantify the optimum tool temperature and tool velocity to improve MRR, the data collected was not supportive. The reason was zeroed out to be due to the inconsistency of the concrete. This issue was also realised during the field tests. The behaviour of concrete from the same sack varies from layer to layer. Since this inconsistency could not be normalized, a method to quantify MRR independent of concrete behaviour was necessary.

Being a novel study, gathering a substantial amount of data on grinding speeds, oscillations, and tool behaviour under different grinding conditions was essential. The successful collection of this data provided valuable insights and will be discussed in detail in the following sections of the report. The scarcity of existing relevant literature was another challenge. The technology of floor grinding has evolved through applied engineering intuition rather than conventional approaches, making it difficult to find adequate prior research. As a result, a significant portion of the information was sourced through interviews with field experts, ensuring that real-world expertise and knowledge were incorporated into the study. The parameters that affect the grinding process can be categorized as machine, tool and surface parameters. The parameters are mentioned as follows:

- **Machine Parameters**: Size of Drum, Size of Grinding Drum, Size of Grinding Disc, Grinding Pressure, Number of Tools, Number of Discs, Rotational Speed of Disc, Rotational Speed of Drum, Travel Speed of Machine, Direction of Rotation Drum, Direction of Disc Rotation, Oscillation Interval, Oscillation Speed

- **Tool Parameters**: Tool grit size, Tool velocity, Tool shape, Tool temperature, Tool life expectancy

- **Surface Parameters**: Surface Roughness, Moisture Content, Concrete Hardness

3.5.2 Knowledge from Field Tests

In order to develop a relevant optimization technique it was necessary to conduct detailed field tests and collect data. The optimization setup was developed through a number of conclusions made during the field tests. Building the optimization setup were developed during the field tests and literature study.

The main disadvantage of all the previous methods to study material removal or the grinding process, was that there were too many parameters involved along with the uncertainties tied to them. This called for a method with reduced dependence on the tool and surface parameters. It was noted that the grinding pattern could
be studied and optimized with just the machine parameters. Although this study would remain theoretical, there would be a certain amount of data about the grinding that could be gathered as a result. In the practical sense, the grinding pattern would be also affected by the consistency of the tool and tool life. There exists a large amount of interdependency between the machine, tool & surface trifecta, but these will be ignored in this study.

The table 3 explains the key parameters that influence the grinding pattern and the ones that do not. The parameters that influence the grinding pattern will later be recognized as optimization parameters.

<table>
<thead>
<tr>
<th>Key parameters that influence grinding pattern</th>
<th>Parameters that have no influence on grinding pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of Grinding Drum</td>
<td>Grinding Pressure, all tool and surface parameters</td>
</tr>
<tr>
<td>Size of Grinding Disc</td>
<td></td>
</tr>
<tr>
<td>Number of Tools</td>
<td></td>
</tr>
<tr>
<td>Number of Discs</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed of Disc</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed of Drum</td>
<td></td>
</tr>
<tr>
<td>Travel Speed of Machine</td>
<td></td>
</tr>
<tr>
<td>Direction of Rotation Drum</td>
<td></td>
</tr>
<tr>
<td>Direction of Disc 1 Rotation</td>
<td></td>
</tr>
<tr>
<td>Direction of Disc 2 Rotation</td>
<td></td>
</tr>
<tr>
<td>Direction of Disc 3 Rotation</td>
<td></td>
</tr>
<tr>
<td>Direction of Disc 4 Rotation</td>
<td></td>
</tr>
<tr>
<td>Oscillation Interval</td>
<td></td>
</tr>
<tr>
<td>Oscillation Speed</td>
<td></td>
</tr>
</tbody>
</table>

3.5.3 Knowledge on Tool & Tool Behaviour

The tools constitute a pivotal aspect of the grinding triangle, exerting a significant influence on the overall grinding outcome, encompassing both material removal rates and grind quality. Husqvarna CE offers a diverse range of grinding tools tailored to different concrete types, such as hard, medium, and soft surfaces. These tools are available in various grit sizes, denoting the number of diamonds per square area, and they also come in different shapes. The rationale behind the availability of different shapes, although not entirely evident, was presumed to be primarily for identification purposes throughout the study. A comprehensive comprehension of these tools was predominantly derived from field tests and insightful interviews with relevant experts. Relevant tool characteristics and the knowledge gathered is mentioned in [4].
<table>
<thead>
<tr>
<th>Tool characteristic</th>
<th>Action &amp; Effect</th>
<th>Available Knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool grit size</td>
<td>In grinding, grit corresponds to the number of diamonds on the tool. Lower grit (30 grit) is used for initial grinding, while higher grit (220 grit and above) is used for finishing processes.</td>
<td>There is substantial knowledge and understanding of tool behavior concerning different grit sizes. However, achieving consistent Material Removal Rate (MRR) in concrete grinding remains challenging due to the inherent variability and inconsistency of the concrete surface.</td>
</tr>
<tr>
<td>Tool velocity</td>
<td>The tool travel speed in grinding is influenced by the machine’s travel speed and the rotational speeds of the discs and drum.</td>
<td>Available data does not clearly indicate the optimum velocity for achieving a fine material removal rate. Mainly due to inconsistency in the concrete.</td>
</tr>
<tr>
<td>Tool shape</td>
<td>Shapes only to identify different tool grits.</td>
<td>-</td>
</tr>
<tr>
<td>Tool temperature</td>
<td>The tool temperature is influenced by travel speed, rotational speeds, grinding pressure, grit size and concrete consistency</td>
<td>Elevated tool temperatures result in the formation of a glazed layer on the tool, hindering effective grinding. Although passive cooling methods like misting are employed, determining the precise glazing threshold and achieving the most optimal grinding conditions remain challenging due to limited investigative data.</td>
</tr>
<tr>
<td>Tool life expectancy</td>
<td>All the factors mentioned above, in addition to other machine and surface parameters, play significant roles in determining the tool life expectancy</td>
<td>The data plot concerning the relationship between life expectancy and material removal presents challenges in drawing definitive conclusions and providing comments.</td>
</tr>
</tbody>
</table>
4 Optimization, Results & Analysis

The objective for optimization was chosen such that there would some sort of immediate relevance to implement it on the current machines itself. The objectives revolved around attaining a uniform grinding pattern considering multiple parameters. The chosen objectives are listed below:

1. Grinding Speeds: Estimate and optimize for the optimum combination of disc, drum and travel speed of the machine to achieve a uniform grinding pattern

2. Oscillations: Estimate and optimize for the optimum combination of oscillations in the machine, rotation and travel speeds with the least amount of tool travel to achieve the best possible uniform grinding pattern

3. Grinding Head Ratio: Estimate and optimize for the optimum ratio of grinding drum to grinding disc size to achieve a uniform grinding pattern

A metric that numerically characterises the grinding pattern was developed. This metric was used to study the objectives mentioned above. The metric essentially categorised how good a grinding pattern was for a given set of inputs.

