Development of a Feeding Chute for Lapping of Silicon Nitride Balls
In Collaboration with AB SKF
Olov Oldeaus
Pranay Khona
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

Driven by the increasing demand for electric vehicles and sustainable energy production, the manufacturing industry anticipates significant growth in the market for hybrid bearings using silicon nitride bearing balls. This material is sought after for its durability, low density, and resistance to corrosion. However, the high production cost represents a major obstacle to widespread adoption. Consequently, this master's thesis focused on addressing the challenges encountered in the production of silicon nitride balls for hybrid bearings, specifically in the realm of surface machining.

This thesis addresses the limitations of the current lapping machine used by AB SKF, to improve its performance. By focusing on the importance of uniform ball feeding for productivity and efficiency, the objective is to analyze the capabilities and constraints of the machine. Additionally, innovative concepts for a feeding chute capable of handling large volumes of silicon nitride balls and ensuring their even distribution within the lapping grooves will be developed and evaluated through prototype production and testing.

Feeding solutions for the lapping process was developed, following the process of establishing requirements, generation of concepts and evaluating them through various methods. As the solutions converged on a feeding chute, an agile product development approach was used for rapid prototyping, testing and refinement. Through multiple short iterations, chute designs were tested and refined on a simulated setup. Based on this testing, final designs were then created. These involved two proposals for a chute design to be evaluated by future tests in the real lapping machine. Finally, recommendations on further development was included regarding further testing, manufacturing and material selection.

Overall, this thesis project provides valuable insights into the design and development of the feeding chute, emphasizing the significance of future research and testing in a realistic manufacturing environment to validate the proposed solutions.

Acknowledgements

We express our sincere gratitude to our academic supervisor, Alejandro Pradas Gómes, and our examiner, Gauti Asbjörnsson, from Chalmers University of Technology. Their constant encouragement and unwavering support played a crucial role in the successful completion of this thesis. Their expertise and guidance were invaluable in shaping our project and expanding our knowledge in the field.

We would also like to extend our heartfelt appreciation to our industrial supervisors, Tomas Gustavsson and Harshad Kurrewar, at AB SKF. Their generous provision of this thesis topic and their valuable industry insights were instrumental in our understanding of real-world challenges and their solutions. Their knowledge, feedback and patience throughout the project were truly invaluable.

Lastly, we would like to thank all the individuals who provided us with their assistance, feedback, and valuable contributions during the course of this project. Their collective efforts have undoubtedly enriched the quality and depth of our work.

<div align="right">Olov Oldeaus, Pranay Khona, Gothenburg, June 2023</div>

Contents

List of Figures

List of Figures

List of Tables

List of Tables

1
Introduction

The purpose of this project is to enhance the productivity of lapping process used in the production of silicon nitride (Si_3N_4) bearing balls by designing and developing concepts for a novel feeding chute. In this section, the background, the case company, problem description, the objective and research question, the scope and limitation and the project approach will be presented.

1.1 Background

The rise of electric vehicles and renewable energy sources has led to an increased use of variable speed drives, which unfortunately cause premature bearing failure due to electrical aging [1]. To combat this issue, the company has recognized the need for ceramic rolling elements, specifically silicon nitride, which boasts superior strength, toughness, and resistance to various forms of wear and damage. The demand for silicon nitride ceramic bearing balls is predicted to rise in the manufacturing industry due to the increasing need for durable, lightweight, and corrosion-resistant materials. Additionally, the market for advanced ceramic materials is expected to experience significant growth in applications such as bearings, valves, and pumps, according to [2]. However, the high hardness and wear resistance of silicon nitride makes the manufacturing process challenging and costly, specifically the surface machining operations, which according to both Kang and Hadfield [3], and Lee et al. [4] presents the main obstacle to widespread adoption of hybrid bearings. While much development has been made regarding alternative methods which would provide a higher efficiency [5] [6], the most commonly used and mature machining method currently is concentric circular groove lapping with a diamond abrasive slurry [7].

1.2 Company

AB SKF is a leading global manufacturer and supplier of high-quality bearings, seals, and related products and services for industries such as aerospace, automotive, and industrial. Founded in 1907, SKF has a long history of innovation and expertise in the field of bearing production and design. The company offers a range of services to support their products, including installation, maintenance, and technical support. SKF invests heavily in research and development and is committed to sustainable manufacturing practices. The company has set ambitious targets to achieve carbon neutrality and reduce water and energy consumption by 2030[8].

SKF group's manufacturing development department in Gothenburg is a hub for research and development, where the team is constantly exploring new technologies and production techniques to improve product performance and reduce waste. With a strong track record of growth and profitability, SKF is well positioned to maintain its leadership in the global bearing and seal industry.

1.3   Problem Description

The production of silicon nitride balls for hybrid bearings is facing a major obstacle in meeting market demand. The surface machining of silicon nitride balls is one of the key manufacturing steps, which usually consists of lapping with a diamond slurry, which has been identified as both time-consuming and expensive [3]. AB SKF currently employs a lapping machine manufactured by SpezialMaschinenfabrik-Schonungen (SMS) which, in its current configuration, presents some issues when used for large diameter balls.

One of the main issues lies in the uneven feeding of balls into the grooves of the lapping plate. This uneven feeding leads to an imbalanced load distribution and inconsistent material removal due to the non-uniform utilization of the lapping grooves. Recognizing the significance of this problem, the organization has identified the feeding system of the lapping machine as a crucial factor affecting overall productivity and efficiency.

After reviewing videos provided by the company, the team has determined that the accumulation of balls at the inlet and inconsistent supply to the machining area contribute to this problem. Consequently, this master thesis aims to address these challenges by designing and developing innovative concepts for a feeding chute that ensures a smooth and reliable supply of balls into the machining area.

However, developing a feeding chute capable of handling silicon nitride balls without causing damage and being compatible with the existing machine poses a significant challenge. Therefore, it is crucial to optimize the machine and its processes in order to enhance efficiency, productivity, and profitability. By doing so, improvements can be made in product quality, cost reduction, and overall competitiveness in the marketplace.

1.4   Objective and research questions

The main objective of the thesis is to analyze the current performance and limitations of the lapping machine with the aim of improving its efficiency by developing concepts of feeding chute capable of handling large volumes of silicon nitride balls and distributing them evenly into the lapping grooves. This is necessary in order to minimize downtime and maximize the productivity of the machine. Along with this the developed concepts feasibility and effectiveness will be evaluated by the produc-

tion and testing of prototypes. Recommendations and guidelines will be provided for implementation, and potential benefits and drawbacks of the proposed solution will be discussed. To achieve these objectives, research needs to be conducted on the following question:

- What are the major process parameters in lapping of silicon nitride?
- How does the feeding impact the lapping process of silicon nitride balls?
- What are the limitation in feeding of the existing machine and how can they be addressed?
- How can potential solutions be validated and tested?

1.5 Scope and Limitation

The enhancement of the performance of the lapping machine is the central objective of the thesis, by creating innovative concepts for feeding solutions. Several areas of interest, including the machine's various components and their impact on the process of introducing silicon nitride balls into the machine, will be encompassed by the research. The challenges will be recognized and addressed, the components responsible for the lapping efficiency will be evaluated, and novel ideas will be generated in order to achieve the overarching goal of the thesis. In other words, inventive approaches will be devised to improve the functioning of the machine, resulting in a more efficient and effective manufacturing process, which is the primary aim of the thesis.

During the initial phase of the thesis, several limitations were encountered. The machine used in which the developed concepts would be used, was located in a factory in the USA, which posed a constraint on conducting physical testing. Therefore, the team had to rely on simulations and could not perform actual testing due to time limitations associated with sending the concepts to the USA. As a result, the team opted to evaluate the performance of the concepts by using a simulated setup and identify areas for improvement.

However, simulating the concepts also had its own limitations. Initially, the team planned to utilize the internal company tool, Bearing Simulation Tool (BEAST), for testing the concepts. Unfortunately, it was found that the software presented limitations in accurately simulating the feeding process due to the need for a large number of contact points. Consequently, simulating the concepts using the BEAST software was not feasible and a strategy of short, low fidelity prototyping iterations was adopted by developing a test environment.

In the context of this master thesis, certain delimitation can be outlined:
- Machine Model: The focus of the thesis is specifically on the lapping machine setup currently used in the process, excluding other machine configurations or types.
- Ball Material and Size: The research is limited to large silicon nitride balls with a diameter larger than 20 mm.

- Feeding Function: The thesis concentrates on the design and development of a feeding solution, specifically addressing its role in ensuring a smooth and reliable supply of balls into the machining area. Other aspects of the lapping machine or additional functionalities are not within the scope of the thesis.

- Experimental Validation: The thesis focuses on the design and development stages of the feeding solution and does not encompass extensive experimental validation. This delimitation clarifies that the research does not cover the implementation and testing of the development feeding solution on the actual machine.

- Time frame: The thesis is limited to a specific time frame, specifically the design and development phase, excluding the implementation or long-term performance evaluation of the feeding solution.

1.6   Project approach

Due to the intricate nature and constraints of the Thesis project, an agile product development approach was deemed suitable for designing and developing a novel feeding chute for the lapping machine[9]. The selected approach facilitated developmental flexibility and refinement. An agile approach was employed, consisting of short iterations of concept development, testing, learning, re-development and re-testing. This approach proved to be effective in designing and developing the feeding chute.
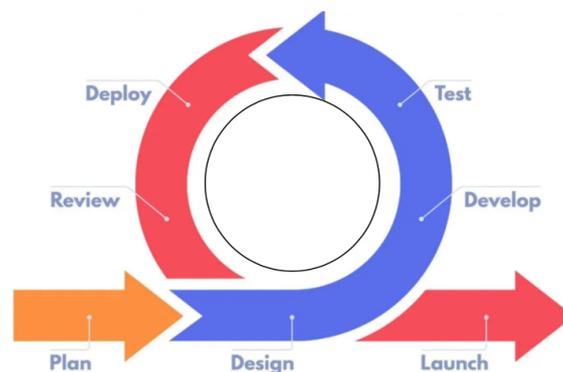
Figure 1.1: Agile Product Development Approach

A comprehensive and thorough investigation of the topic and concepts was pursued through several stages as follows:

- Literature study.
- Observations.
- Concept Development Process.
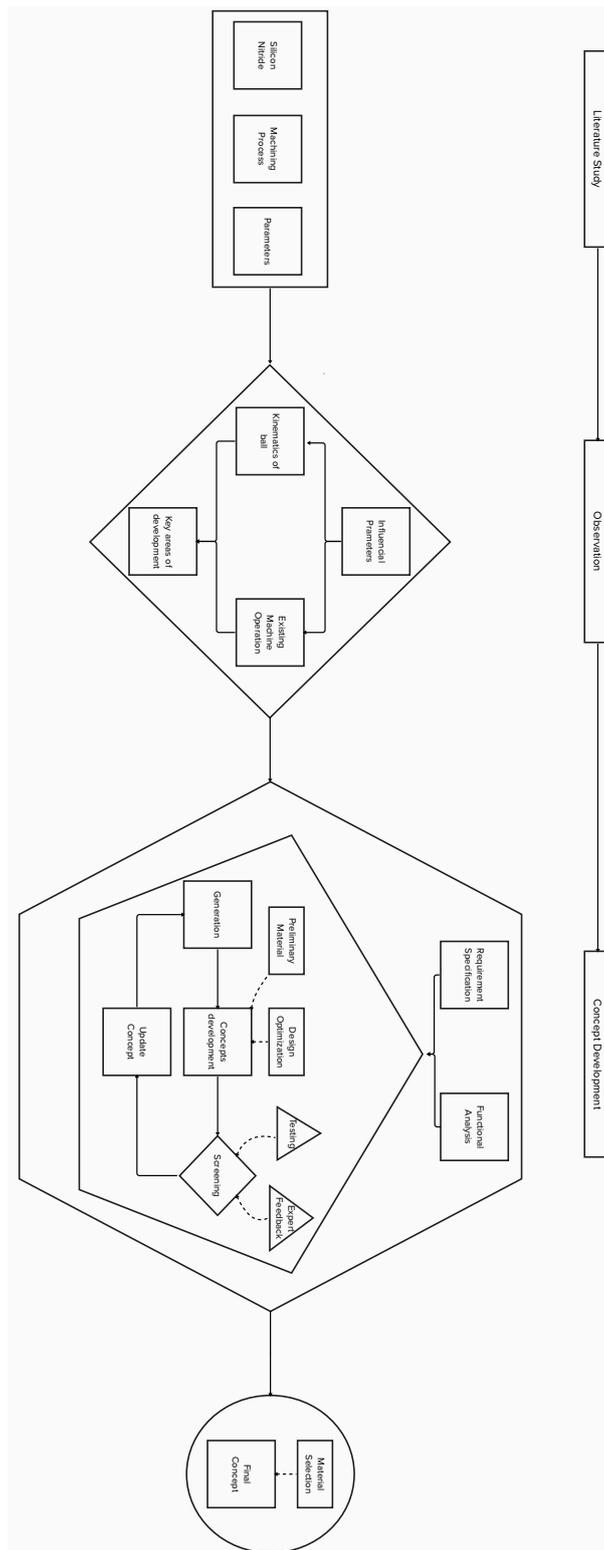
Figure 1.2: Project Approach

In the initial phase of the project, a comprehensive literature study was undertaken to gain a deeper understanding of the material properties of silicon nitride through various articles, patent studies of existing solutions for silicon nitride ball lapping,

and the essential parameters involved in machining. In the subsequent stage of the project, a series of observations were made from several working machines to explore the different parameters that could impact the productivity of the lapping process. Moreover, experiments were conducted on a conceptual machine that was available at the factory to gain a better understanding of the kinematics of the ball during the lapping process. This led to the identification of crucial areas for development that could enhance the productivity of the machine for lapping silicon nitride (Si_3N_4) balls. In the final phase of the project, various concepts were generated and tested on a simulated setup due to the existing limitations. This phase involved continuous re-designing and re-testing of the concepts based on feedback from the experts at the company until the desired results were achieved. The iterative approach ensured that the project achieved its objectives of improving the productivity of the machine for lapping silicon nitride balls.

2

Theory

This chapter presents background information on silicon nitride, the process used in production of Silicon nitride, the machine currently used for production as well as existing solutions to the problem of feeding addressed in this project.

2.1   Silicon Nitride

Silicon nitride (Si_3N_4) is a high-performance ceramic material known for its exceptional mechanical, thermal, and electrical properties. In the case of bearings, this material has been found useful for rolling elements in all-ceramic or so called hybrid bearings [10] [11]. Silicon nitride's high compressive strength, stiffness and chemical resistance combined with the low friction coefficient, density, thermal and electrical conductivity results in a very long-lasting and reliable bearing compared to steel variants[10]. Due to these properties, hybrid bearings are suited to applications where high performance is needed such as the aerospace or automotive industry [10] as well as in adverse conditions such as electric drives and generators where the ceramic's low conductivity prevents erosion from currents passing through the bearing [1]. For example, the XL hybrid bearings with larger silicon nitride balls used in wind turbine generators for this reason [12].

Although silicon nitride possesses exceptional mechanical properties, its manufacturing process presents several challenges due these same properties, which according to Kang and Hadfield [3] represents the main obstacle to widespread adoption. They describe the overall process in four steps, consisting of: powder production, green body forming, sintering and surface machining, with the latter being the most costly operation [3]. Estimations of this manufacturing step have ranged from half [13] to two thirds [14] of the total manufacturing cost. Machining is, however necessary in order to remove the surface skin from the sintered part and to achieve the needed surface quality for use in bearings [3] [15]. Figure 2.1a displays a silicon nitride ball right after the sintering process which is called a blank and figure 2.1b shows another ball after the machining process.

However, the exceptional mechanical properties of silicon nitride also make it difficult to machine without damaging the material, leading to surface damage, cracks, and other forms of degradation[16]. Therefore, special care must be taken to avoid damaging the material and ensure the final product meets the required specifications.

(a)

(b)
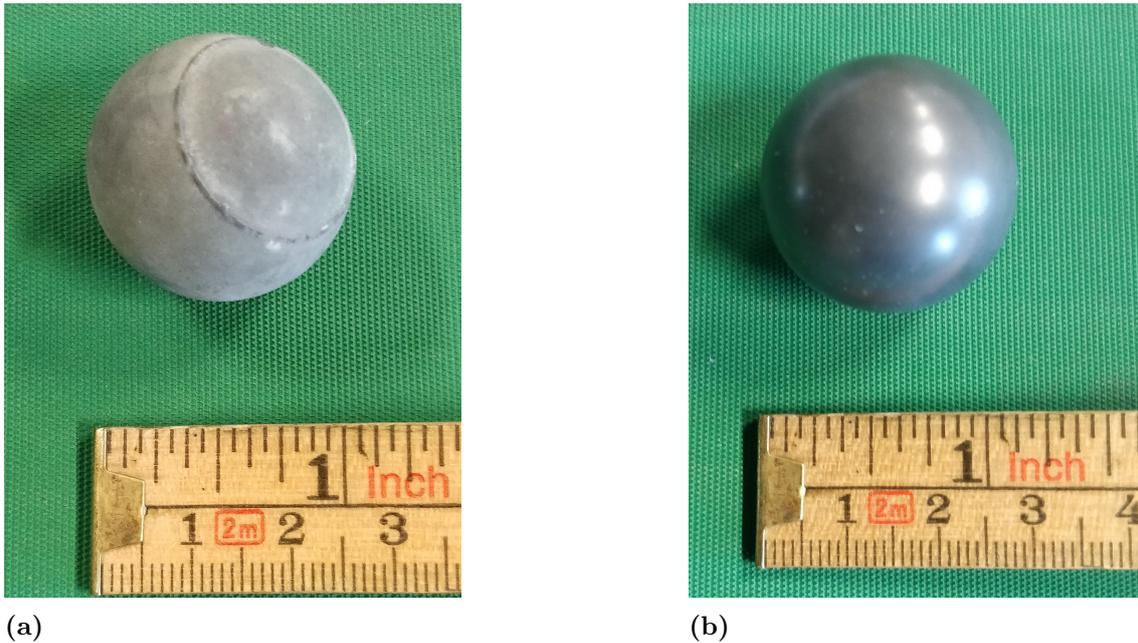
Figure 2.1: Silicon nitride ball before (a) and after machining (b)

2.2 Machining of Silicon Nitride

Machining silicon nitride is a difficult task due to its high hardness, brittleness, and low thermal conductivity. Various techniques are used for machining silicon nitride but for the machining of spherical shapes, lapping is the most popular mechanism used [3]. This process involves using a slurry containing abrasive particles and a rotating lap to generate the abrasive machining action [15]. The quality of the workpiece is influenced by several parameters, including the type of abrasive slurry, concentration of abrasive particles, lapping geometry, lapping speed, applied force, slurry flow rate, and lap condition [10]. For instance, excessive lapping load has been shown to result in surface damage as demonstrated by Kang and Hadfield [17]. Studies have been done on optimization of both the lapping geometry [4] and process parameters [14] to increase the efficiency of the lapping process.

The lapping machine used for production in SKF is based on the concentric circular groove lapping mechanism. This consists of multiple circular grooves machined into a plate or disc [4]. The balls are placed into these grooves and a force is applied to them by a top plate (see figure 2.2). As the bottom plate is rotated, the balls are rolled along the grooves and the diamond particles of the slurry abrades the material where the balls contacts the plates. To achieve a precise spherical shape, it is necessary for this material removal to be spread over the entire surface of the ball. As explained by Lee et al. [4] this is usually done by unloading the balls from the machining area into a external magazine after each circulation to randomize their orientation before they are returned. This magazine also enables larger batches to be processed.

Lapping load
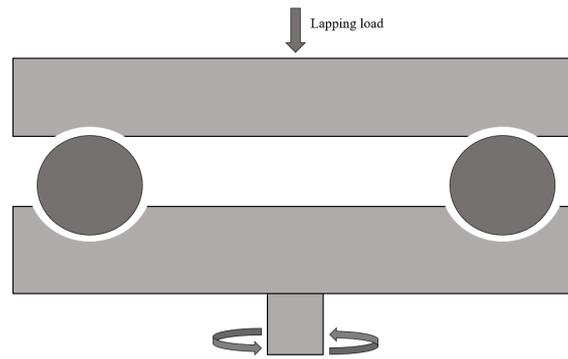
Figure 2.2: Cross-section of a concentric circular lapping groove.

2.3 Lapping Machine

The lapping machine is widely utilized in the manufacturing industry for its high precision machining. It is specifically designed to achieve exceptional accuracy, speed, and efficiency in the lapping process. With its precise surface finishes and strict tolerances, the machine is well-suited for machining high-performance components used in sectors such as aerospace, automotive, and medical industries. The lapping machine is constructed to be robust and durable, offering a variety of customized options to cater to specific manufacturing requirements [18].

Figure 2.3: Lapping Machine

The machine comprises key components that play crucial roles in its operation:
- Top plate: This integral component of the lapping machine serves as a primary element responsible for supplying the required force for abrasive machining the workpiece. Constructed from cast iron, it incorporates an opening that allows the entry and exit of the ball within the machining area. Moreover, the top plate secures the ceramic ball in the grooves throughout the lapping process.

Its design features multiple circular groove profiles, enabling precise rotational movement of the workpiece and facilitating the abrasion from the diamond particles between the plate and workpiece.

- Bottom plate: Similar to the top plate, the bottom plate fulfills the function of providing the necessary rotational force for the machining process.
- Divider: Acting as a barrier between the inlet and outlet of the lapping wheel, the divider ensures that the ceramic balls receive an equal amount of lapping. By doing so, it minimizes the risk of uneven wear of the ceramic ball.
- Stripper plate: Positioned below the divider, the stripper plate, in conjunction with the nozzle plate, lifts the balls from the grooves using stripper teeth.
- Magazine: The magazine or hopper plays a vital role in the lapping machine by facilitating the delivery of ceramic balls into and out of the lapping wheel. Encircling the plates, it maintains a circular motion, ensuring the smooth operation of the machine.

2.4 Existing solutions

As this type of machining technique of multiple concentric grooves has been used for a relatively long time and is well established, there have been multiple solutions proposed for the issue of feeding balls in different machine set-ups. With the exception of [19], the patents presented here have expired. Three types of solutions were found to be of particular interest and included in the concept generation in 4.2.5. The first was the principle of switching the balls from one channel or groove to another sequentially and was proposed in different variations in the following patents:

- Messerschmidt proposed in US3348338A an apparatus consisting of a magazine with multiple channels that guide balls to grooves in a sequential progression [20].
- Kunio and Hajime's patent JP2001260008A describes guiding channels made to sequentially shift balls from inner grooves to outer adjacent ones [21].
- A similar device to the above mentioned channels was also proposed by Si in WO2011140693A1 [19] in the context of lapping plates with a horizontal axis of rotation.

Patents involving grooves or channels to direct the balls from the magazine into a uniform flow were also identified:

- Okura proposed in JP2000318814A, an inclined feeding chute with grooves [22]. This was designed for lapping machines with an horizontal axis of rotation on the lapping plates.
- In patent US5921851A, Suzuki et al. presents inlet and outlet chutes consisting of separated channels to direct balls into multiple grooves [23]. As with the above mentioned patent, this was designed for horizontal lapping plates.
- Pinders presented in GB191100408A a mixing chamber where passages direct balls to grooves sequentially to create a circulation path [24].
- Matteson proposed in patent US1898979A a feeding mechanism consisting of a rotating drum or chamber lined with pockets for balls to be loaded into and

thereby re-circulated back into the lapping process [25].

3
Methods

This chapter will cover what methods and tools were used during the development process, an explanation of their use and the reasoning behind including them in the process. The overall structure and approach to the development process was adopted from the book *Product Design and Development* by Ulrich et al. [26] and formed a development funnel as seen in figure 3.1.

Requirement
Specification

Generation of 12
initial concepts

8 remaining
after elimination

Evaluation of
concepts

Elimination of 2

Generation of
4 additional
variations

Scoring,
ranking and
selection

3 concepts
remaining,
converging
on chute

Generation
of 5 detailed
chute

Two
selected for
prototyping

Evaluate and
refine based
on tests

One
additional
variation

Final
Selection

Figure 3.1: Overview of the resulting development process

The main method employed to identify the problems and needs was consultations with personnel at the company and observation of the current production process. As the production is located in the USA, the observation of the machine used in production was limited to video recordings of the process. Videos of the same process with smaller diameter balls were also observed to give a clearer idea of how the ball diameter affected the process. First hand observation of ceramic machining was done on a smaller, experimental machine with a single v-groove to better understand the basic operating principle and the behaviour of balls during lapping. For a more detailed study of the operation of the lapping machine, the manual and operating instructions were studied. The needs were formulated and organized as close as possible to the guidelines explained in Ulrich et al. [26], expressed as solution neutral attributes of a design.

3.1 Literature and Patent Search

To better understand the theory and principles involved in the lapping process as wells as recent developments have been made in this area, a literature search was done during the early phases of the project. This was mainly done through the search engine Google Scholar as well as Chalmers library. A patent search was also conducted to explore what has been done to address the problem of feeding and see if any designs were currently protected. The search was done through the online database Espacenet. The patents that were used as an input to the later idea generation are presented above in chapter 2.4, and for example led to concepts such as the Switcher presented in chapter 4.2.5.

The search process was done according to the suggestions of Ulrich et al. [26]. The first step was a broader search to understand what keywords, search terms, authors and classifications were relevant to this project. Broader search terms such as "grinding", "lapping" and "silicon nitride" primarily used. Introductory literature was also provided by the personnel at SKF which provided insight into relevant authors and search terms. It was noticed that for example authors Kang and Hadfield had published multiple articles relevant for the project [14] [3]. With these, scope of the search was then narrowed down to a manageable search result. Classifications B24B11/2 and B24B37/2 were used to search for patents related to grinding, lapping or polishing of spheres, while B65G11 and B65G37 was used as it related to devices for conveying and feeding.

3.2 Requirement specification

A requirement specification was compiled to translate the identified needs and problems into a precise description of design constraints, targets and objectives of any generated solution alternatives. This included a short justification for each requirement for the sake of traceability, a proposed method of evaluation and target values when applicable. A description was also added for extra clarification. Design constraints and functional requirements were to be used for eliminating concepts that do not fulfill necessary functions or demands and are outside the design space. Performance requirements were used to evaluate the performance of remaining concepts and compare them to each other. These were formulated as either to be maximized or minimized. Wishes or "nice-to-haves" were also included for this purpose. An importance scale was also added ranging from 1 to 5, with 5 being the most important. This was later used as a basis for establishing weights in the evaluation of the concepts. This specification was continuously updated and refined during the project as more knowledge was gained and the process narrowed down to a smaller set of solutions.

In formulating the requirements, the general criteria described by Hull et al. [27, p. 107] in *Requirements Engineering* was followed as close as possible to ensure that

the specification was processable and useful to the project. According to these criteria, each requirement should be: singular, unique, feasible, legal, clear, precise, verifiable and abstract. This would avoid having a bloated and vague specification or imposing a solution to the problem too early.

When a specific solution type was chosen, the final specification were set which included more focused requirements. These were slightly more constraining compared to the first specification according to the decisions, evaluations and trade-offs made during the project. Requirements related to production and installation was also introduced here to ease the implementation a final design. Introducing these requirements at an earlier stage was determined to limit the design space too much. As the testing progressed, additional requirements were added which also served to guide further designs and to document the knowledge gained from the test results.

3.3 Function analysis

A function analysis was performed to decompose the problem into simpler and more manageable pieces [26]. This would make the late idea generation phase easier as ideas could be generated for separate sub-function instead of having to solve the total function in one step [28]. First a black box and process flow model was created to give a clear overview of the grinding process and to show where the basic function of the solution would fit into it. A hierarchical function structure was also created to aid in the decomposition of the total function with the requirement specification as a basis. This was in the form of a function-means, similar to the structure presented by Malmqvist [29], and which also served as the start of the idea generation. As functions were decomposed, sub-solutions were proposed for each of them which in turn were given their own respective sub-functions. The benefit of this structure was that sub-function could be proposed to specific solution-types without imposing a overall solution. The process of functional decomposition was repeated at a more detailed level for the chosen solution type.

3.4 Idea generation

When generating ideas, different complementary methods were used to ensure a wide and diverse set of solutions. This was foremost the combination of systematic and creative methods which can be also be described as searching for ideas externally and internally according to Ulrich et al. [26]. The more systematic, external search for ideas involved finding existing solutions in patents and published literature. These could be both solutions for the problem at hand or for similar problems in other technical areas. The internal search for ideas involved using the groups creativity in generating solutions. Brainstorming sessions were held to generate more novel ideas and draw analogies to completely different scenarios for inspiration. During these sessions, focus was placed on generating a large variety of ideas without placing

limitations on effectiveness or feasibility until afterwards in the screening process as this could limit the creative process.

The sessions were kept at under an hour at a time in order to keep a high level of creativity. In total, two brainstorming sessions were held early in the project and one at the later stage, complemented by smaller follow-ups. These smaller sessions were for example held when generating variations during the evaluation stage. In order to generate the variations, the method of distortion of ideas was used [26, p. 134] consisting of rearranging fragments of the solution. The format of the brainstorming sessions changed during the process as it converged on a solution. For example, the last session was merged with the prototyping as the group found it useful to have prototypes and the test setup as inspiration, also called related stimuli [26]. Idea generation was however not confined to group sessions since Ulrich et al. [26, p. 133] points out that individual creative work within a group will generate more divergent solutions. Idea generation was therefore performed individually or through more spontaneous communication between members as well.

Concepts were then synthesized from the generated solution alternatives with the use of a morphological matrix. In this matrix, a set of solution alternatives were given for each identified sub-function and these were then combined in different permutations. Instead of using all possible permutations in this matrix, focus was placed on generating varied and distinct concepts. This was done in order to ensure wide coverage of the possible design space and to keep the amount of concepts at a manageable level. As suggested by Pahl et al. [30, p. 104], the solution alternatives were combined if they were compatible and preferably if some synergistic effect could be obtained.

In the early phases of the project, the different solution alternatives and concepts were sketched by hand to illustrate the function and to get a clearer understanding of the layout. Later, when the sets of solutions were narrowed down and increased in detail, CAD models were created using Creo Parametric to give a more accurate representation and precise dimensions. This also made it easier to check how the concepts could be fitted into the design space and where they could interfere with surrounding components. The CAD models were also used to better communicate the function and receive feedback [31]. An example of this process can be seen in figure 3.2.