In order to run an optimization, the optimization variables, sample space and objective functions need to be defined. The optimization variables are defined in the following section. It is necessary to note that the study of the oscillations was carried out as a multi-objective optimization, studying the trade-off between uniform grinding pattern and tool travel. Two objective functions were developed and defined to conduct the optimization. They are discussed below:

4.1 Simulation & Physics

In order to keep the optimization consistent, the following factors were frozen

1. All the simulations on SIMGRIND is to be conducted with the PG 690 machine and the XX2 tool[19]. The same machines and tools would be used in the physical validation as well

Figure 19: XX2 Tool
2. In every simulation the machine would run a distance of 1m. This is done in order to achieve a pattern good enough for grinding while keeping in mind the computational constraints.

3. The area of interest in the plot is the area marked within the white frame and any analysis of simulation data would be conducted within this area alone.

4. A mesh grid of size 4mm x 4mm would be standardized considering the computational constraints, as mentioned in the previous section.

5. The time step would be calculated by the equation and it is limited to 0.0001s, for computational reasons.

4.2 Objective Function 1: Metric for Grinding Pattern

The first objective function that was developed was a metric to grade the grinding pattern. The grinding pattern until now was characterized only visually, through plots. For the optimization, this needed to be numerically characterized. A metric was developed which was used as the objective function for determining the quality of the grinding pattern. As mentioned in the previous sections, the grinding pattern is visualized through the density plot and the cross-sectional plot. The density plot visualizes the number of times a tool travels across each mesh grid. The idea behind the metric was to basically use this value to characterize the grinding pattern. This value will be referred to as points or density points in the coming sections. A major part of the thesis was about developing a good grinding metric. Four different metrics were developed in this process and one of the metrics was chosen due to its...
advantages over the rest. The metric would also double as an optimization objective. The requirements for a metric were defined as follows:

1. Should numerically characterize a grinding pattern - should also double as an optimization objective
2. Should estimate the amount of standard deviation of grinding density across a grinding section
3. Should facilitate comparison between different constituent grinding inputs
4. If it can independently point out different grinding regions, that would be a bonus

The most important point of the metric was that it should be normalized allowing comparison between two different grinding inputs. For a given rotation speed, a slower travel speed of the machine would result in a higher density point value than a higher travel speed. Naturally, a direct comparison of these two cases would not make sense. Hence, a comparison between a central tendency of the density points of these two cases would not be possible. This was inferred at a later point in time while conducting the thesis.

4.2.1 Standard Deviation method

The initial method was to find the standard deviation of the density points straight-away. It is necessary to note that the standard deviation is derived from the mean. The lower the deviation, the better the grinding pattern. During cases, as mentioned above, the standard deviation was too huge for some and too small for some, due to the mean. This method was hence not supportive.

4.2.2 Coefficient of Variance method

This was an attempt to normalize the output obtained in the previous method. The normalization factor was the mean itself. As before, the lower the deviation, the better the grinding pattern. However, although the output was normalized, it was difficult to compare some outputs because the values were too close to have a fair comparison. Hence this method was also not supportive.

4.2.3 Mean - Max Ratio method

The third method made use of the mean & maximum value of the density points. Unlike the previous cases, the higher this ratio was, the better the grinding pattern. A higher ratio meant that the mean value is closer to the maximum value or vice versa. Naturally, this method was biased to the peak values and did not consider deviation of the values below the mean.
4.2.4 Average Difference method

The average difference method compares three pivotal values with the mean. It takes the density values along CoD, CoH and the maximum value and calculates the ratio of each with the mean density value. The mean of these ratios put together would be the metric. This metric was observed to overcome all the disadvantages mentioned in the other methods while allowing comparison between individual regions such as only along the COD, CoH and peak values.

4.3 Objective Function 2: Tool Travel

The second objective function developed was for the tool travel. A function that calculates the total distance travelled by each tool was defined. This was done in a simple way by utilizing the inbuilt functions that calculate the position of each tool at every time step. The objective was to minimize the amount of tool travel and to explore achieving uniform patterns at low tool travel.

4.4 Optimization Parameters

The parameters for the optimization were chosen based on what would impact the grinding pattern alone. The ranges for these parameters were selected such that it would be relevant and physically feasible to validate the results on the current machines themselves. The table mentions all the optimization parameters used in this study. It is necessary to note that all the parameters were not used together for any optimization.

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameter</th>
<th>Units</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Step Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rpmS (Disc RPM)</td>
<td>RPM</td>
<td>400</td>
<td>5000</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>rpmL (Drum RPM)</td>
<td>RPM</td>
<td>10</td>
<td>150</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>rLarge (Distance - from CoH to CoD)</td>
<td>mm</td>
<td>200</td>
<td>450</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>rSmall (CoD to CoT)</td>
<td>mm</td>
<td>50</td>
<td>f(x2)</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>travel speed</td>
<td>m/min</td>
<td>1</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>number of discs</td>
<td>#</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>number of tools per disc</td>
<td>#</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>dirL</td>
<td>#</td>
<td>-1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>dirS</td>
<td>#</td>
<td>-1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>oscillation amplitude</td>
<td>rad</td>
<td>0.0174</td>
<td>0.438</td>
<td>0.0174</td>
</tr>
<tr>
<td>11</td>
<td>oscillation frequency</td>
<td>rad</td>
<td>0.0822</td>
<td>0.274</td>
<td>0.0822</td>
</tr>
</tbody>
</table>

Since the discs are mounted on the grinding drum, the size of the discs is constrained

35
by the number of discs and the size of the drum. The $f(x2)$ mentioned in the table would be:

1. if number of discs = 3:

\[ r_{small} < 2 \cdot r_{large} \cdot \cos(30^\circ) \] (6)

2. if number of discs = 4:

\[ r_{small} \leq r_{large} \cdot \sin(45^\circ) \] (7)

4.5 Simulations & Reasoning

This section will describe the different simulation studies that were conducted and implemented during the study. The simulation process was categorised into four, Initial Optimization Exploration, Optimizing Speed, Optimizing Speed & Oscillation and Optimizing Grinding Head size.

4.5.1 Simulation Study 1A: Initial Optimization Exploration

Though a number of optimization algorithms are available on Pymoo, GA was chosen for its ease of working with engineering design problems and for the availability of support. Although the algorithm was chosen, there are other multiple factors like the number of cores available in the processor, the number of optimization parameters, simulation time per analysis and visualization to name a few. It was difficult to predict the behaviour of the parameters and the simulation time in the initial stages itself, so an optimization exploration was conducted as a start. This part of the study helped in understanding methods to handle mixed variable parameters, issues with discrete variables in Pymoo & utilizing different sampling methods.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameter</th>
<th>Units</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Step Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rpmS (Disc RPM)</td>
<td>RPM</td>
<td>300</td>
<td>1500</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>rpmL (Drum RPM)</td>
<td>RPM</td>
<td>5</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>travel speed</td>
<td>m/min</td>
<td>1</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>dirL</td>
<td>#</td>
<td>-1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>dirS</td>
<td>#</td>
<td>-1</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

To begin with, the impact of rotational speeds, travel speeds & direction of rotation of the drum and disc was set to be studied. The parameters of the study were fixed to what the PG690 is capable of - grinding head size & number of discs. During Simulation Study 1A, all the five parameters mentioned previously were included. Since the direction of rotation was treated as binary (-1 for anti-clockwise and 1 for clockwise) and the rest were treated as integers, the Mixed Variable GA was used as the algorithm. The details of the optimization are mentioned in 7. During the time
of this study, the “Average Difference Method” was yet to be developed as an objective function. Hence, the objective function used in this and in Simulation Study 1B was the “Coefficient of Variance Method”. Study 1A and 1B were both cases for studying how effective the “Coefficient of Variance Method” was. It became increasingly difficult to differentiate simulation results since it was not sensitive enough.

Figure 21: Impact of different machine parameters on the grinding pattern

The study found that the direction of rotation has minimal impact on the grinding pattern, allowing it to be disregarded as a parameter. Additionally, by considering the relevant parameters and with the computational advantage of a multi-core system, the convergence pattern was comprehended effectively. Parallel Coordinate charts were decided to be the mode of visualization.
Table 7: Simulation Study 1A: Initial Optimization Exploration

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function</td>
<td>Coefficient of Variance</td>
<td>rpmL, rpmS, travel_spd, dirL, dirS</td>
</tr>
<tr>
<td>Number of Parameters</td>
<td>5</td>
<td>Improved coverage of parameter space</td>
</tr>
<tr>
<td>Algorithm Used</td>
<td>Mixed Variable GA</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Sampling</td>
<td>LHS</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Population Size</td>
<td>100</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Number of Generations</td>
<td>10</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Total Number of Iterations</td>
<td>1000</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Termination</td>
<td>Number of Generations</td>
<td>Default Characteristic of Mixed variable GA</td>
</tr>
<tr>
<td>Selection</td>
<td>Random Selection</td>
<td>Default Characteristic of Mixed variable GA</td>
</tr>
<tr>
<td>Crossover</td>
<td>SBX()</td>
<td>Default Characteristic of Mixed variable GA</td>
</tr>
<tr>
<td>Mutation</td>
<td>PM()</td>
<td>Default Characteristic of Mixed variable GA</td>
</tr>
</tbody>
</table>

4.5.2 Simulation Study 1B: Initial Optimization Exploration

Following the exclusion of the direction of rotation as a parameter, a similar simulation study to 1A was undertaken, maintaining the Coefficient of Variance method as the objective function4.5.2. As previously stated, Simulation Study 1 was conducted entirely within the capabilities of PG 690, thus setting the travel speed and rotational speeds as specified in the table above. Despite allowing all three parameters to vary during the optimization process, the results revealed that only a limited portion of the sample space was explored, leaving significant regions unexplored 22. It became evident that a relationship exists among the three parameters that could yield favourable outcomes. The purpose of the optimization was to investigate these results; however, it is important to note that no definitive conclusions were expected or obtained from this study.

Table 8: Optimization Parameters for Simulation Study 1B & 1C

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameter</th>
<th>Units</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Step Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rpmS (Disc RPM)</td>
<td>RPM</td>
<td>300</td>
<td>1500</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>rpmL (Drum RPM)</td>
<td>RPM</td>
<td>5</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>travel speed</td>
<td>m/min</td>
<td>1</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 9: Simulation Study 1B: Initial Optimization Exploration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function</td>
<td>Coefficient of Variance</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>method</td>
<td>rpmL, rpmS, travel_spd</td>
</tr>
<tr>
<td>Number of Parameters</td>
<td>3</td>
<td>Improved coverage of parameter space</td>
</tr>
<tr>
<td>Algorithm Used:</td>
<td>GA</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Sampling</td>
<td>LHS</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Population Size</td>
<td>100</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Number of Generations</td>
<td>5</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Total Number of Iterations</td>
<td>500</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Termination</td>
<td>Number of Generations</td>
<td>Default Characteristic of GA</td>
</tr>
<tr>
<td>Selection</td>
<td>Tournament Selection</td>
<td>Default Characteristic of GA</td>
</tr>
<tr>
<td>Crossover</td>
<td>SBX()</td>
<td>Default Characteristic of GA</td>
</tr>
<tr>
<td>Mutation</td>
<td>PM()</td>
<td>Default Characteristic of GA</td>
</tr>
</tbody>
</table>
Figure 22: Results of Simulation Study 1B
4.5.3 Simulation Study 1C: Initial Optimization Exploration

Unlike the preceding two study cases, Simulation Study 1C served as a data-gathering exploration rather than an optimization exercise. In essence, it resembled Study 1B, but instead of employing an algorithm, a normally distributed sample space was used. The "Average Difference Method" was introduced as the objective function, and it immediately exhibited superior performance compared to all previous methods. This new method proved to be highly sensitive to even minor changes in the input parameters, significantly enhancing the categorization of patterns.

The main objectives of this study were to comprehend the interdependency of the parameters and explore effective visualization methods for the gathered data. Similar to previous studies, the parameter range was limited to the capabilities of PG 690. To achieve the aforementioned goals, a new visualization approach was developed. Instead of visualizing the three parameters independently in the PCC, they were represented as ratios: rpmL/travel_speed and rpmS/rpmL. This visualization method offered a more insightful way to analyze patterns in the results. The image [21] shows the impact of different machine parameters on the grinding pattern (expressed as the average difference (objective function)).

Through this approach, it was discovered that specific combinations of rpmL/travel_speed and rpmS/rpmL ratios led to optimal patterns. In other words, for a particular travel speed, there exists an ideal rpmL value, and correspondingly, for a particular rpmL, there exists an optimal rpmS [23]. Interestingly, it was speculated that this set of ratios might remain constant across all travel speeds, potentially explaining why the algorithm explored only a limited sample space of rpmS & rpmL in Study 1B. Hence, the range of rpmL & rpmS was increased in the following study to facilitate the exploration of new areas for each travel speed.

Given the promising results and insights gained from this new visualization method, it was decided to implement it in subsequent studies. The constant ratios would be retained to aid in identifying optimum patterns efficiently. This approach would be applied in the following studies to further investigate and refine the grinding process optimization.
Table 10: Simulation Study 1C: Initial Optimization Exploration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function</td>
<td>Average Difference Method</td>
<td>rpmL, rpmS, travel_spd</td>
</tr>
<tr>
<td>Number of Parameters</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Algorithm Used:</td>
<td></td>
<td>Improved coverage of parameter space</td>
</tr>
<tr>
<td>Sampling</td>
<td>LHS</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Population Size</td>
<td>800</td>
<td>-</td>
</tr>
<tr>
<td>Number of Generations</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total Number of Iterations</td>
<td>800</td>
<td>Understanding convergence &amp; exploration</td>
</tr>
<tr>
<td>Termination</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Selection</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Crossover</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mutation</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 23: Results of Simulation Study 1C
4.5.4 Simulation Study 2: Optimizing Speeds

Speculating that the rpmL/travel speed & rpmS/rpmL would remain constant, individual optimizations were run for each travel speed. Hence, there were 10 independent optimizations that were conducted starting from 1m/min to 10/min. The range of rpmL was increased to 150RPM & rpmS was increased to 5000RPM. The range was decided on a fairly theoretical range in order to understand the grinding pattern. 600 iterations were run for each optimization and it was noted that the Average Difference Method was effective in categorizing results. As mentioned earlier, the average difference is a relative metric and not an absolute metric. It means that a similar pattern between two different travel speeds would have different metric values. This means it is still difficult to compare similar grinding patterns between two different travel speeds only through this metric.