(a)

(b)

(c)

(d)
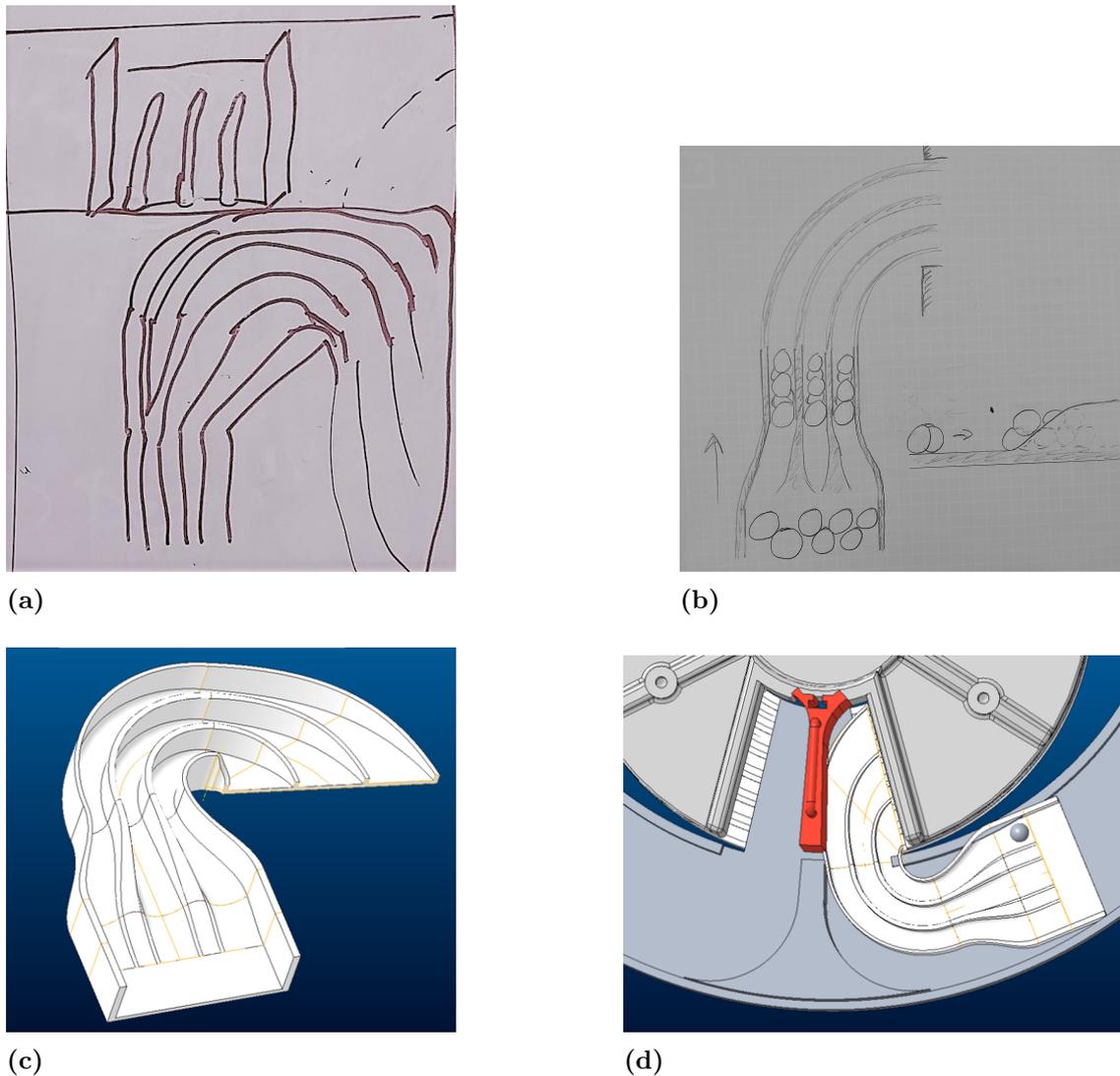
Figure 3.2: Example of process from extremely rough whiteboard sketch (a), to more detailed sketch (b), to a CAD model (c), to a rough check in assembly (d)

3.5 Evaluation and Screening

In the screening phase of the process, an elimination matrix was first created to disqualify the clearly unsuitable concepts. This was inspired by the matrix presented in Pahl et al. [30, p. 108] where each concept was given either a pass, fail or question mark on a set of criteria. The criteria were however based on the functional requirements and design constraints previously established instead of the ones suggested by Pahl et al. Passing concepts had to fulfill these criteria to be accepted past this stage. There were however some exceptions to this as there were considerable knowledge gaps in this early stage. While those concepts were given a pass, question marks were used to highlight any knowledge gaps and uncertainties that existed for the concepts which would need further study. This lessened the risk that potentially valuable working principles would be lost through a too harsh selection which Pahl

et al. also cautioned against [30, 106].

Strengths and weaknesses for the remaining concepts were compiled to give a quick overview of their attributes and to give a first basis of the following evaluation stage. This was followed by a Pugh's matrix as shown in the paper by Frey et al. [32, p. 44]. Here concepts were compared against each other and ranked based on the objectives and wishes from the requirement specification. One concept was selected as datum or reference, and the others were give a "+", "-" or "0" for each criteria depending on if the performed better, worse or on the same level as the datum. After the first evaluation, the datum was changed to the best performing concept and another iteration was done to observe how the performance changed. The choice of datum was based on which concept was considered well understood and of high performance as suggested by Frey et al. [32].

This type of matrix was chosen for the early part of the evaluation since its a low resolution was considered more suitable to early concept design compared to alternatives requiring weighting and detailed scoring [32, p. 43]. The idea of this matrix was foremost not to disqualify concepts and end up with a single winner, since the criteria were not weighted according to importance and has only three levels, but to be a basis for discussing the strengths and weaknesses of them. This would then reveal opportunities for improving them further which according to Raudberget [33] was the main intention of the method. Thereby, a concepts which excels in different aspects but performs poorly in others could borrow design aspects from each-other through cross-pollination resulting in an overall improvement.

The number of iterations of the Pugh's matrix was limited to two. Additional iterations could have resulted in the development converging on a dominating solution as described by Frey et al. [32], hence the original name of Pugh's Controlled Convergence. However, it was determined to be quicker to complement this limited use by additional selection methods as well as relying on input from SKF personnel. After first screening phase, two concept presentations were held, the second including the engineering manager at the production site in the US, to receive feedback from the people with most experience in this area. The feedback was then incorporated in the more detailed scoring of the concepts which was done using Kesselring's matrices [26, p. 169]. Here, a score from 0 to 5 was given for each criterion and then multiplied with a weight factor according to the importance of the criterion. The weights were determined by pairwise comparison of importance similarly to Raudberget [33]. The weighted scores from each criterion were then summarized and the concept alternatives were ranked based on the result.

3.6 Prototyping

Initially, it was planned to use the BEAring Simulation Tool (BEAST) software to verify the working principle of selected concepts and refine them through repeated simulations and optimization. BEAST is a multi-body and contact simulation tool

developed by SKF, primarily for simulation of bearings [34]. However, it was later revealed that to simulate a chute with a sufficiently large amount of balls passing through it would demand more time in both setting up and running the model than expected. The reason for this was that, as the balls move in a more or less unpredictable manner (depending on the specific design), each ball has the potential to contact every other ball. Therefore, contacts must be assigned not just between the balls and each surface element of the machine, but between each and every ball as well, which BEAST then calculates detailed surface data for. This results in a significantly more calculation heavy model than compared to more predicable systems such as bearings. It was therefore decided that an alternative method had to be used to study the macroscopic behaviour of the feeding.

Complete testing on the real machine would require spending both time and resources on detailed integration of each prototype into the machine, shipping it to the US and then making potential modification to it afterwards. Therefore, a strategy of lower fidelity tests were determined to be more suitable for shorter test cycles and rapid feedback [9]. This would enable repeated testing and modifications in a manageable amount of time due to the comparatively low cost of 3D-prints and a printing time of about 3 days. The aspects of the machine that were critical to the feeding design then had to be emulated. These were determined to be the rotation of the magazine bottom, its width and the balls behaviour when flowing from the magazine the machining area. For this purpose, the conveyor belt of a demagnetizing machine (see figure 3.3) was used to approximate the rotating bottom of the magazine as it was both readily available, cost effective, and it did not interrupt any ongoing production. Steel beams were used to act as the walls of the magazine and prototypes were then held in place by hand at end of them. An amount of silicon nitride balls, ranging from 70 to 100, were then placed on the conveyor and fed into the prototypes. The speed of the conveyor belt was not variable and measured to be approximately 0.1 m/s. This would be equivalent to a rotational speed beyond the upper limit of the real magazine's capability and therefore limited the possibility of comparing the speed of the balls in machine observations to the those in the tests. In addition, balls would have a differing tangential velocity in the outer versus inner part of the magazine which was not reflected in this set-up.

The silicon nitride balls used for these tests were both blanks with waistlines and machined versions to ensure that the feeding design was able to handle both types during the machining process (see table 4.2). Their differing surface roughness and presence of waistline was thereby accounted for in the testing in the event they had a major influence on the performance of the solution. A major limitation of the testing setup was that a continuous flow of balls through the chute could not be achieved over a longer time due to a lack of means to re-circulate the balls and the limited amount of them. Therefore, no quantitative data could be obtained and instead focus had to be shifted to a more qualitative approach. This consisted of studying and evaluating the prototype performance during shorter, repeated observations. The limited amount of balls also negatively affected the reliability of the test results, as the force from the balls pushing each other was considerably weaker.
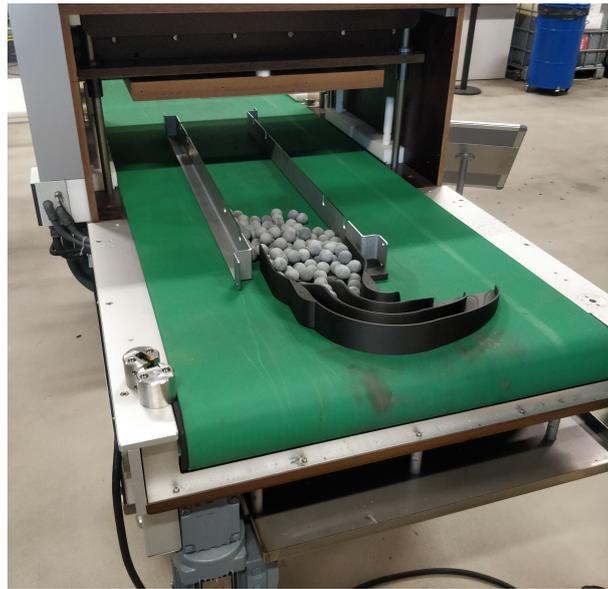
Figure 3.3: Test setup with conveyor belt, steel beams acting as magazine walls and prototypes held in place at one end.

An initial exploratory round of tests were done to better understand the flow of balls, the influence of different design features and to detect potential design problems early before starting the test iterations for refinement. This was inspired from the lean product development method of test-design-build cycles in Raudberget & Gustafsson [35] which entails testing as early as possible, not mainly to verify designs to specifications but to build knowledge before further designing. This would then help explore the possibilities more thoroughly before developing the detailed proposals. Figure 3.4 illustrates how this process would look. The test objectives were therefore what Camburn et al. [31] called exploration and active learning. New solution proposals were then made during the course of testing which were either applied to the prototypes at hand by simple modification or added in the later idea generation process. Concepts were only developed to a level of a minimum viable prototype for these tests, where they were operationally testable and where improvements could be identified as suggested by Raudberget & Gustafsson [35].

After the initial round of exploratory tests, the process moved on to the agile process of short tests, modifications and refinement with two concept-types selected for what Camburn et al. called parallel prototyping [31]. These were later made into modular pieces for increased development flexibility as suggested by Thomke and Reinertsen [9]. Combinations of the two chute-types then tested to examine if a merging of the concepts was beneficial.
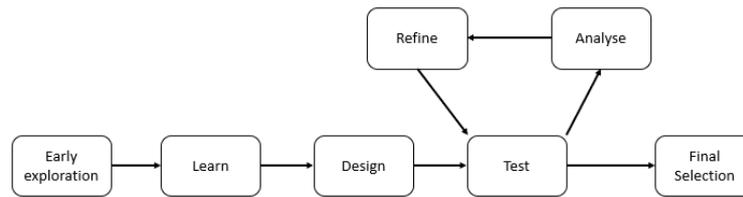
Figure 3.4: Overview of the resulting testing process

The final concept proposals were then adjusted based on the testing iterations. The assembly model of the machine provided by SKF was used to examine ways of how the designs could be integrated, both before and after detailed design work. The focus here was on non-intrusive means of integration as the final proposals required testing in the machine to fully validate the designs before full implementation. This would for example be proposals for utilizing pre-existing interfaces. Advantages and drawbacks of each method was discussed to base a final decision on. Simple finite element analysis using Creo Simulate were done to examine the structural integrity and check for stress concentrations in the final design.

Finally, the degree to which the design fulfilled the requirement specification was assessed to highlight areas where further development work and verification was needed. This provided a basis for future recommendations regarding testing. Proposals for future selection of material and manufacturing process was based on a coarse analysis using the ANSYS software Granta Selector [36].

3.7 Ethical and sustainability aspects

To ensure the security of sensitive information from SKF during the thesis work, storage and handling was confined to the company's internal systems. During the prototyping and testing phase of the project, the safety procedures of SKF was fop1llowed to avoid any accidents or damage to company property. This included safety training from SKF personnel, proper use of personal protective equipment and safety features of machines.

The method of testing mentioned above provided some additional benefits regarding sustainability as compared to repeated testing on the complete machine since no diamond abrasives or coolant was required. While prototyping was done extensively with 3D-printed models, requiring large amounts of polymer material, emphasis was put on utilizing each printed model to its limit to minimize material needed for re-printing. This consisted of making modifications to existing prints were possible rather than re-printing and designing interchangeable modules if larger features were shared between multiple models (see chapter 4.3.1).

4

Results

This chapter covers the process of development, including the results of the methods and tools used as well as the decision-making process throughout the development.

4.1   Identified Needs and Problems

Two main issues were identified from observation of the production process, namely the uneven distribution of balls between the lapping grooves at the inlet area and the pile-ups of balls near the ends of the magazine. These issues were only noticeable in machining of the large diameter balls as in the observations of the smaller diameter machining, the balls behaved closer to a fluid.

The uneven distribution of balls was identified as an area with potential for improvement. It was observed that the outer lapping grooves of the plate were served significantly more balls than the inner ones which was determined to be an underutilization of the machining area. In addition, the few balls that were fed into the innermost grooves risked getting stuck at the outlet since the discharge of balls back into the magazine was dependant on balls pushing each other out from the grooves. By overfeeding the outermost grooves, the exiting balls were then blocking balls in the innermost grooves from re-circulating back to the magazine and would therefore receive less machining time. The efficiency of the process could therefore be improved with an equal distribution.

(a)

(b)
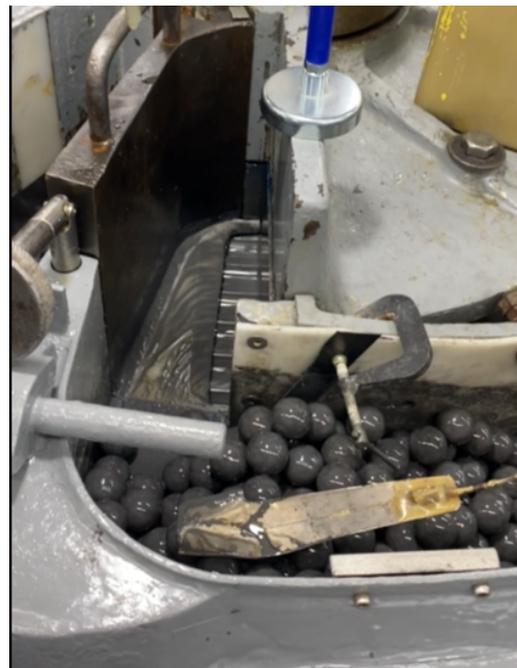
(c)

Figure 4.1: Highlighted area in (a) shows the innermost grooves which were seen to be under-served. Figure (b) indicates the area of the outlet where balls became stuck instead of being unloaded back into the magazine. Figure (c) shows a pile-up of balls at the inlet.