Table 11: Optimization Parameters for Simulation Study 2

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameter</th>
<th>Units</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Step Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rpmS (Disc RPM)</td>
<td>RPM</td>
<td>400</td>
<td>5000</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>rpmL (Drum RPM)</td>
<td>RPM</td>
<td>10</td>
<td>150</td>
<td>5</td>
</tr>
</tbody>
</table>

The following were obtained as results from this simulation study:

1. The method to visualize the data as ratios, is more effective for analysis

2. The impact of speeds can be seen in the figure [24] where optimum speed combination can result in a better grinding pattern

3. An optimum grinding pattern can be achieved by establishing an ideal ratio between rpmL/travel speed (rpmL in RPM units & travel speed in m/min) & rpmS/rpmL (rpmS & rpmL in RPM units). The ratio remains constant across different travel speeds, as seen in figures [25] [26] [27]

4. The ideal rpmL/travel speed ratio for an optimum grinding pattern would be between 20 - 35 (rpmL in RPM units & travel speed in m/min). The ideal rpmS/rpmL ratio for the optimum grinding pattern would be between 30 - 40 (rpmS & rpmL in RPM units) (some values have been corrected to match real-world scenarios)

5. There is now a metric that says whether a good grinding pattern can be achieved at rotational speeds for a given travel/forward speed

6. This ratio would remain constant with machines of other sizes as well
### Table 12: Simulation Study 2: Optimization for Speeds

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function</td>
<td>Average Difference Method</td>
<td>rpmL, rpmS</td>
</tr>
<tr>
<td>Number of Parameters</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Algorithm Used:</td>
<td>GA</td>
<td>Default Characteristic of GA</td>
</tr>
<tr>
<td>Sampling</td>
<td>Random Sampling</td>
<td>Sufficient population to have a fair distribution across sample space</td>
</tr>
<tr>
<td>Population Size</td>
<td>60</td>
<td>Number of generations for acceptable exploration and exploitation rate &amp; convergence</td>
</tr>
<tr>
<td>Number of Generations</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Total Number of Iterations</td>
<td>600</td>
<td>Result of population size and generations</td>
</tr>
<tr>
<td>Termination Selection</td>
<td>n_gens = 10 Random Selection</td>
<td></td>
</tr>
<tr>
<td>Crossover</td>
<td>SBX()</td>
<td>Default Characteristic of GA</td>
</tr>
<tr>
<td>Mutation</td>
<td>PM()</td>
<td>Default Characteristic of GA</td>
</tr>
</tbody>
</table>

(a) Result of Worst Combination of Machine Parameters
(b) Result of Optimum Combination of Machine Parameters

**Figure 24: Simulation Study 2 - Studying Impact of Speeds**
Figure 25: Results of Simulation Study 2: Travel Speed 5m-min
Figure 26: Results of Simulation Study 2: Travel Speed 8m-min
Figure 27: Results of Simulation Study 2: Travel Speed 10m-min
4.5.5 Simulation Study 3A: Optimizing Oscillation & Speed for PG 690

The objective of this study was to explore optimum grinding patterns with the least amount of tool travel. In this set of simulations, oscillation amplitude & oscillation frequency were introduced as parameters and tool travel was added as the second objective function. However, the optimization was conducted for 1m/min only. Additionally, the range of rpmL & rpmS was reduced and limited to the capabilities of PG 690.

Typically in an MOO, the pareto front is visualised to understand the behaviour & for optimum points. However, in this case although a pareto front was visualized, the important result was to verify was whether the oscillations resulted in full coverage of the grinding area as the most desired grinding pattern is one which is homogenous and with full coverage.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameter</th>
<th>Units</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Step Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rpmS (Disc RPM)</td>
<td>RPM</td>
<td>400</td>
<td>5000</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>rpmL (Drum RPM)</td>
<td>RPM</td>
<td>10</td>
<td>150</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Oscillation Amplitude</td>
<td>rad</td>
<td>0.0174</td>
<td>0.438</td>
<td>0.0174</td>
</tr>
<tr>
<td>4</td>
<td>Oscillation Frequency</td>
<td>rad</td>
<td>0.0822</td>
<td>0.274</td>
<td>0.0822</td>
</tr>
</tbody>
</table>

The following were obtained as results from this simulation study:

1. A full coverage of the grinding pattern was not obtained and the most optimum result was not desirable.

2. Different optimum results were explored, however, there did not exist a most optimum result. It is possible that there could be a non-linear relationship between objectives.

3. Interestingly, the point with the lowest Average Difference metric did not have the highest tool travel, which was initially suspected so. The point with the lowest average difference was found at rpmL = 60RPM, rpmS = 1400RPM, oscillation amplitude = 0.25rad & oscillation frequency = 0.38rad (some values have been corrected to match real-world scenarios). The tool travel is not much of a concern.
Table 14: Simulation Study 3A: Optimization for Oscillation & Speed for PG 830

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function</td>
<td>Multi Objective: Average Difference Method + Tool Travel</td>
<td>rpmL, rpmS, oscillation amplitude, oscillation frequency</td>
</tr>
<tr>
<td>Number of Parameters</td>
<td>4</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
<tr>
<td>Algorithm Used:</td>
<td>NSGA 2</td>
<td>Sufficient population to have variations of oscillation characteristics</td>
</tr>
<tr>
<td>Sampling</td>
<td>Float Random Sampling</td>
<td>Number of generations sufficient for convergence</td>
</tr>
<tr>
<td>Population Size</td>
<td>50</td>
<td>Result of population size and generations</td>
</tr>
<tr>
<td>Number of Generations</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Total Number of Iterations</td>
<td>500</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
<tr>
<td>Termination</td>
<td>n_gens = 10</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
<tr>
<td>Selection</td>
<td>Random Selection</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
<tr>
<td>Crossover</td>
<td>SBX()</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
<tr>
<td>Mutation</td>
<td>PM()</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
</tbody>
</table>

(a) Optimum Results without Oscillations  
(b) Optimum Results with Oscillations

Figure 28: Simulation Study 2 - Studying Impact of Speeds
4.5.6 Simulation Study 3B: Optimizing Oscillation & Speed for PG 830

This study was conducted just to reflect the results of PG 690 on the PG 830 machine. Since a fully homogenous pattern was not possible through oscillations on the PG 690, this test explored if it is possible on the PG 830. The same settings were implemented, just with the dimensions changed to match the PG 830. The following were obtained as results from this simulation study:

1. Unlike the case with the PG 690, a homogenous pattern on the density plot and a fully flat pattern on the cross-section plot was obtained on the PG 830, as seen in figure 29.

2. Interestingly like before, the fully flat pattern on the PG 830 was not obtained at the highest amount of tool travel, as it was suspected.