Intermittent pile-ups were identified at the transition between the magazine and inlet area right before the flow narrows down and makes a u-turn into the grooves. As explained in 2.2, the lapping load is a major factor in contributing to the material removal rate of the balls. Variations of the number of balls in the machining area

caused by these pile-ups could lead to variations in material removal rate as the load would be concentrated on fewer balls. This could negatively impact both the roundness of the balls and size variation within the batch. In addition, a too high force per ball can cause surface damage on the ball. A regular flow therefore would enable a much more controllable process with a stable force per ball that could be reliably set to an optimal value. Slowing down the rotation of the magazine was found to be the current way to alleviate the issue of pile ups, as a compensating action, but would in turn increase the machining time of an already relatively slow process.

Apart from these key problems, other needs and desirable features were that the solution should be easily implemented into the current machine set up with minimal re-design of surrounding components. The potion of the lapping grooves where the actual lapping takes place, called the machining area, should not be decreased at this would result in less machining time per ball. The design should not need many spare parts to be kept for replacement as well. As the solution would be implemented in a factory environment, it should be sufficiently durable, not just to withstand the operating process but also general rough handling. Due to the stiff and brittle nature of silicon nitride, intense collisions between balls should be avoided as this could lead to surface damage.

4.2 Concept Development

This chapter presents the initial concept development process, beginning with the establishment of requirement specification and functional analysis. From these foundations, concepts were generated and subjected to a screening process, resulting in the selection of the most viable concepts for detailed design.

4.2.1 Requirement Specification

The initial requirement specification was compiled based on the previously identified needs and progressively updated. In this early stage, it was deemed appropriate to keep the amount of requirements low as this would enable a more extensive exploration of the solution space. Performance requirements were also preferred at this stage, instead of constraints, as these could be weighted and compared instead of immediately disqualifying solutions. For example, the issue of applying a solution to the machine was initially reflected in only one performance requirement instead of directly including space constraints. Solutions that required redesigns to the machine were thereby retained when their performance could justify the changes. This also was thought to alleviate the potential risk that no solution could be found without significant redesigns. However, a constraint was added to ensure that concepts were compatible with both blanks and finished balls (see table 4.2). The issue outlet pile-ups was initially merged with the inlet pile-ups as a secondary objective. This was done in order to avoid an additional parallel development process and instead

enabling an outlet solution to be selected later in the process based on the evaluation for the inlet. In addition, certain concepts such as the switchers addressed both the inlet and outlet in one single solution step. The extent to which the pile-up issue at the outlet was connected to the distribution issue was uncertain and it was therefore decided to prioritize addressing the distribution issue.

No	Type	Requirement	Imp.	Value	Unit	Description	Justification	Evaluation method
1	Func	Balls must be uniformly distributed over grooves	5			Equal number of ball in inner as outer grooves	Utilization of machining area	Expert assessment. Testing of prototype
2	Func	Balls must be supplied in a regular flow	5			No pile-ups	Even machining	Expert assessment. Testing of prototype
3	Wish	There should be an even MRR over the batch	4			Every ball should enter the inner grooves as much as the outer grooves	Different MRR between grooves needs to be evened out	Expert Assessment
4	Wish	Should avoid collisions between balls	4			Balls colliding with each other creates defects	Ensure good surface quality	Expert assessment.
5	Wish	Should have smooth flow of balls at outlet	2			Unloading balls back into magazine without pile-up	Avoid balls getting stuck resulting in decreased machining time	Testing of prototype
6	Perf	Minimize wear	2				Ensure long service life	Material selection
7	Perf	Minimize complexity	3		part nr	Few parts as possible	Avoid having to stock additional spare parts	CAD
8	Perf	Maximize machining area	3		m	Avoid taking space away from grooves	Maintain efficiency of process	CAD
9	Perf	Minimize redesigns of surrounding components	4				Quick and inexpensive implementation	CAD
10	Const	Must handle force from moving balls	5				Durability	Material selection and FEA
11	Const	Must accept balls with size variation in diameter	5	27-25	mm		Handle both blanks and ground balls	CAD

Figure 4.2: Initial requirement specification

4.2.2   Function Analysis

As a first step in the functional decomposition, a black box model was made for the core function of supplying balls from the magazine to the six grooves (see figure 4.3). The process flow model was created to illustrate where the developed solution would be in the overall machining process 4.4. The main function was then decomposed into sub-functions based on the functional requirements specified. However, challenges were encountered in performing the decomposition at a detailed level while staying solution neutral. To overcome this, a function-means tree was used (see Appendix A.1), which enabled an exploration of the solution space while performing the decomposition. General solution categories began to emerge, such as re-designing the feeding into a single line of balls or to guide the flow by means of separate channels. This could then be broken down in further detail independently of each other. Sub-solutions were proposed for each decomposed function which done both in brainstorming sessions and a more spontaneous piece-wise fashion. This activity then served as a natural transition into the concept generation phase.
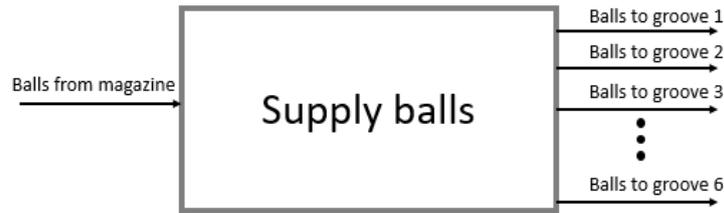
Figure 4.3: Black box model with function of supplying balls from magazine to each groove.
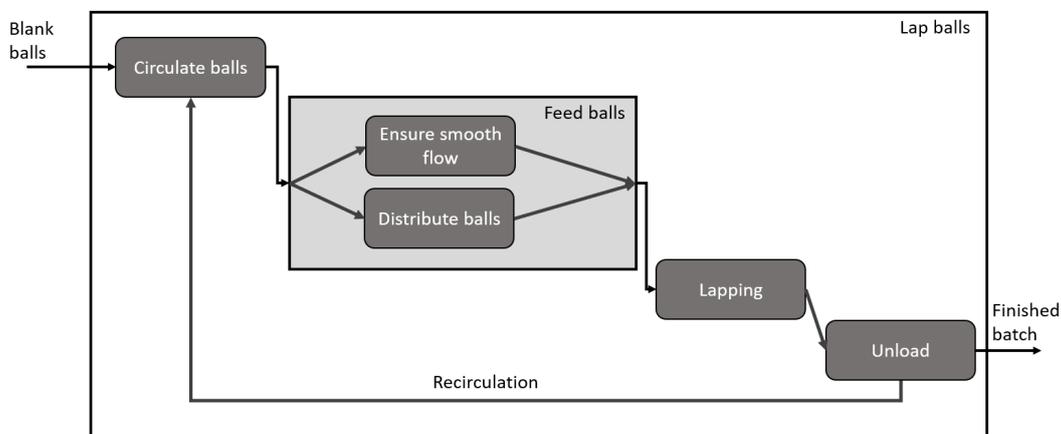
Figure 4.4: Process flow chart illustrating the repeated cycles of feeding, abrasion and re-circulation.

4.2.3 Concept Generation

During the idea generation phase, the brainstorming sessions further expanded the function-means tree. The group then utilized a Morphological matrix (see Appendix B.1) to generate further sub-solution alternatives and synthesize concepts by combining various functions with one another. Both the function-means tree and the matrix was gradually expanded by addition of ideas generated from individual creative work and the more free form discussions. The new additions were then explained and discussed during additional sessions.

The different functions identified in the previous phase were reformulated into general functions applicable to any solution type. The functions were arranged in rows, with several suggestions for sub-solutions. The order of these rows was here based on a rough estimation of importance, with the core function placed at the top. Functions specific to solution types in the function-means tree had to be disregarded in the matrix until a final solution type was selected to avoid creating an excessively complicated matrix. It was also realized that in some cases, solutions to one function heavily influenced other functions. Therefore, a function-means tree was relied

upon to keep track of the concepts overall structure. This proved more useful at this stage in synthesizing concepts while the morphological matrix was mainly used as an aid to identify areas of sub-solutions that had significantly fewer alternatives than others and should be expanded.

The overall goal of the synthesis was focused on searching for synergistic effects between sub-solutions and creating distinct concepts. It was thought that creating distinguishable and varied concepts would be more beneficial during the early development phase for solution space coverage. To accomplish this, various directions were explored such as generating the most minimalistic concept possible as well as going in the opposite direction and aiming for complexity.

4.2.4 Elimination

Four general criteria were specified to disqualify concepts through the elimination matrix in table 4.1. Two of them were based on the functional requirements of distributing balls and ensuring regular flow without pile-ups. These could efficiently exclude ideas that did not adequately address the main problems. However, instead of having one single requirement for these, splitting them up was thought to be useful if there was a need of reusing or recombining them later. The other criteria two were: compatibility to check that the solution could work with the existing process, and feasibility which was a broad criteria meant to take into account cost and complexity. Company personnel were consulted on some concept ideas where extensive knowledge gaps existed to gain a firmer basis for decisions on exclusion such as the spiral concept.

Out of the twelve generated concepts, four were eliminated in table 4.1. Number 11 was removed on the basis that it did not fulfill functional requirements it was estimated to not address the issue of distribution. Number 5 or the spiral concept was eliminated for not being compatible with the process. It was revealed from consulting the personnel at the company that this method results in too high wear on the tool-piece since the area widening effect of the guiding grooves on the top plate was not possible achieve. Finally number 7 and 11 were determined not to be feasible to implement due to too many uncertainties regarding interference with the process and machine setup. However, at this early stage it was decided to go ahead with other concepts where minor uncertainties were present as these could not be properly cleared up without a more detailed study. Further comments on uncertainties that were identified were also included in the matrix to document important points to be addressed.

Table 4.1: Elimination matrix for initial concepts

No.	Concepts	Distribute	Pile-up	Compatibility	Feasibility	Decision	Comment
1	Groove Switcher	+	+	?	+	Yes	Unclear if balls can be switched reliably
2	Magazine Switcher	+	+	+	+	Yes	
3	Banked	+	?	+	+	Yes	
4	Double stack	+	?	+	+	Yes	Check if balls can be stacked reliably
5	Spiral	+	+	-	-	No	Unsuitable due to lack of area widening
6	Top-down	+	+	+	+	Yes	
7	Flush	?	?	+	-	No	
8	Paddle wheel	+	+	+	?	Yes	
9	Magazine track	+	+	+	+	Yes	
10	Mech. pushing arm	-	+	+	+	No	
11	Conveyor	?	+	?	-	No	
12	Minimal track	+	?	+	+	Yes	Kept for ease of combination

4.2.5 Concepts

The eight remaining concepts were further developed by more detailed sketches to give a clearer visualization and a rough idea of the layout. Potential strengths and weaknesses of each concept were also discussed and presented below.

Groove Switcher

In the concept named Groove Switcher, the ceramic balls are fed in a single row from the magazine to the innermost groove, travels trough the machining area and are transferred to the next groove using a switcher as can be seen in figure 4.5. This is repeated until the balls passes all grooves and are then returned to the magazine from the outermost groove. The advantages of this concept is that it would primarily guarantee that all balls passes through every groove and therefore receive equal machining time as well as wearing the plates in an even fashion. As they travel in one single row at all times, the risk of pile-ups at both inlet and outlet is decreased as well. However, implementing this concept would require significant changes to the machine's design, including the divider, feeding plate and magazine. This concept was inspired by the patents by Messerschmidt as well as Kunio and Hajime presented in chapter 2.4.
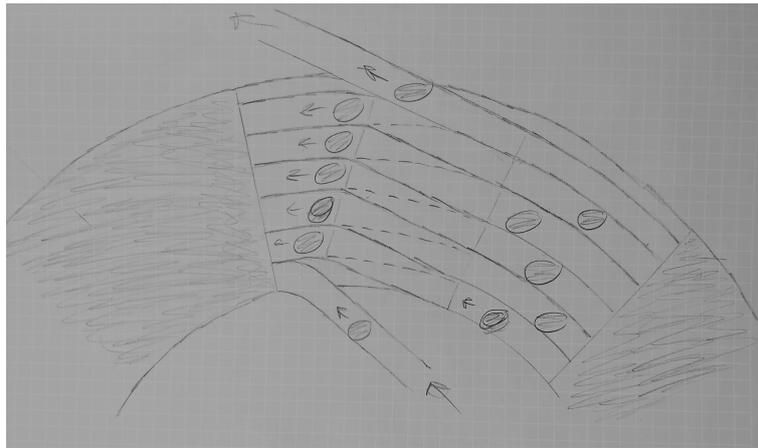
Figure 4.5: Groove Switcher concept sketch illustrating balls sequential motion through the lapping grooves

Magazine Switcher

Another result from the patent study was the concept of called Magazine Switcher inspired by the Messerschmidt patent in section 2.4. The magazine is divided up into channels that equals the number of grooves. The balls in each channel are then guided directly into one groove, and upon exiting are switched to another channel as indicated in figure 4.6. The channel running from the innermost groove then bridges the others to form a closed loop. Similarly to the groove switcher above, this would in theory guarantee equal distribution and decreased risk of pile-ups as balls are fed in a single line. The concept would in addition likely need less redesign of the magazine compared to the Groove Switcher, requiring only partitions for the channels. The major drawback would be the the gap in the top plate would have to be widened to accommodate channels for six grooves at the inlet and outlet which would result in decreased machining area and overall slower machining.
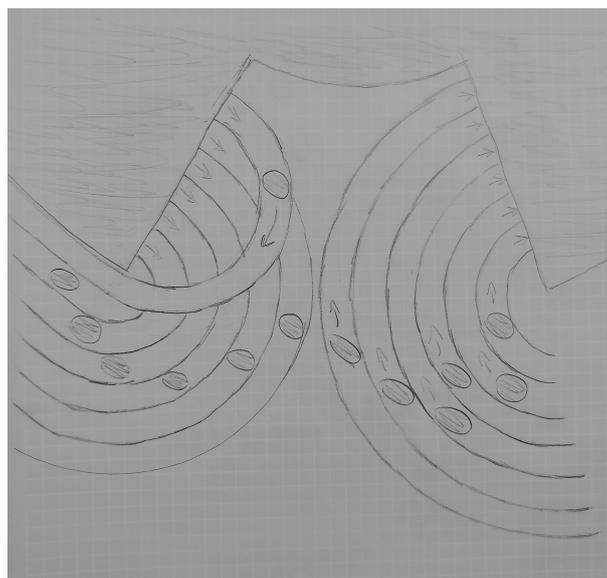
Figure 4.6: Magazine Switcher concept sketch.

Double Stack

The double stack concept was designed to gradually narrow down the flow of balls in the magazine and divide it up into three separate channels, as shown in figure 4.7. These channels would then be narrow enough to fit in the gap plate without re-designs and widen out right at the exit to the machining area. As the flow would be divided up at the magazine, before the bend in the flow, the distribution of balls between the channels would be equal. A less sharp bend in the flow compared to the current design was also intended to improve the distribution as well as the flow regularity. Separating the balls by means of dividing walls would avoid interference and friction between balls, thereby avoiding pile-ups. An added feature was the double stack idea which involved shaping the dividing walls of the channels in such a way that balls would be smoothly transferred from one layer to being stacked on top of each other. This could then help to avoid slowing the flow of balls down during the narrowing sections. The advantages of this concept were that it required little re-design, had a low level of complexity and was estimated to be reliable in distributing balls evenly. However, there was some uncertainty regarding if the idea of stacking would work as intended as high friction between balls rolling on top of each other could create to much resistance.
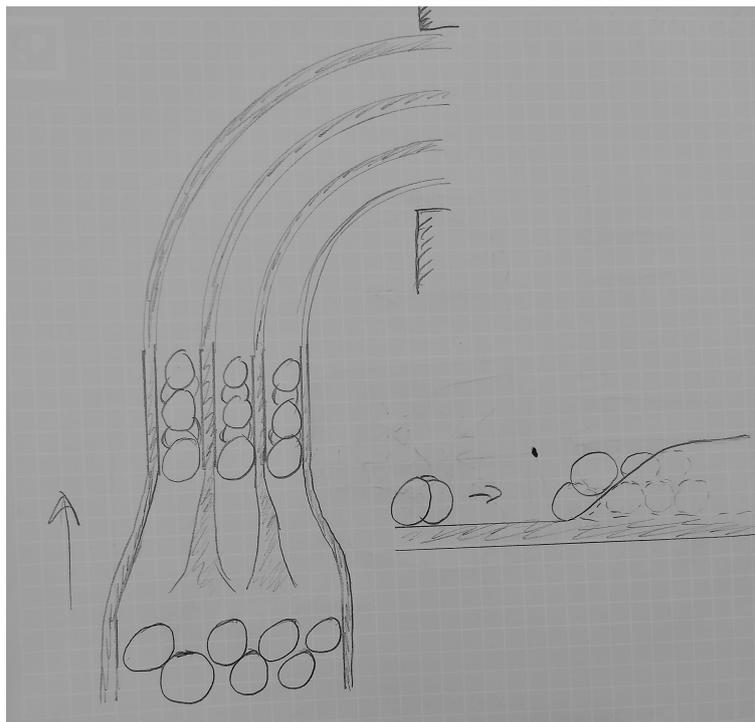
Figure 4.7: Double stack concept guiding balls from magazine

Banking

This concept was the outcome of a brainstorming session. The main principle was to provide the ceramic balls with sufficient kinetic energy to be delivered into the inner grooves of the machine. This was to be achieved by tilting or banking the magazine inwards to achieve the desired speed and height difference as the balls exited the

magazine. The idea was to utilize gravity to prevent pile-ups by allowing the balls to fall into the inlet area. This was regarded as a relatively simple approach to address the issues. However, uncertainties existed regarding the feasibility of tilting the magazine, the extent to which it could be tilted without disrupting the flow of balls going out from the machining area, as well as its effectiveness in the core functions of distribution.
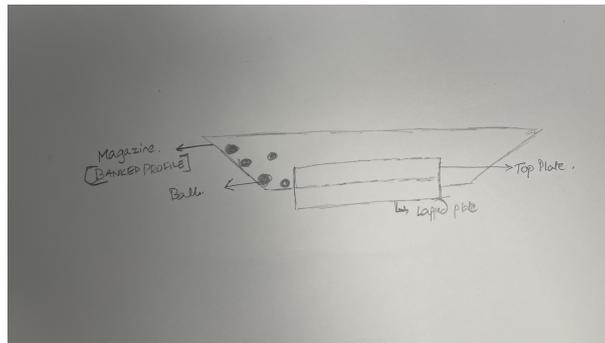
Figure 4.8: Banked Concept Sketch

Top-Down
This concept the result of the initial brainstorming session and involved directing the flow of balls up on a ramp to approach the inlet area from on top. It would then be split up into separate channels directed down perpendicular to the lapping grooves. This turned out to similar to the chutes used in machines where the plates rotation axis is tiled or completely horizontal. As there would be no need to narrow the flow of balls in the gap and divider in this concept, the risk of pile-ups would be eliminated and equal distribution would be ensured. This would also provide the opportunity of narrowing the gap of the top plate, resulting in increasing the machining area. However, significant design changes to the magazine were definitely necessary. A risk was also identified that the height the balls would fall from down could result in collisions and surface cracks.
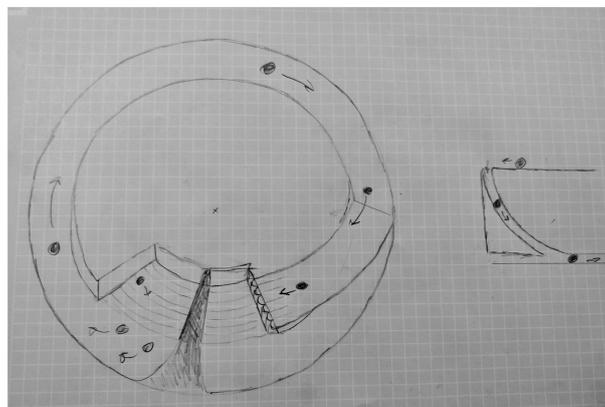
Figure 4.9: Top-down concept sketch with a ramp leading from the magazine, up onto the top plate.

Paddle Wheel

Paddle wheel concept aimed to provide the necessary force to deliver the ceramic balls into and out of the system. This would be achieved by re-designing the magazine and placing a rotating wheel between the inlet and the outlet of the magazine (see figure 4.10). The stirring action would then provide the force to drive the balls into and out of all the grooves. The wheel would forcibly dislodge any piled up balls, ensuring a regular flow. A similar wheel has already been used in lapping of smaller diameter balls in a different machine for lifting the balls up from the outlet to the magazine. The advantage of this concept is that it drives balls both in and out simultaneously and is likely to avoid pile-ups. However, there is some uncertainty regarding how well it would distribute balls among grooves, and significant re-design of the machine would likely be required.
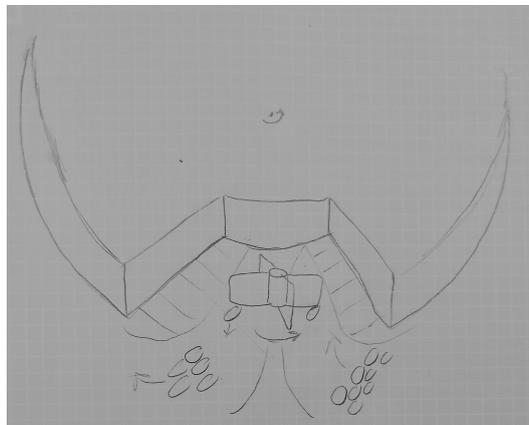
Figure 4.10: Paddle wheel concept sketch

Mini-Track

The aim of the Mini-Track concept was to guide the ceramic balls to the inner grooves with minimal changes in the overall design of the machine. In this concept, the existing plate below the divider was given a few tracks to guide the balls into the innermost grooves. It was observed that the two innermost grooves were the ones mainly affected by the uneven distribution, and this would be the minimalist way to address this issue. However, the ability to solve the problem of pile-ups was questionable. Nevertheless, this concept was retained as it was still considered useful since its working principle could be easily combined with other concepts if needed.
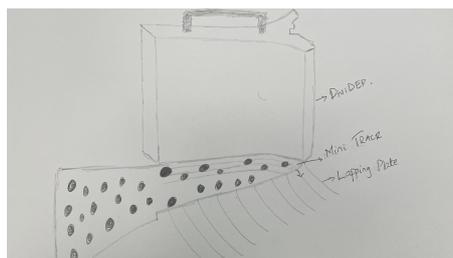
Figure 4.11: Mini Track Sketch Concept

Magazine-Track

The magazine-track concept involved feeding balls in separate channels by incorporating tracks in both the magazine and the divider, aligned with each other. In this case, the relevant track of the divider will receive the ceramic balls from the magazine's rotation, ensuring a consistent supply of balls to each groove. To implement the proposed solution, a significant redesign of the machine is required to enable smooth transfer of the balls from the magazine to the divider and then to each groove. The magazine must also be angled to provide the height difference required to feed the balls into the system. This concept was the result of the brainstorming session with the intention of a maximalist solution. The continuous track from outlet to inlet would would ensure a regular flow and improve the performance of the process by feeding balls evenly to all the grooves.
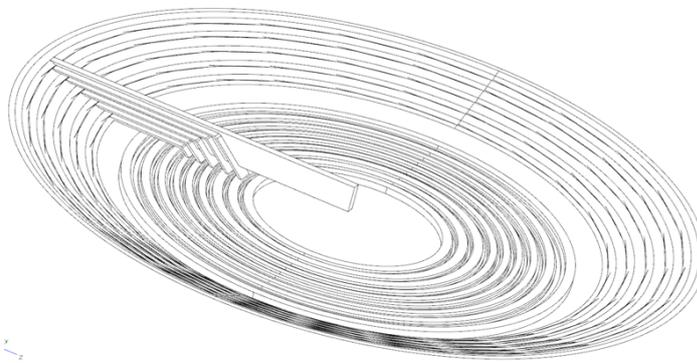
Figure 4.12: Magazine track concept sketch

4.2.6 Evaluation

The Pugh's matrix was done in two iterations with two different concepts selected as references, the Banked concept and Double stack (see table 4.2 and 4.3). The Banked concept was chosen as the datum as it was considered relatively well understood compared to the rest and the Double Stack was then chosen for its strong performance. From this, it could be seen that some concepts were rather balanced in their performance such as the Banked while others were more varied, for example both of the switcher concepts. The matrix was useful in giving a more detailed view of the relative strengths and weaknesses while being easily navigable. It was noticed that this matrix was easier to use in this early stage as it only involved comparing concepts rather than trying to quantify their performance individually. While the Pugh's matrix usually demand more iterations to reach convergence as explained in 3.5 it was decided to be a more efficient use of time to instead present the concepts to the personnel at SKF for feedback after two iterations. As can be seen from these matrices, the issue was identified that the majority of the concept had weaknesses regarding the criterion of minimizing complexity and redesigns to the machine which was also confirmed at the first concept presentation held.

Table 4.2: Pugh's matrix, 1st iteration

Criteria	Concepts								
	Banked	Groove switch	Magazine switch	Double stack	Top-Down	Paddle Wheel V	Paddle Wheel H	Magazine Track	Minimal track
Distribute uniformly	Datum	+	+	+	+	0	0	+	0
Even MRR		+	+	0	0	0	0	-	0
Avoid pile-up inlet		+	+	+	+	+	+	+	-
Avoid ball-ball collision		-	-	0	0	-	-	+	0
Minimize redesign		-	-	0	-	0	0	-	+
Minimize complexity		-	-	0	-	-	-	0	+
Maximize machining area		0	-	0	+	0	0	0	0
Avoid pile-up at outlet		+	+	0	-	+	+	0	-
Sum +	0	4	4	2	3	2	2	3	2
Sum 0	0	1	0	6	2	4	4	3	4
Sum -	0	3	4	0	3	2	2	2	2
Net	0	1	0	2	0	0	0	1	0

Table 4.3: Pugh's matrix, 2nd iteration

Criteria	Concepts								
	Banked	Groove switch	Magazine switch	Double stack	Top-Down	Paddle Wheel V	Paddle Wheel H	Magazine Track	Minimal track
Distribute uniformly	-	0	0	Datum	0	-	-	0	-
Even MRR	0	+	+		0	+	+	+	0
Avoid pile-up inlet	0	+	+		0	0	0	0	-
Avoid ball-ball collision	0	-	-		0	-	-	0	0
Minimize redesign	0	-	-		-	-	-	-	+
Minimize complexity	0	-	-		-	-	-	0	+
Maximize machining area	0	0	-		+	0	0	0	0
Avoid pile-up at outlet	-	+	+		-	+	+	0	-
Sum +	0	3	3	0	1	2	2	1	2
Sum 0	6	2	1	0	4	2	2	6	3
Sum -	2	3	4	0	3	4	4	1	3
Net	-2	0	-1	0	-2	-2	-2	0	-1
Rank									
Decision	mini variant			bridge variant		check compatibility in assembly	check compatibility in assembly	modified variant	

It was decided that the paddle wheel concepts would be eliminated due to the uncertainty regarding its performance in distribution combined with the above mentioned weaknesses. To address the identified weakness for the other concepts, additional variations were created after a shorter ideation session. A modified Magazine track concept was created to reduce changes to the magazine and divider. This consisted of limiting the guiding tracks to a plate running from the magazine to the inlet and outlet, merging it with the concept of Minimal track. The flow of balls would then not be split up into individual channels but instead guided passively by shallow tracks on an underlying plate. It was estimated that the distribution may not be as even compared to the original, but the complexity was reduced significantly.

A variation of the banked concept called Mini Banked was also created (see Appendix C.1 based on the evaluation results which involved limiting the banked shape to a specific part at the end of the magazine, fulfilling a similar function to banking the

entire magazine. This would considerably simplify the implementation while not affecting the core function of the concept. As stated earlier there was some uncertainty regarding the stacking aspect of the concept Double stack. A variation of this concept, called the Bridge, was therefore created. The concept involved letting balls fall into the channels from a downward slope instead of being pushed together. Gravity would then aid in dividing up the flow into the channels instead of a horizontal flow. However, this came with its own concerns as the initial slope upwards could slow the flow of balls to a stop if the driving force on the balls was insufficient to push them up.

The newly created variations as well as the original concepts were scored using a Kesselring's matrix (see table 4.4) for a weighted sum of the concepts performance. While both the switcher concepts performance in addressing the distribution and pile-up problem were estimated to be good, this did not outweigh the complexity and re-design. The top-down concept was also eliminated for similar reasons, as the ramp leading up above the gap could obstruct the operation of the machine. To drive the flow up on the ramp, an additional driving mechanism would be necessary as well. The Top-down and Groove switcher concept were however considered better suited for other machining configurations, for example a tilted or horizontal lapping plates, where a height difference between the inlet and outlet would enable flow of balls to be driven solely by gravity. The discussions revealed that the possibility of banking the magazine was more limited than initially estimated, which impacted its scoring negatively. The four lowest performing concepts were thus eliminated. As can be seen in the matrix 4.4, there was only a small margin in the score between the eliminated concepts and the lowest performing concepts remaining. However, further eliminations were put on hold until the second concept presentation was held to incorporate further feedback into the scoring.

Table 4.4: 1st Kesselring's matrix. Disqualified concepts are marked in grey.