3. The point with the lowest average difference was found at $\text{rpmL} = 60\text{RPM}$, $\text{rpmS} = 1600\text{RPM}$, oscillation amplitude = 0.1258rad & oscillation frequency = 0.265rad (some values have been corrected to match real-world scenarios).
Table 15: Simulation Study 3B: Optimization for Oscillation & Speed for PG830

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function</td>
<td>Multi Objective: Average Difference Method + Tool Travel</td>
<td>rpmL, rpmS, oscillation amplitude, oscillation frequency</td>
</tr>
<tr>
<td>Number of Parameters</td>
<td>4</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
<tr>
<td>Algorithm Used:</td>
<td>NSGA 2</td>
<td>Sufficient population to have variations of oscillation characteristics</td>
</tr>
<tr>
<td>Sampling</td>
<td>Float Random Sampling</td>
<td>Number of generations sufficient for convergence</td>
</tr>
<tr>
<td>Population Size</td>
<td>50</td>
<td>Result of population size and generations</td>
</tr>
<tr>
<td>Number of Generations</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Total Number of Iterations</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Termination Selection</td>
<td>Number of Generations = 10</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
<tr>
<td>Crossover</td>
<td>SBX()</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
<tr>
<td>Mutation</td>
<td>PM()</td>
<td>Default Characteristic of NSGA 2</td>
</tr>
</tbody>
</table>

(a) Optimum Results without Oscillations  
(b) Optimum Results with Oscillations

Figure 29: Simulation Study 2 - Studying Impact of Speeds
4.5.7 Simulation Study 4: Optimizing Grinding head size

The last study that was conducted was optimizing for the grinding head size.

Table 16: Simulation Study 4: Optimization for Grinding head size

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function</td>
<td>Average Difference Method 2</td>
<td>rLarge, rSmall</td>
</tr>
<tr>
<td>Number of Parameters Algorithm Used:</td>
<td>GA</td>
<td>Default Characteristic of GA</td>
</tr>
<tr>
<td>Sampling</td>
<td>Random Sampling</td>
<td>Sufficient population to have a fair distribution across sample space. Parametric Constraints existed hence higher population</td>
</tr>
<tr>
<td>Population Size</td>
<td>60</td>
<td>Number of generations for acceptable exploration and exploitation rate</td>
</tr>
<tr>
<td>Number of Generations Total Number of Iterations</td>
<td>10</td>
<td>Result of population size and generations</td>
</tr>
<tr>
<td>Termination</td>
<td>Number of Generations = 10</td>
<td></td>
</tr>
<tr>
<td>Selection</td>
<td>Random Selection</td>
<td>Default Characteristic of GA</td>
</tr>
<tr>
<td>Crossover</td>
<td>SBX()</td>
<td>Default Characteristic of GA</td>
</tr>
<tr>
<td>Mutation</td>
<td>PM()</td>
<td>Default Characteristic of GA</td>
</tr>
</tbody>
</table>

This was a SOO with the average difference as the only objective. This optimization was also a little different compared to the other optimizations. The parameters, in this case, were rLarge and rSmall since the objective was to find the most optimum grinding head size. A travel speed of 5m/min was chosen and the optimum rpmL & rpmS of 75RPM and 2300RPM were chosen referred from simulation study 2. The following results were obtained:

1. The idea grinding head size for the optimum grinding pattern would be where 
   \[ r_{Large} = 2.25 \ast r_{Small} \]

2. The PG 830 is running a better grinding head ratio as opposed to the PG 690
Figure 30: Impact of varying disc ratios
5 Discussion

The development of floor grinding technology to date has been based on gathered engineering intuition rather than the conventional approaches that are applied during other cases. As mentioned in chapter 2, the main reason behind this is due to unpredictability in the behaviour of concrete. Scientific methods to study the behaviour of concrete has always resulted in a dead end. All the above reasons have led to studying an optimization methodology for floor grinders without the effect of concrete surface.

The evolution of floor grinding technology has primarily relied on accumulated engineering experience rather than conventional approaches employed in other fields, as mentioned in chapter 2. This preference stems from the inherent unpredictability in the behaviour of concrete, which has proven to be a challenging subject for scientific investigation. Consequently, the pursuit of scientific methods to study concrete behavior has reached a standstill. Given these factors, our thesis aims to develop an optimization methodology for floor grinders that circumvents the complexities introduced by the concrete surface.

The thesis report commenced with a comprehensive exploration of the material removal rate (MRR) and its underlying complexities. Despite numerous attempts in previous chapters, achieving a thorough understanding of MRR remained elusive due to various challenges. Upon careful analysis of factors that could be moderately controlled, the focus shifted to the grinding pattern as a potential avenue for optimization. While acknowledging that the grinding pattern might not represent the ultimate solution for machine optimization, it was deemed a promising starting point. Throughout the study, efforts were made to quantify the MRR by investigating methods to attain a uniform flat pattern. Although debates surrounding the viability of this approach persisted, the subsequent sections of this thesis delved into a detailed account of the optimization process, results, and comprehensive analysis conducted during the research.

5.1 Data Gathering & knowledge of tools

In the preceding chapters, the acquisition of knowledge and relevant literature was primarily accomplished through interviews with field experts. The systematic collection of data and information from these experts allows for a comprehensive review and subsequent application in the optimization of similar machines. As this thesis explores a novel method for optimizing a floor grinding machine, external literature on the subject was relatively scarce. The significance of conducting field tests cannot be overstated, as they played a crucial role in gathering essential information about existing machines and establishing the parameters for optimization. However, during these field tests, it became evident that the physical validation of the grinding pattern could pose challenges, a matter that is thoroughly discussed in the subsequent section. Moreover, the behavior of tools on concrete surfaces was noted to be inherently unpredictable, as highlighted by tool engineers. To address this issue, innovative approaches involving standardized testing rigs is proposed in the
following section as potential solutions to effectively test and evaluate tools under controlled conditions. Such methods hold promise in enhancing the understanding of tool performance and its implications for optimizing floor grinding machines.

![Figure 31: Tools damaged due to excessive grinding speed & grinding pressure](image)

### 5.2 Optimization

The thesis study focused on the optimization of the grinding pattern, representing an inaugural step towards optimizing floor grinding machines. It is crucial to emphasize that no prior research has been conducted on the subject of grinding patterns, resulting in a dearth of existing data. As a result, this study served a dual purpose: firstly, it sought to identify the optimum parameters for attaining improved grinding results, and secondly, it concurrently collected valuable data regarding the behavior of the grinding pattern under various conditions. These objectives were inherently intertwined, complementing each other throughout the research. Undertaking an optimization approach was deemed the most appropriate and effective means of studying floor grinders. While it is acknowledged that there may exist more sophisticated models or metrics for future investigations, the optimization conducted in this work was the most viable achievement within the given time frame. The study represents a significant contribution to the understanding of grinding pattern dynamics and offers valuable insights into enhancing the performance of floor grinding machines.