Criteria	Weight	Ideal values		Groove Switcher		Magazine Switcher		Double stack		Bridge		Magazine Track		Minimal track		Banked		Mini Banked		Mod. Mag tack		Top-down	
		v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t
Uniform distribution	5	5	25	5	25	5	25	5	25	5	25	5	25	3	15	3	15	3	15	5	25	4	20
Regular flow / no pile-ups	5	5	25	3	15	4	20	4	20	4	20	5	25	2	10	4	20	4	20	4	20	3	15
Even MRR	4	5	20	5	20	5	20	4	16	4	16	4	16	3	12	4	16	3	12	3	12	3	12
Avoid collisions	4	5	20	3	12	4	16	4	16	4	16	5	20	2	8	3	12	3	12	3	12	2	8
Minimize wear	3	5	15	4	12	4	12	5	15	5	15	4	12	5	15	3	9	3	9	3	9	2	6
Maximize machining area	3	5	15	3	9	1	3	4	12	3	9	3	9	3	9	3	9	3	9	2	6	5	15
Minimize complexity	3	5	15	1	3	1	3	4	12	4	12	2	6	5	15	4	12	4	12	4	12	3	9
Minimize redesign	5	5	25	0	0	0	0	4	20	4	20	2	10	5	25	3	15	5	25	4	20	2	10
Applicable to outlet	2	5	10	5	10	5	10	4	8	1	2	2	4	2	4	0	0	0	0	3	6	0	0
Score			170	29	106	29	109		144		135		127		113		108		114		122		95
Score/Max score					0,62		0,64		0,85		0,79		0,75		0,66		0,64		0,67		0,72		0,56
Rank									1		2		3		6				5		4		

To better communicate the concepts and receive more accurate feedback, quick CAD mock-ups of the concepts were created in Creo Parametric (see Appendix C). These were also used in discussing how they would be integrated into the machine and which components could be affected as a 3D representation was found easier to

use when pointing out potential issues as compared to sketches. Another concept presentation was held to discuss the concept with personnel close to the machine at the production site. Here, possibilities and limitations of modifying the lapping machine were discussed in detail as well the remaining concepts. From this it was determined that the issue of redesigns was too great for the original Magazine track concept. This feedback was reflected in the scoring on a second Kesselring's matrix which resulted in the elimination as seen in table 4.5. The Mini Banked and Minimal track concepts were also eliminated due to overall low performance.

Table 4.5: 2nd Kesselring's matrix. Disqualified concept are marked in grey.

Criteria	Weight	Ideal values		Double stack		Magazine Track		Minimal track		Mini Banked		Mod. Mag tack		Bridge	
		v	t	v	t	v	t	v	t	v	t	v	t	v	t
Uniform distribution	5	5	25	5	25	5	25	3	15	3	15	4	20	5	25
Regular flow / no pile-ups	5	5	25	4	20	5	25	2	10	2	10	4	20	4	20
Even MRR	4	5	20	4	16	4	16	3	12	3	12	3	12	4	16
Avoid collisions	4	5	20	4	16	5	20	3	12	3	12	3	12	4	16
Minimize wear	3	5	15	5	15	4	12	5	15	3	9	5	15	5	15
Maximize machining area	3	5	15	4	12	3	9	4	12	3	9	4	12	4	12
Minimize complexity	3	5	15	4	12	0	0	5	15	4	12	5	15	4	12
Minimize redesign	5	5	25	4	20	0	0	5	25	5	25	5	25	4	20
Applicable to outlet	2	5	10	4	8	1	2	1	2	1	2	1	2	3	6
Score			170		144		109		118		106		133		142
Score/Max score					0,85		0,64		0,69		0,62		0,78		0,84
Rank					1								3		2

4.2.7 Detailed design

The three remaining concepts Double stack, Bridge and Mod. Magazine track were designed. The top performing concept Double stack consisted of three equally spaced channels, where the flow of balls from the magazine would gradually be divided up evenly and narrowed down (see figure 4.13). This would allow for larger radius of the turn that the balls have to perform compared to the current machine, which was intended to improve the flow. The channels widen out towards the end to line up the three channels with the six grooves of the lapping plate. The bottom of the channels transition from curved to flat to allow the balls to randomly roll into either one of the two lapping grooves per channel. An additional variation of this concept was generated during this designing phase, called Saw-tooth. This consisted of narrowing the transition to the dividing walls and including a saw-tooth shaped entry to gently direct the balls into ordered rows.

(a)

(b)

(c)
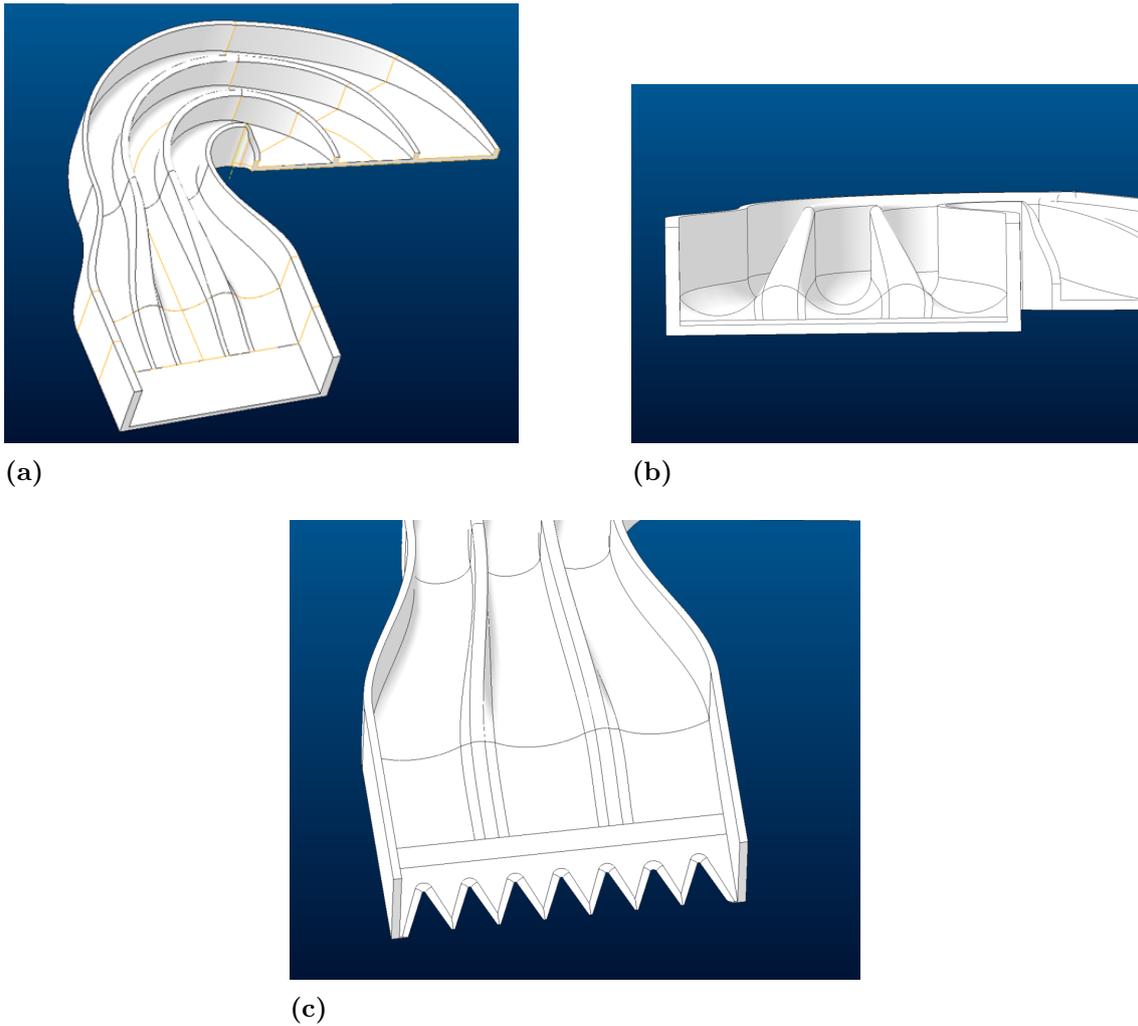
Figure 4.13: Double stack concept (a) with sloped transition to three channels (b). The newly created variation Saw-tooth can be seen in (c).

The concept called the Bridge mentioned earlier consisted of the upwards sloping entry, with a height difference of approximately 40 mm (see figure 4.14). The balls would then push each other up onto this in order to transition into the channels by falling into place. The intention with this variation was to use gravity to aid in separating the flow. However, the initial upwards slope was thought to be a risk as there was considerable uncertainty regarding how high of a slope the balls could be driven up onto solely by the rotation of the magazine.

(a) **(b)**

Figure 4.14: Bridge concept with an initial slope (a) transitioning downwards into the channels (b).

Finally, the Modified Magazine track concept involved a simple plate with shallow grooves, running from the magazine to the machining area (figure 4.15). These grooves would the guide the balls and distribute them while still allowing balls to cross over between them. Compared to the designs usi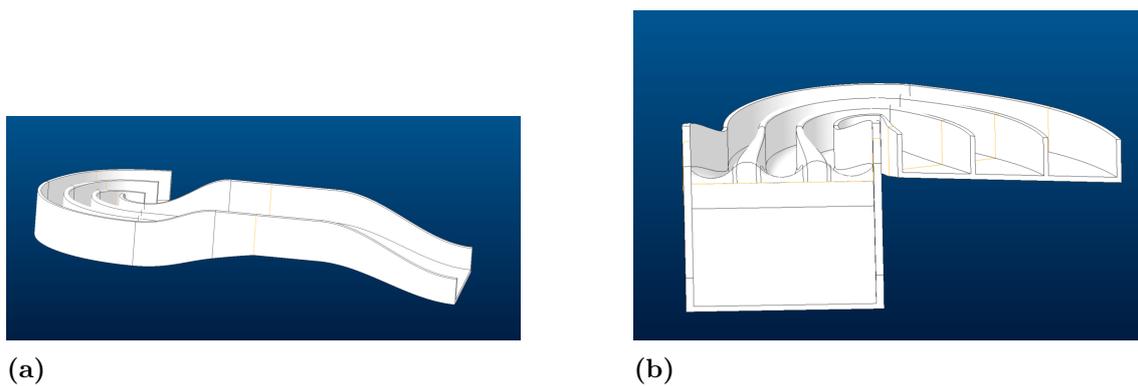ng dividing walls presented above, this open design was intended as a safe option should the other designs prove less effective than initially estimated.
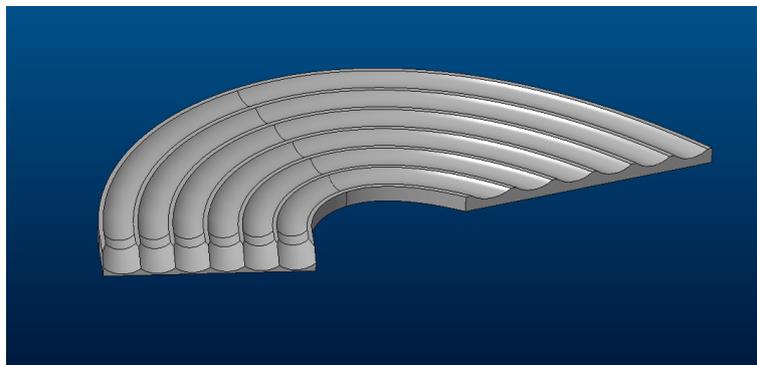
Figure 4.15: CAD geometry of the Modified Magazine track concept

4.3 Chute Prototyping

It was noticed that the development converged on a specific solution type since the remaining three concepts shared the basic principle of a chute running from the magazine to the inlet, guiding the flow of balls. The requirement specification was therefore updated with more focused requirements specifically for chute-type designs, incorporating stricter design constraints from the machine (see Appendix D). This specification led to additional sub-functions being formulated specifically. A process-flow model (see figure 4.16) was made to illustrate how the chute functions would be performed sequentially as balls passed through. The formulated requirement were then categorized according to the newly identified sub-functions to create

a organized specification that would easier to navigate. This categorization proved useful since the new design constraints enlarged it considerably as can be seen in Appendix D. A category of requirements was also created for an outlet chute which was later developed separately through a shorter selection, in section 4.3.4.

Figure 4.16: Process-flow of how balls would pass through chute designs

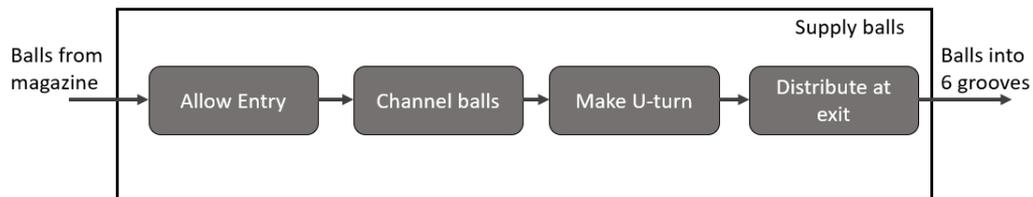A new iteration of the brainstorming session was held, later complemented by individual proposals based on spontaneous ideas. Based on the functions specified in the new function analysis, another morphological matrix was created for concept synthesis (see Appendix B.2). As before, the focus was on generating distinct and varied concepts from the sub-solutions. The original chute-type concepts were merged in the matrix to enable design features to be mixed up and shared. During the later prototyping iterations, this matrix was continuously added to as new design features were proposed to serve as a means of documenting new ideas. Crosses were added over certain individual features were deemed unsuitable based on later testing.

4.3.1 Exploratory tests

It was determined that further decisions regarding a final design selection required establishing a firmer knowledge foundation regarding the flow of balls from the magazine. Physical prototypes were therefore relied on to explore the design alternatives. An exploratory testing was done in parallel with the idea generation to serve as an input to the new concept generation and to gain a more tacit understanding of silicon nitride balls behaviour. The initial chute concept Double stack and the variant Saw-tooth was produced to study influence of different design features. These were 3D-printed in two different polymer materials, ASA (Acrylonitrile styrene acrylate) and PET (Polyethylene terephtalate) to investigate in the influence of the material properties on the chutes and the durability of the prints regarding layer-to-later adhesion.

The test was conducted with the conveyor setup described in chapter 3.6 and with the main objective to study how the balls behave during the entry, channeling and exit part of the design. Issues with function of the design could thereby be caught early, before the production of additional variations and refinement. This would also include inspecting how the balls stacked in the channels to see if the principle of the Double Stack concept was reliable as this would have a major influence on

further design decisions of chutes. As these variants had the same geometry at the exit, the front areas were made into modular pieces to shorten the production time and save material (see figure 4.17). As can be seen in Appendix E.1 and E.2 the exit part was mirrored as it was initially planned to screw the prototypes in place at the side of the conveyor belt. This idea was however discarded as it was noticed that holding it in place by hand was sufficient for the purpose of this low accuracy testing.

Figure 4.17: Modular prototypes

The early prototypes were produced before the exact magazine width was known. The entry area of the two chutes were therefore 30 mm wider than required which resulted in a sharper narrowing of the flow and an increased risk of pile-ups. The overall performance of these prototypes were therefore not considered reliable. However, it would still provide an opportunity to inspect the balls behaviour in detail and give some useful information on the influence of different design features.

The result of this test revealed multiple issues with some of the design features of the first prototype. As can be seen in Appendix E.1, balls entered the channels, slowed to a stop and piled up right at the sloped area where the dividing walls began. This behaviour was especially prominent when blanks were used as compared to finished balls, which led to further tests using blanks. It was observed that balls stacked on top of each other had a significantly higher resistance in rolling due to the friction between them, thus slowing down the flow. This effect may also be exacerbated by the presence of waistlines on the blanks that lock into each other. Additionally, the large sloped entry area of the channels further slowed down the balls. The principle of stacking the balls was therefore decided to not be a desirable feature for channeling of balls. The few balls that entered furthest into the channels still had a relatively high rolling resistance. This could be the result of the large contact area between the ball and the rounded bottom of the channel, as the curvature of the bottom follows that of the ball. A solution was then proposed to use v-shaped channels that would limit the contact to two single points so as to reduce the friction (see figure 4.18). This would have the added benefit of keeping the balls centered

in the channels instead of sliding against the dividing walls. The material ASA was noted to be very tough and durable from handling the prototype with a good layer-to-layer adhesion, even on the thinner <1 mm sections.

Figure 4.18: Contact (highlighted in red) between ball and chute in rounded vs v-shaped cross-section

The second variant tested consisted of a thinner transition to the channel walls with a smaller sloped area as well as a saw-tooth pattern at the entry zone. The result of this design was a marginal improvement as a slightly reduced pile-up could be observed (see time-lapse in Appendix E.2). This indicated that thinner and sharper transitions for the dividing walls were preferable to the large sloped areas of the previous prototype. However, the flow still came to a stop as it reached the channels and narrowed down. The prototype was printed in PET polymer which was noticeably harder and stiffer which resulted in less friction to the balls. It was considerably less durable than ASA as the layers separated easily at sections with around 1 mm in thickness. A modification was done to the previous prototype to investigate if the narrowing of the ball flow could be aided by the balls remaining in contact with the underlying conveyor during this action. The modification consisted of cutting a v-shaped notch into the bottom of the chute, reaching into the middle channel (see figure 4.19). The cut was made progressively larger. It was discovered that while issue of pile-ups remained, the balls in the middle channel continued to rotate from the contact with the conveyor which aided in driving the balls further into the chute. This later lead to the idea of keeping the chute open at the bottom of the entry area where balls are channeled to maintain the driving force of the conveyor for as long as possible.

Figure 4.19: Modification to the entry

Additional force was applied by hand to balls to test if these pile-ups were only due to a decreasing driving force when a lesser portion of the balls were in contact with the conveyor. It was noticed that even this was insufficient to force a flow of balls. When giving both the prototypes a slight upwards tilt of approximately 10 degrees, it was noticed that balls could not be driven up far onto sloped planes and were instead rolling in place, even with increasing the amount balls to 100. This negatively affected the evaluation of the Bridge as the possibility of using a high entry slope was limited. However, tilting the chutes slightly downwards, by approximately 5 degrees, had a significant positive impact flow of the balls into the channels. Results from these initial tests were incorporated into the requirement specification (see Appendix D), and used to guide the further designs together with the exact magazine dimensions.

4.3.2 Selection and Refinement

Based on the morphological matrix (Appendix B.2) and the initial tests, two additional concepts were designed. The new variations were called Cutout and 6-Grooves. The Cutout concept consisted of three separate equally spaced channels similar to the previous prototypes but with the added features of v-shaped cross-sections. Thin dividing walls were used instead of the large sloped area as can be seen in figure 4.20. The entry area was inspired by the modification done to the initial prototype where the bottom was cut out to let the balls remain in contact with the rotating surface underneath while being channeled into the chute. An opportunity identified with this design was the ability to control and fine-tune the

distribution between channels by adjusting the width of the protruding entry walls. This was however not included in the testing due to time limitations. The v-shaped channels gradually transitioned to a flat-bottomed exit in order for the balls to fall into the two corresponding lapping grooves of the plate in a random manner.

(a)

(b)

(c)
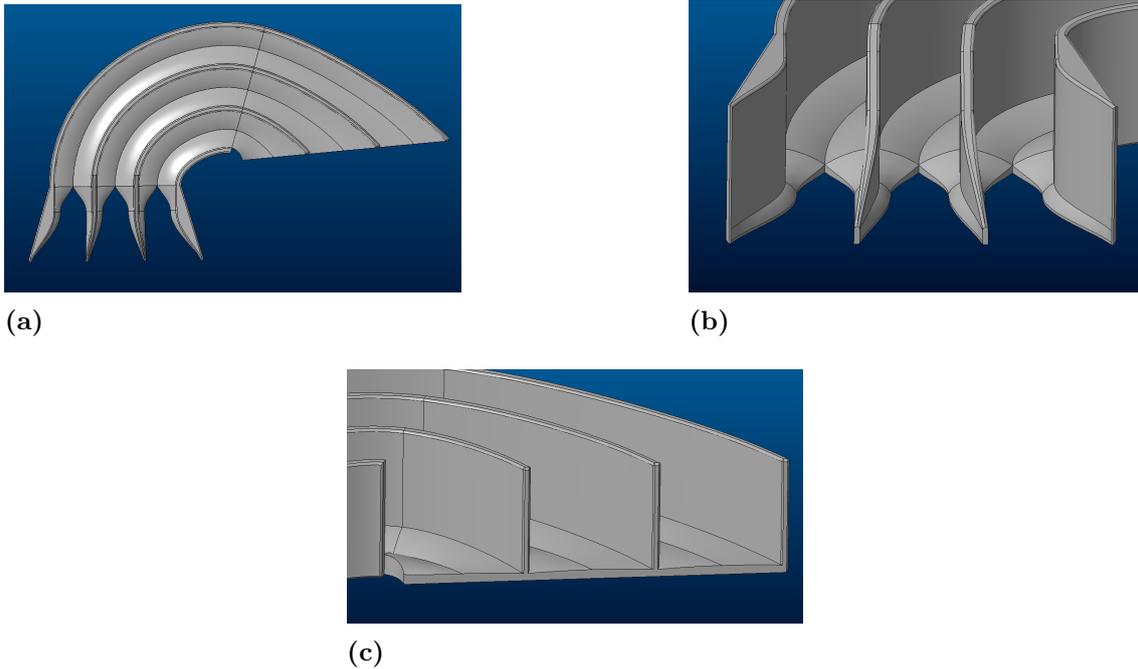
Figure 4.20: CAD geometry of Cutout concept with open entry (a), v-shaped channels (b) transitioning to a flat exit (c).

The 6-Grooves was the result of merging the older concept of the modified magazine track with the shape outline of the Cutout chute. The bottom of this chute consisted of six shallow, evenly spaced and v-shaped grooves as seen in figure 4.21. These would guide the balls in a more passive manner compared to separation into channels while still ensuring that they were distributed equally. The absence of dividing walls was expected to ease the flow through the chute, but as a trade-off, there was a risk that balls would press in on each other from all sides during the entry instead.

(a)   **(b)**

(c)

Figure 4.21: CAD geometry of the 6 Groove concept with a saw-tooth entry (a), v-shaped shallow grooves (b) which run throughout the chute (c).

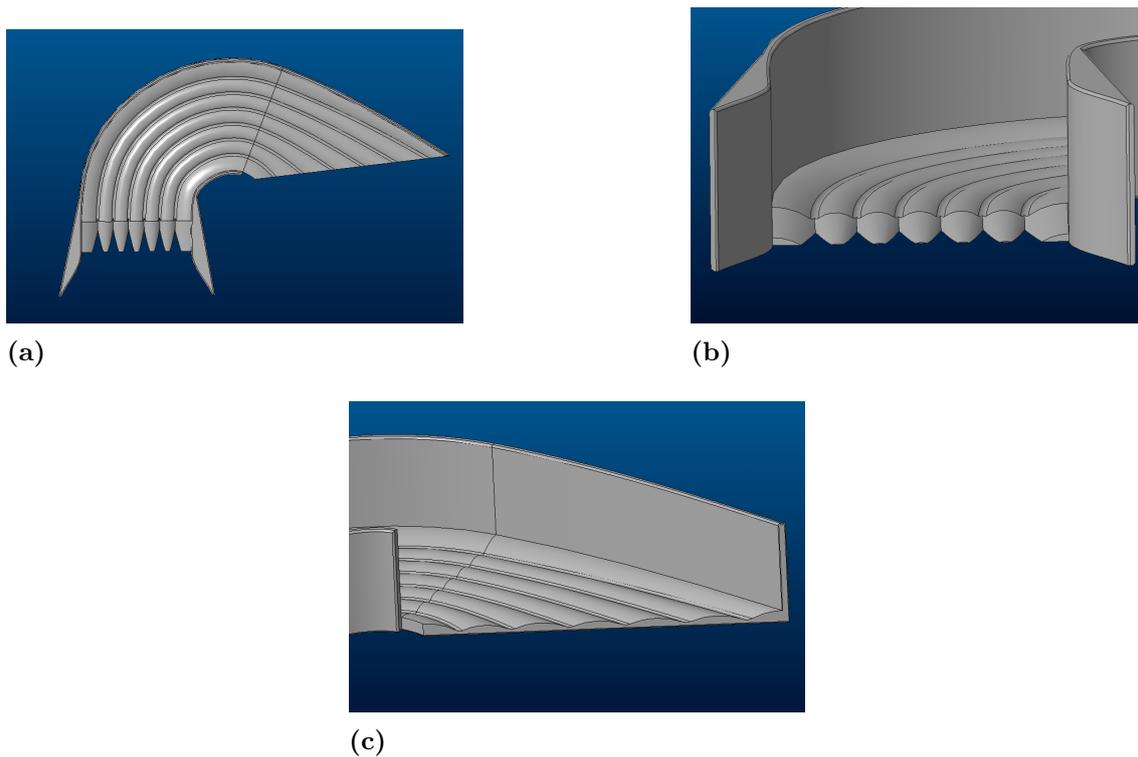These concept variations were, together with the previously tested concepts and the Bridge, included in smaller Kesselring's matrix with criteria based on the new functions (see table 4.6). An additional criteria of reliability was which represented estimations of how sensitive the chutes functioning were to the changes in conditions between the test on the conveyor belt and the actual machine. This included the lower speed of the magazine and higher pressure from additional balls in the magazine. Scoring was then based on the experience gained during the exploratory testing. These scores were then continuously adjusted during the following prototype iterations. Based on the initial result, Cutout and 6 Groove were selected for parallel prototyping and refinement. A further variation was later added in the matrix after the first test iterations called 3 - 6 Transition, which was the result of modifications and merging done to the Cutout and 6 Groove concepts during the prototyping. These prototypes were printed in PET polymer to keep the cost and printing time low.

Table 4.6: Evaluation of concept variations using a new Kesselring's matrix.

Criteria	Weight	Ideal values		Double Stack		Saw-tooth		Bridge		Cutout		6 groove		3 - 6 Transition	
		v	t	v	t	v	t	v	t	v	t				
Allow Entry	5	5	25	2	10	3	15	1	5	4	20	4	20	4	20
Channel	5	5	25	1	5	1	5	3	15	4	20	3	15	4	20
Exit distribution	5	5	25	3	15	3	15	3	15	3	15	4	20	4	20
Reliability	4	5	20	2	8	2	8	2	8	3	12	5	20	4	16
Score			95	8	38	9	43		43		67		75		76
Score/Max score			1		0,40		0,45		0,45		0,71		0,79		0,80
Rank					5		4		4		3		2		1

4.3.3 Test iterations

Prototypes of the two selected concept were 3D printed and tested using the same conveyor belt setup. The tests were repeated 7 to 10 times for each prototype with balls being stirred to randomize their orientation between tests. The test objective was first of all to check if a continuous flow of balls through the chutes could be achieved with the 100 available balls. The flow of balls would then be examined at the entry, the turning section and at the exit of the chutes. The result of the first tests indicated some improvement in the flow compared to the exploratory tests as it was noticed that the decreased contact area at the bottom significantly eased the travel of balls in both prototypes. This was confirmed by rolling individual balls by hand through the chutes.

The open entry area of the Cutout prototype positively influenced the entry performance, with noticeably smaller pile-ups (see Appendix E.3). There were however still some blockages where balls had stacked on top of each other, which resulted in only 5 - 6 balls completely passing through the chute during each iteration. The flow slowed to a complete stop after approximately 5 seconds as can be seen in the time-lapse presented in Appendix E.3. It proved possible to force the balls through the chute by hand with the pile-up, indicating that it was less severe than the blockage present in the exploratory tests. To closer examine the distribution of balls in the exit area, balls were repeatedly rolled through each channel by hand at various speeds. This indicated that the flat shape of the exit was insufficient in transitioning balls from the 3 channels to the 6 lapping grooves evenly. Due to the centrifugal force on the balls during the turning section, they had a tendency to exit on the outermost side of the channels when passing at higher speeds.

Tests with the 6 Groove prototype revealed that the shallow groove design was sufficient to guide the balls and distribute them evenly. Balls appeared to move with ease in the end part compared the Cutout. However, the lack of dividing walls resulted in a minor pile-up at the entry as balls pressed on each other from both behind, in front and at the sides. This occurred after approximately the same time passed as with the Cutout, as indicated by the time-lapse in Appendix E.4.

To address the issue of distributing balls from three separated channels to the six lapping grooves in the Cutout concept, a modification was done to the exit area. This consisted of cutting out portions of the bottom to form a ridge at the center that would allow balls to fall to either side as shown in figure 4.22. This was tested in a new iteration, both in the conveyor setup and by repeatedly rolling balls by hand at various speeds through the channel. The ridge shape was then changed by gradually filing it. The ridge proved to be functional but highly sensitive to both the speed of the balls and small changes in the geometry of the ridge.

Figure 4.22: Modification in the form of a ridge to exit of the Cutout concept

The idea of merging the two prototypes was proposed as an additional alternative. This involved combining the entry section of the Cutout with the end-part of the 6 Groove. Thus, the balls would be separated during the entry section, and then transitioning to 6 shallow grooves. This was intended to create an even and separated flow at the entry, while freeing it up after passing the narrow gap. To quickly test this idea, the prototypes were split in half and taped together in the new configuration as shown in figure 4.23. Even while the grooves did not align completely with the 3 channels, the balls still distributed relatively evenly compared to the previous tests, as can be seen in Appendix E.5 when pushed through by hand. This indicated better performance than the Cutout concept.
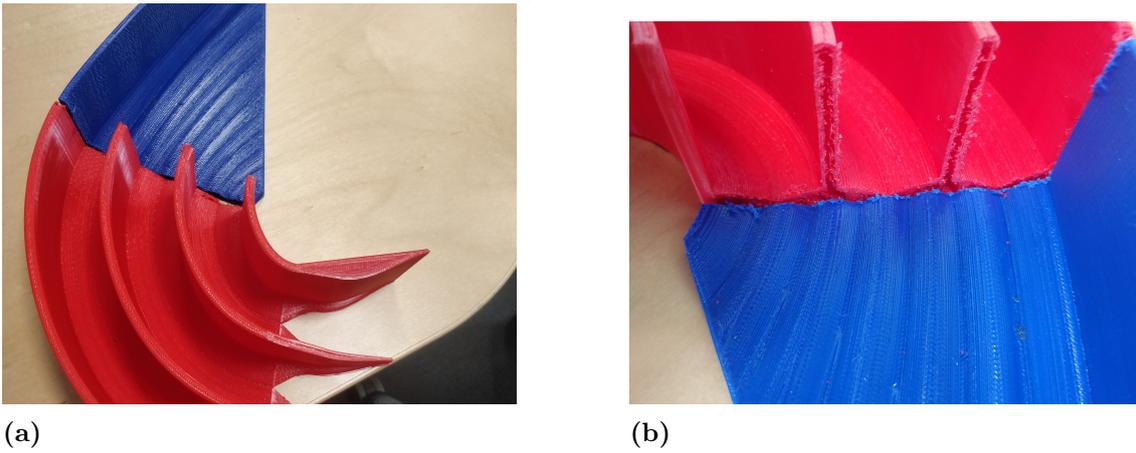
(a)

(b)