Extensive literature studies had already indicated that gradient descent methods would not be well-suited for the probable multi-nodal and multi-parameter optimization required in this study. The implementation of GA was successfully facilitated by the Pymoo framework, which provided a robust setup for conducting the optimization. However, it is important to acknowledge that using Pymoo also presented certain conservative disadvantages. For instance, handling discrete variables required manual adjustments, wherein the variables were multiplied by a step value. Additionally, when employing specific sampling methods like Latin Hypercube Sampling (LHS), the final samples had to be appropriately scaled from a 0-1 range. Despite these limitations, it is highly improbable that the algorithm or its pa-
The primary objective of the thesis work was to develop a metric for grading a grinding pattern. This metric was designed as a relative measure, specifically relative to the travel speed of the machine. This implies that the grinding patterns of two different travel speeds cannot be directly compared using this metric. However, it allows for an easy and meaningful comparison within the context of a specific travel speed. In essence, the relative metric provides a sense of comparison between different grinding patterns when considering the same travel speed. On the other hand, devising an absolute metric for grading grinding patterns, irrespective of the travel speed, might prove to be challenging or even unattainable. By adopting the relative metric, the study was able to effectively assess and evaluate the quality of grinding patterns concerning a particular travel speed, contributing valuable insights into the optimization process. This approach represents a practical and appropriate way of evaluating and comparing grinding patterns in the context of the specific operating conditions.

Maintaining a relevant parameter range was a crucial aspect of the study to ensure practical applicability and feasibility on the current machines. By doing so, the optimization process could be effectively validated through rigorous testing on the machines. The chosen parameter range allowed for comprehensive validation tests, ensuring that the results were directly applicable to real-world scenarios. While the current study employed a specific parameter range with certain intervals, it is recognized that a future study could explore a wider range of travel speeds with shorter intervals. Such an extended investigation might yield additional insights and potentially uncover more optimal results for different operating conditions. Although the prospect of finding better results cannot be guaranteed, conducting such a future study would undoubtedly be intriguing and could offer valuable knowledge for further advancements in floor grinding machine optimization. The continuous exploration of different parameter ranges and optimization techniques can contribute significantly to the ongoing improvement of floor grinding processes and machine performance.

5.3 Results & Analysis

The results of this thesis were unexpected due to the absence of an actual pre-study, and the initial uncertainty surrounding the solution to the material removal rate (MRR) issue. The lack of prior research in the area further contributed to the unpredictability of the findings. Despite these challenges, the study generated valuable discussion points, which are outlined below. To visualize and interpret the results effectively, the parallel coordinate chart was employed. This visualization technique was chosen for its numerous benefits, allowing for a clear representation of multi-dimensional data and facilitating the identification of patterns, trends, and
relationships among various parameters. The unexpected nature of the results and the utilization of the parallel coordinate chart underscore the significance of the study, providing valuable insights and potential directions for future research in the optimization of floor grinding machines.

5.3.1 Simulation Studies

The results of the first simulation study played a foundational role in the optimization process and can be considered one of the most pivotal steps taken in this research. This initial study addressed several critical unknowns, including constraints related to computational power and time, as well as providing clarity on the subsequent optimization objectives. The use of the parallel coordinate chart proved to be the most effective method for visualizing trends within the results. This visualization technique enabled the researchers to gain valuable insights into the complex multi-dimensional data, identify patterns, and make informed decisions based on the observed trends. Overall, the exploration of optimization strategies was of paramount importance, as it laid the groundwork for the subsequent investigations, allowed the resolution of crucial uncertainties, and provided a robust approach for addressing the material removal rate (MRR) issue in the context of floor grinding machines.

In the second simulation study, the range of rpmL and rpmS was increased beyond the capabilities of current machines, and the rationale behind this decision is as follows; in Simulation Study 1B, it was observed that the optimization algorithm predominantly explored a specific region within the sample space, which was limited by the parameters set according to the capabilities of the PG 690 machine. As a result, the algorithm identified the most optimum grinding patterns achievable within the operational limits of the machine, which corresponded to travel speeds ranging from 1m/min to 3m/min.

To explore the potential for achieving good grinding patterns at higher travel speeds, it became essential to increase the rotational speeds beyond what the current machines can achieve. The results indicated that for higher travel speeds (e.g., 5m/min and above), rotational speeds of 2000RPM and above were required. These values are significantly higher than the nominal rotational speeds typically used in present machines, raising doubts about their practical viability. However, it is worth considering that floor grinders can compensate for speed and grinding pressure. Therefore, it remains a possibility that higher rotational speeds could be explored by reducing grinding pressure. This approach could offer an avenue to investigate the feasibility of achieving grinding patterns and material removal rates at higher travel speeds beyond the current machine’s nominal capabilities.

The study on oscillations was undertaken to assess the possibility of achieving a fully flat pattern on the cross-sectional plot by utilizing the machine’s oscillation feature. While the objective of achieving a flat pattern was successfully attained, it was observed that this outcome could only be achieved when the machine oscillated at a rate of 12°s⁻¹. However, it is important to note that practically achieving such a high oscillation rate of 12°s⁻¹ may be quite challenging, if not impossible.
The findings underscore the limitations and practical constraints that need to be considered when attempting to achieve specific grinding patterns using oscillation features on floor grinding machines. Despite the challenges associated with achieving high oscillation rates, the study provides valuable insights into the capabilities and limitations of the oscillation feature for obtaining uniform grinding patterns, guiding advanced users in making informed decisions about optimizing floor grinding processes.

The study on grinding head sizes yielded an intriguing result, revealing that the PG 830 machine has the capability to produce a better grinding pattern on average compared to the PG 690 machine. This finding is particularly noteworthy as both machines use the same discs, implying that the improved performance of the PG 830 is attributed to the larger drum size, which allows for a more distributed arrangement of the tools. Moreover, the study suggested that utilizing a smaller disc on the PG 690 machine could potentially enhance the average grinding result. This observation opens up possibilities for optimizing the performance of the PG 690 machine by experimenting with different disc sizes, allowing for a more comprehensive exploration of grinding patterns and material removal rates. The investigation into grinding head sizes provides valuable insights for floor grinding machine operators and manufacturers, offering strategies to improve grinding performance through suitable adjustments in tool distribution and disc size selection.

### 5.4 Physical Validation

During the planning stage of the thesis, the idea was to physically test the outputs from the simulation. The idea was to not only observe the grinding pattern but also to understand the material removal for each corresponding grinding pattern. Floordar is a tool that is developed in-house at Husqvarna that has a LED sensor mounted on a linear guide that measures the floor cut. The idea was to use the floordar before and after the grinding process. No specifications of the floordar are available.

![Floordar](image1.jpg)  
(a) The Floordar

![Process of Physical Validation](image2.jpg)  
(b) Process of Physical Validation

Figure 32: Physical Validation of Simulation Results

By studying the grinding pattern, the impact of speeds and oscillations would be validated. However, the validation was not entirely successful and some notable points are discussed below:

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• The idea was to reflect exactly how the simulations were conducted. The machine would grind a distance of 1m and the area of interest shown would be measured here. Naturally, the simulations considered the entire area itself. However, the floordar’s sensor can measure only one line at a time. Reducing the measurement to a few lines in the area would compromise the result.

• Concrete played a huge role in the testing. Multiple layers were poured to flatten the surface before grinding, however, even small uncertainties in the floor resulted in random results.

• Some outputs from the machine which had extremely high speeds could naturally not be realised on the grinding floor. Either the floor would get over grinded or the tools would heat up too soon.

• None of the current machines run above 1200RPM on the discs. This would only be possible if the grinding pressure is reduced and the speeds are increased.

• A more standardized testing method is necessary. The tools need to be studied first from which specific material removal rates should be drawn. The study should also be fixed to a certain concrete material or even a block of concrete. Just the grinding head can be included instead of the entire machine.

With all this being discussed, the physical validation was unsuccessful. But it opened up newer methods to study the grinding pattern physically which needs to be explored in the future studies.

Figure 33: Issues identified during Physical Validation
5.5 General Reflection

To summarize the thesis:

- Higher drum speeds for the Husqvarna machines could help in achieving better grinding patterns. The HTC machines already run with higher speeds than the Husqvarna machines and these can be adopted.

- Grinding pressure as a function on SIMGRIND can definitely support future studies. This however requires standardized physical testing methods.

- It is clear that the machine performance is constrained by a lack of tool data. If more tool data can be generated, the machine can be built around its performance.

- The studies have been conducted only for the machine’s current running parameters. A larger study with extended parameters can result in some interesting outcomes.

- A cross-study between tool velocity, tool temperature and machine parameters would be ideal to understand an optimization of the entire grinding ecosystem.
6 Conclusions

A methodology to study and optimize the grinding pattern has been established. A metric has also been developed and with this metric, there is knowledge on how to attain a good grinding pattern consistently. The results of the simulations could not be tested on the machines directly, however, they can be looked into for future studies. The next focus should be on developing standardized testing methods and building a test bed like a concrete block. Although the oscillations look good on theory, it would be impossible to grind with such oscillations on the machine. The process of connecting the pattern and material removal is still not concluded.
References


A First Appendix

A.1 Interview Guide - System Engineer

Machine Optimization and Grinding Patterns:

1. During what time period did the investigation into the impact of the grinding pattern commence?

2. How was the relationship between the grinding pattern and its effects established?

3. To what extent are the grinding patterns or grinding methods optimised?

4. Why optimize the grinding pattern? How can it improve the machine’s output?

5. How can optimized patterns, in turn, optimized machines, benefit Husqvarna as a company? How will the company have an edge over its competitors?

6. What factors affect the material removal rate?

7. What factors affect the grinding pattern?

8. How much can this optimization be extended?

9. What is the challenge with achieving uniform grinding patterns? What would be the solution sought through this thesis work?

Machine Construction, Features and Relations:

1. Why is the planetary grinding system very popular with Husqvarna machines?

2. What are the best methods used today at Husqvarna to achieve a uniform grinding pattern?

3. What are the methods used by other companies to solve the issue of uniform patterns?

4. Husqvarna’s machines possess two driving technologies, the dual drive and the single ratio technology. How are the driving ratios varied on the machines?

Post-Optimization Analysis:

1. How can the optimization results and analysis be implemented right away? What categories of these can be tested? How difficult would it be to implement the ratios on single-speed machines?

2. Do you think the oscillations are interesting?
A.2  Interview Guide - System Engineer 2

Machine Construction, Features and Relations & Post-Optimization Analysis:

1. To what extent can this optimization be implemented on the machines?
2. What is the future work of this optimization process?
3. What kind of an edge will the optimization results provide over Husqvarna’s competitors?

A.3  Interview Guide - Product Specialist

Machine Construction, Features and Relations & Product User:

1. What are the best methods used today at Husqvarna to achieve a uniform grinding pattern?
2. What methods have Husqvarna’s competitors implemented to achieve a uniform grinding pattern?
3. Would it be beneficial to introduce a feature that controls machine parameters to deliver a good grinding pattern? And how much would it benefit the operator?
4. Could you provide information on the typical parameters used by the PG 690 RC in the current generation?
5. What would you expect more of the PG 690 regarding grinding outcomes?

A.4  Interview Guide - Tool Specialist

Tool Construction, Relations & user parameters:

1. Has any testing been done to comprehend the velocity traits of the tool?
2. At what machine parameters maximum tool life expectancy is achieved?
3. Have experiments been performed to understand the material removal rate?
4. What would be the impact of higher rotational speeds on the diamond tools?
B Second Appendix

B.1 Interview Results - System Engineer

Machine Optimization and Grinding Patterns:

1. During what time period did the investigation into the impact of the grinding pattern commence?
HTC Professional Floor Systems was fully integrated with Husqvarna Construction in 2017. HTC initiated studies in the early 2000s to gain insights into the underlying characteristics of the grinding pattern through basic simulations. Serious simulations were not carried out and decisions mainly were validated with the help of visual aids. Instead, the understanding of the grinding pattern relied solely on the subjective experience shared among operators. Since 2017, Husqvarna’s dual-drive technology has looked promising due to the independent turning of the drum and discs in their machines.

2. How was the relationship between the grinding pattern and its effects established?
No experiments or simulations have been conducted solely to establish the effect of the grinding pattern itself. Hence the impact of the pattern lies only on engineering judgement and is yet to be proved.

3. To what extent are the grinding patterns or grinding methods optimised?
In the context of optimization, it appears that various manufacturers, including Husqvarna, have their own criteria for evaluating grinding methods. However, Husqvarna’s floor grinders still need to achieve proper optimization.

4. Why optimize the grinding pattern? How can it improve the machine’s output?
In the context of material removal, it is currently necessary for operators to compensate by inspecting the areas behind the grinding machines after completing the grinding process. This does not give conclusive results, nor does it improve the grinding process. Also, improper grinding results in unnecessary power consumption as additional grinding is performed on other sections. However, by minimizing the frequency of tool passes in specific areas or, in other words distributing the grinding pattern, it is possible to reduce excessive grinding. Utilizing even patterns can optimize the time spent on the machine’s width, ensuring that grinding is carried out efficiently without any unnecessary excess grinding.

5. How can optimized patterns, in turn, optimized machines, benefit Husqvarna as a company? How will the company have an edge over its competitors?
Furthermore, to these considerations, the influence of both the tool and the concrete surface remains uncertain. However, it is plausible to optimize the grinding pattern without taking into account the specific impact of the tool and the surface. It is expected that any potential influence on the outcome will likely be negligible.
6. What factors affect the material removal rate?
Numerous factors exert influence on the material removal rate within the grinding process. These factors encompass machine parameters, tool parameters, and even specific attributes of the surface being subjected to grinding. Machine parameters, including machine size, movement speed, rotational speeds of drums and discs, and the applied grinding pressure, play a pivotal role. Likewise, the grit size, hardness, temperature, and overall consistency of the tool can significantly impact the grinding outcome. Notably, the behaviour of the tool itself is contingent upon specific machine parameters, such as the rotational speed of the drums. Furthermore, the consistency of the concrete, moisture content, hardness, and surface finish all contribute to the material removal rate.

7. What factors affect the grinding pattern?
Objectively, the tool and the surface do not influence the pattern at all. All the machine patterns other than the grinding pressure can affect the pattern in theory. However, in reality, this also depends on factors from elements that control how the machine functions.

8. To what extent can this optimization be extended?
Extending the optimization principles can result in the advancement of machine development, including improved functionalities such as oscillation and movement techniques. Additionally, if a new planetary head is conceptualized, it would be advantageous to draw insights from optimization practices. This involves considering factors such as acceleration and speed and accurately predicting the attack angle of the diamond tools to optimize performance. Furthermore, exploring the functionality of the diamond tail and optimizing the tool itself can enhance overall efficiency. Moreover, expanding optimization efforts to achieve the maximum flatness of diverse grinding discs can yield favourable outcomes in the grinding process.

9. What is the challenge with achieving uniform grinding patterns? What would be the solution sought through this thesis work?
In the pursuit of achieving uniform grinding patterns, given that not much is known about achieving desired patterns, several challenges arise. At the moment, only the product specialists and experienced operators know how to extract the best from the machine. One significant challenge is the scarcity of sufficient data collection, coupled with existing design constraints. Previously, there was a belief that slower drum rotation would yield superior pattern results. However, there remains a lack of certainty regarding the actual pattern outcome, as it proves difficult to predict accurately. The interpretation of smaller-scale simulations has proven to be challenging and unreliable. Consequently, extensive physical testing becomes necessary to analyze and compare the shape of the patterns generated by basic simulations. Complicating matters further, diverse grinding approaches are prevalent, making it challenging to identify a universally correct method. As of now, only guidelines and thumb rules exist, lacking solid and conclusive evidence in support of specific grinding practices, which is what is being sought through this work.
Machine Optimization and Grinding Patterns:

1. Why is the planetary grinding system very popular with Husqvarna machines?  
   Planetary grinders and Rotary grinders are the most common kind of floor grinding technologies. Planetary systems are Husqvarna’s choice. The HTC machines earlier also came with a planetary system.

2. What are the best methods used today at Husqvarna to achieve a uniform grinding pattern?  
   Oscillations are introduced in the machines, but the extent is arbitrary and inconclusive. The rest just depends on the experience of the operator.

3. What are the methods used by other companies to solve the issue of uniform patterns?  
   There is not enough knowledge on how the pattern is affected by different machine parameters. The RPMs, disc and drum sizes are standardized.

4. Husqvarna possess two driving technologies, the dual drive and the single ratio technology. How are the driving ratios varied on the machines?  
   In the dual drive technology, the drum and disc speeds can be independently controlled. However, the Duratiq technology from the old HTC machines has ratios between 1:15 and 1:11. These ratios were decided based on earlier thought processes& legacy-based engineering judgment.

Post-Optimization Analysis:

1. How can the optimization results and analysis be implemented right away?  
   What categories of these can be tested? How difficult would it be to implement the ratios on single-speed machines?  
   The findings obtained thus far offer immediate opportunities for implementation, such as integrating functions on the machines to minimize tool wear and ensure consistent grinding patterns. However, specific outcomes, including oscillation techniques and achieving higher grinding ratios, may present challenges in terms of immediate implementation. Technical hurdles emerge when attempting to test simulation results on the actual floor directly. The complexities arise from the structural characteristics of the existing machines, making it intricate to assess oscillation capabilities. Achieving an overall optimized machine may necessitate compromises in other parameters to overcome these challenges.

2. Do you think the oscillations are interesting?  
   The optimization results on the oscillations are interesting. It might be strenuous on the gear box at higher speeds, but the outcome is fascinating. It is necessary to adapt to the oscillations at those speeds and build prototypes to test the same.
B.2 Interview Results - System Engineer 2

Machine Construction, Features and Relations & Post-Optimization Analysis:

1. How much can this optimization be implemented on the machines?
Since the correct ratios for consistent patterns are determined, the machine can be instructed to grind and provide uniform coverage. The operator can easily detect whether the machine is providing overcoverage, par, or under coverage. Additionally, since the grinding speed is linked to the machine’s moving speed, it can be programmed in a way that setting one parameter automatically sets all other parameters. This simplifies the operator’s job.

2. What is the future work of this optimization process?
It is essential to relate the grinding pattern with the material removal. The whole process ends at making the machine more efficient, and the grinding pattern is the most crucial part of this process. The optimization of the grinding pattern gives an idea of what to expect from the tool. With more data from the tool, their geometries, consistency and behaviour can be altered to work cohesively with the machine.

3. What kind of an edge will the optimization results provide over Husqvarna’s competitors?
The optimization process appears to be innovative and highly advantageous for both the machine operators and the grinding process. Nonetheless, it is essential to simultaneously enhance the entire eco-system and associated tools to produce superior machines and improve overall efficiency.

B.3 Interview Results - Product Specialist

Machine Construction, Features and Relations & Post-Optimization Analysis:

1. What are the best methods used today at Husqvarna to achieve a uniform grinding pattern?
The oscillations is probably one method. From an operators perspective, it is hard to identify a uniform grinding pattern visually on the floor. But achieving a good finish depends on the experience of the operator.

2. What methods have Husqvarna’s competitors implemented to achieve a uniform grinding pattern?
The machines produced by ScanMaskin feature a faster drum rotation. However, this could potentially have a negative impact on the lifespan of the grinding tools used with the machines. Typically, higher rotational speeds lead to faster tool wear, resulting in reduced tool life despite efficient machine performance.

3. Would it be beneficial to introduce a feature that controls machine parameters to deliver a good grinding pattern? And how much would it benefit the
user/operator?
It would definitely benefit the operator. A metric and a feature that gives feedback to the operator about the performance would improve productivity. It could be implemented as an optimized setting parameter.

4. Could you provide information on the typical parameters used by the PG 690 RC in the current generation?
The training center advises against utilizing all travel speeds. Typically, the recommended travel speeds range from 3m/min to 4m/min, while the drum rotational speed falls within 35-50 RPM and the discs speeds between 550-750 RPM. When exceeding these parameters, the tool’s performance and lifespan may rapidly deteriorate.

5. What would you expect more of the PG 690, in terms of grinding outcomes?
Faster results are sought, but the tools tend to wear out sooner when grinding at higher speeds. A grinding method that reduces the number of passes the machine takes would be helpful, allowing for steps to be skipped.

B.4 Interview Results - Tool Specialist

Machine Construction, Features and Relations // Tool Construction, user parameters:

1. Has there been any testing done to comprehend the velocity traits of the tool?
   It is currently unknown which velocities optimize tool performance as no tests have been conducted to establish the velocity characteristics.

2. At what machine parameters maximum tool life expectancy is achieved?
   Currently, this knowledge is not widely known. The grinding surface plays a significant role in determining the behavior of the tool, making it challenging to pinpoint what factors affect its life expectancy. Nonetheless, there are noticeable patterns in how the tool performs on concrete surfaces.

3. Have experiments been performed to understand the material removal rate?
   Numerous experiments have been conducted to understand the material removal rate of tools, but the outcomes of most of these experiments still need to be more conclusive. The MRR is calculated by determining the amount of material removed by a specific machine in kilograms over a certain period. However, even to this day, the results have yet to be conclusive.

4. What would be the impact of higher rotational speeds on the diamond tools?
   When tools are used at extremely high speeds, the heat generated can cause damage. This damage can lead to glazing, which prevents diamonds from properly opening up and results in the tools sliding across the surface instead of grinding. It’s important to remember that the behaviour of the tools is determined by the surface being worked on. No absolute reference is available.