Figure 4.23: Modification leading to concept of merging prototypes

A new design was therefore created, named the 3-6 Transition (SEE figure 4.24, and added to the Kesselring's matrix above (see table 4.6). A downwards sloping channel was used to alleviate the issue of balls slowing down when passing in a tight row as seen the previous tests in Appendix E.3. The transition between the channels and shallow grooves were aligned in order to divide the ball flow in the same manner as the ridge modification in figure 4.22.
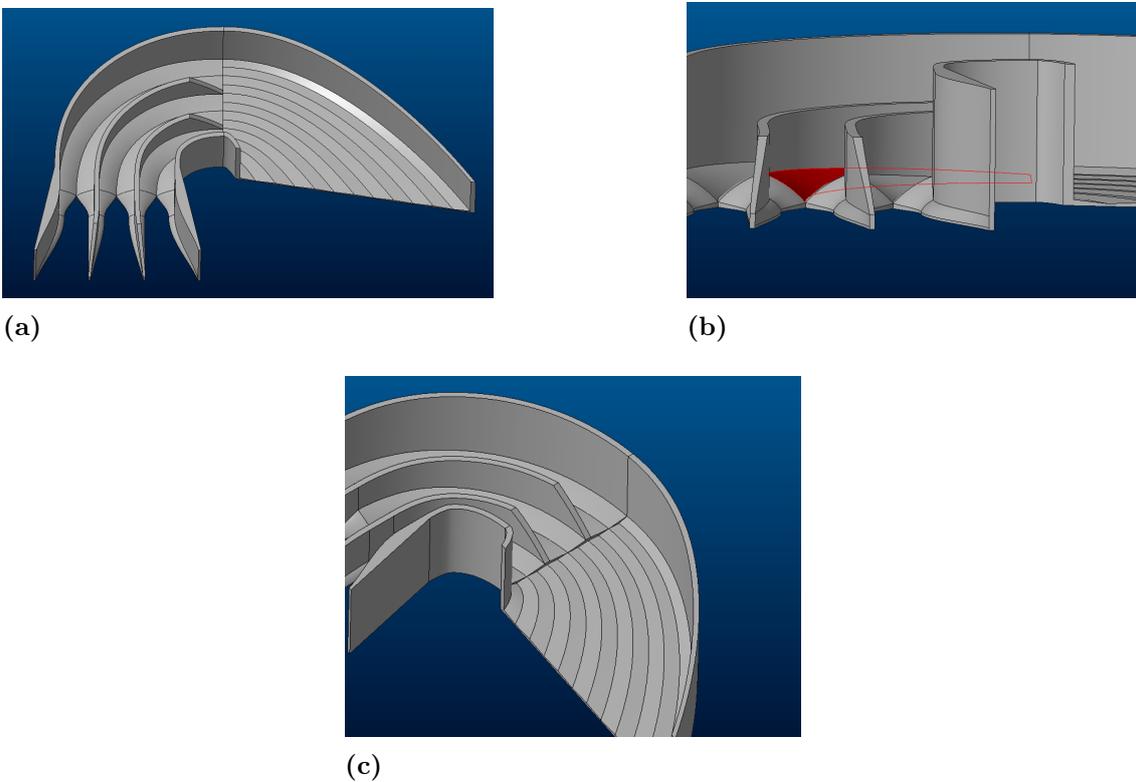

(a)

(b)

(c)

Figure 4.24: CAD geometry of the 3-6 Transition concept (a) with a downward sloping channel (b). Separated channels transition to shallow grooves (c).

Due to the low accuracy of the testing, it was decided that a conclusive selection of a final design could not be done before testing in the actual machine. Two concept alternatives were therefore selected for a final proposal. Based on the testing and evaluation in table 4.6, the 3-6 Transition concept was selected as a top contender for its overall performance. The 6 Groove was chosen as the second option, considered to be the most reliable solution with a relatively simple geometry.

4.3.4 Outlet Design

Based on the previous evaluation and scoring in 4.2.6, a solution proposal for the issue of outlet pile-ups was selected. This was the principle of dividing up the flow, similar to the Double Stack concept, which would avoid balls exiting from the outermost lapping grooves from blocking the innermost ones. Inspiration was taken from the basic principle of the Minimal track concept as the design space in the outlet could not accommodate three separate channels. The solution therefore focused on ensuring that the two innermost grooves were separated as these were most affected by pile-ups. This would be accomplished with a dividing wall running from the where the balls exit the machining area to the magazine (see figure 4.25).

The driving force on balls in the outlet was estimated to be significantly higher compared to the inlet since the balls exiting the machining would be driven by the lapping action. Therefore, potential minor pile-ups resulting from a narrowing of the flow was considered not to be as detrimental to the process. However, these conditions were significantly more difficult to replicate than the inlet. It was therefore decided that the solution had to be validated through testing in the machine.
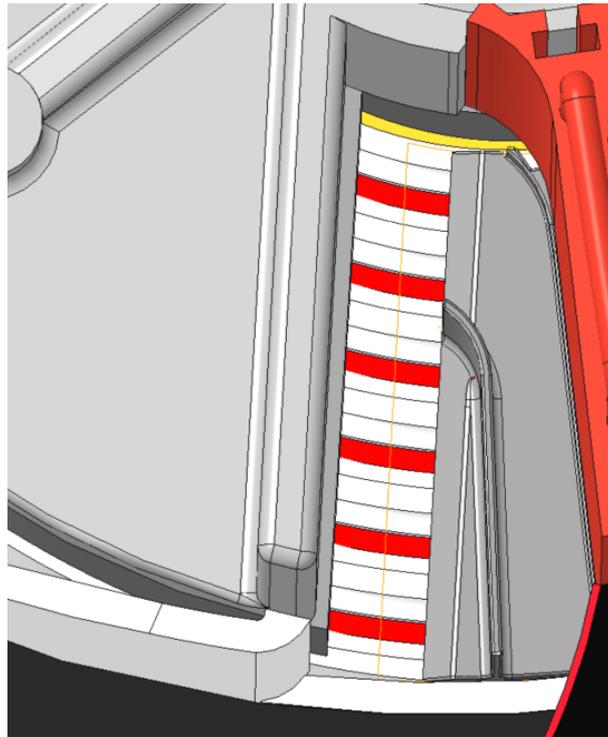
Figure 4.25: Dividing wall in the outlet

4.4 Final Design

After the refinement phase, the final chute design was created, intended for testing in the real machine. This involved selecting a means of attachment and material. Ideas for attachment methods had previously been proposed in the morphological matrix (see Appendix B.2). A meeting was held with personnel at the US site to discuss the different options. There was still some residual uncertainty regarding the chutes performance in the machine which had to be addressed through testing. Therefore, it was determined that the attachment method should be easily executed with minimal modification to the machine.

Bolting the chute in place was suggested as it would ensure a secure attachment, but was rejected as it would require drilling through the thick steel magazine wall. Integrating the chute with the divider component was considered as could be firmly fixed to the top plate with preexisting means. This would however enlarge the design significantly and require significantly more material to 3D-print.

The solution decided on was to spilt up the chute into two separate pieces, similarly to the modification in figure 4.23. The entry part would then be clamped to the inner magazine wall, while the end part as well as the outlet would be integrated into the stripper plate and screwed into the divider (see figure 4.26). This had the added benefit of leaving the magazine height adjustable and keeping the part sizes small enough for printing. The entry part of the chute could easily be swapped between the two design proposals while the outlet and end part could be firmly fixed

in place. The attachment area of the two different entry part versions both follow the curvature of the magazine wall. This combined with the tight fit of the turning section was intended to minimize the risk that the chute would be misaligned when clamping it to the machine.
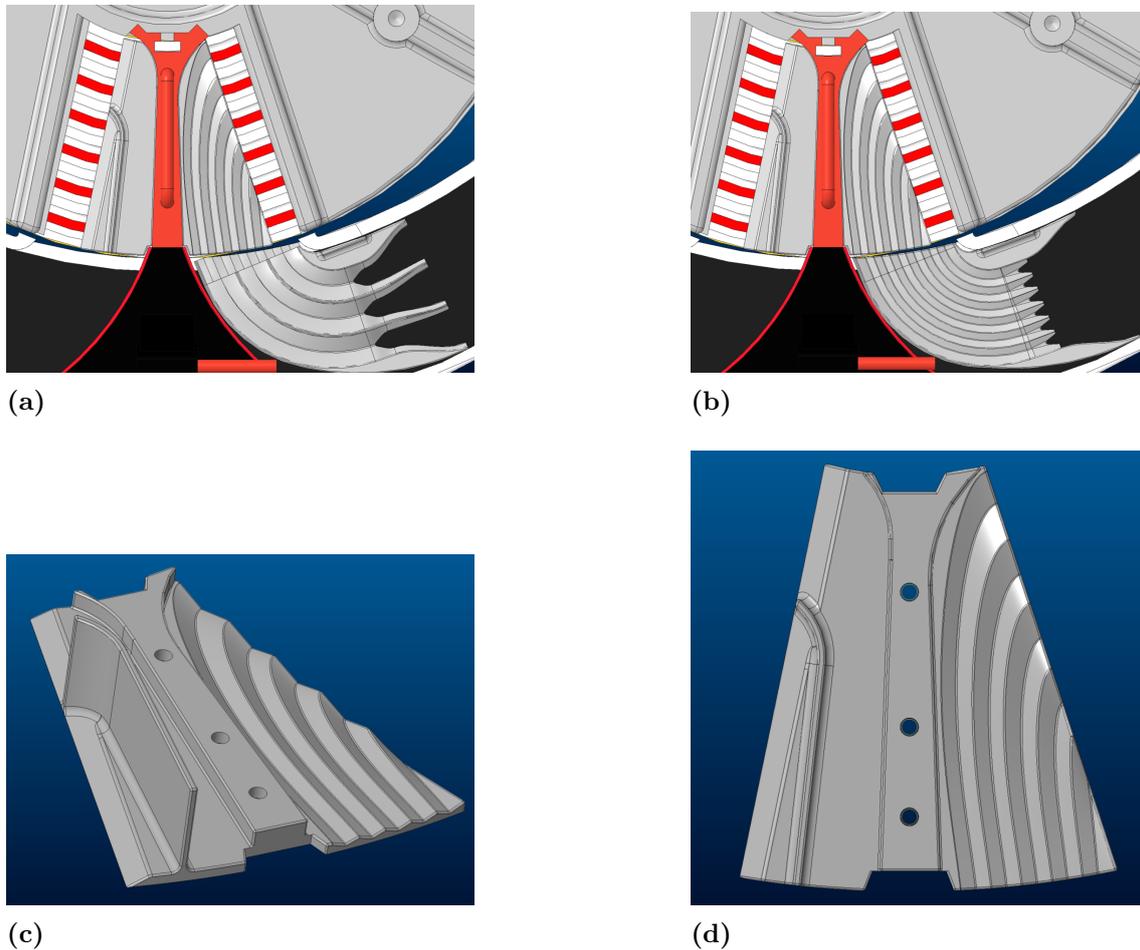

(a)

(b)

(c)

(d)

Figure 4.26: CAD geometry of the two final inlet proposals (a) and (b) to be clamped to the inner magazine wall. Outlet and end part (c) of the chute with holes (d) for attachment to the divider with screws.

The material selected for the chute was ASA polymer as this was suitable for high quality printing, had a high toughness, rigidity and chemical resistance. This was based on recommendations of SKF personnel and the experiences of prototypes previously printed in this material. The choice of a polymer material would enable quick in-field modification during testing in the US in case part did not fit as intended based on the CAD assembly of the machine.

To examine the structural integrity of the design and verify requirements related to durability, a quick finite element analysis using Creo Simulate was conducted. This included studying the thin wall of the outlet part. The reason for this was that the risk of blockages still remained, as the outlet remained untested, which could exert

pressure on the wall from balls still in machining area. A large deflection of the wall could in turn constrict the passage of balls exiting from the innermost grooves, thereby further worsening the outflow.

The analysis also included the end of the inlet as it was relatively thin and concerns were raised regarding its stiffness, as a downward deflection from the weight of the balls could lead to it coming into contact with the rotating lapping plate. Due to the difficulty in determining exact load conditions during machining, which could be both dynamic and irregular, the forces that were applied were set considerably higher than expected to ensure some margin of safety. The simulation results were therefore intended to be used to check for stress concentrations and provide a rough estimate of stress and displacement.

The mesh was generated using the Automatic Geometric Element Mesher and checked for potential singularities using the in-built diagnostic tool. Mesh refinements were made to areas of stress concentrations in the form of a maximum size limit of 5 mm to study the influence on the result. For boundary conditions, the holes for attaching the component were constrained in all degrees of freedom. A force of 50N was applied along the positive x-direction to the dividing wall at the outlet. A force of 10N in the negative z-direction was applied on the inlet as shown in figure (see figure 4.27). The magnitude of these forces not directly related to the machining conditions but significantly higher which meant the results would not reflect the real stresses and deflection present experienced. The material used in the analysis was ABS (Acrylonitrile butadiene styrene) polymer, available in the software's material library, as it has very similar structural properties to ASA. Since the design would be 3D-printed, the material was expected to have some anisotropic properties, specifically regarding the yield strength in the printing direction, which meant that the resulting analysis could differ from the real variant. However, as the loads applied were greater than estimated in real machining conditions, this was thought to provide adequate margin of safety for this.
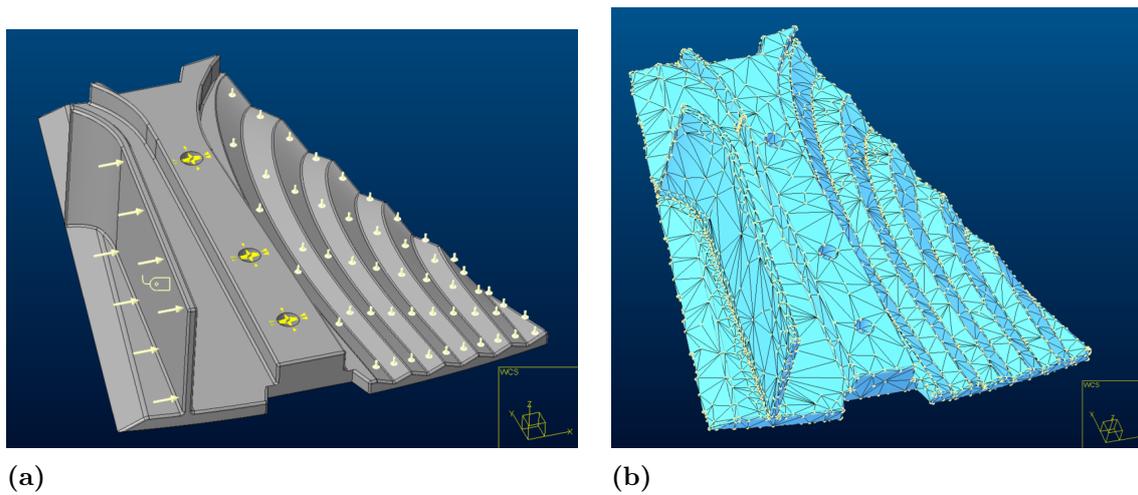
(a)

(b)

Figure 4.27: Boundary conditions applied which constraints marked in yellow arrows and loads in white (a). Generated mesh is shown in (b).

As shown in figure 4.28 significant stress concentrations (in kPa) were seen in the corner where the wall connects to the rest of the part. It was noted that even with the exaggerated load conditions applied, the von Mises stress of approximately 5800 kPa, remained well below the material's yield stress of 41000 kPa . The total displacement was also examined to get a rough estimation of the rigidity of the part. This did not exceed 1 mm either at the inlet or outlet area, which was considered to be adequate to avoid the part coming into contact with the rotating lapping wheel underneath.
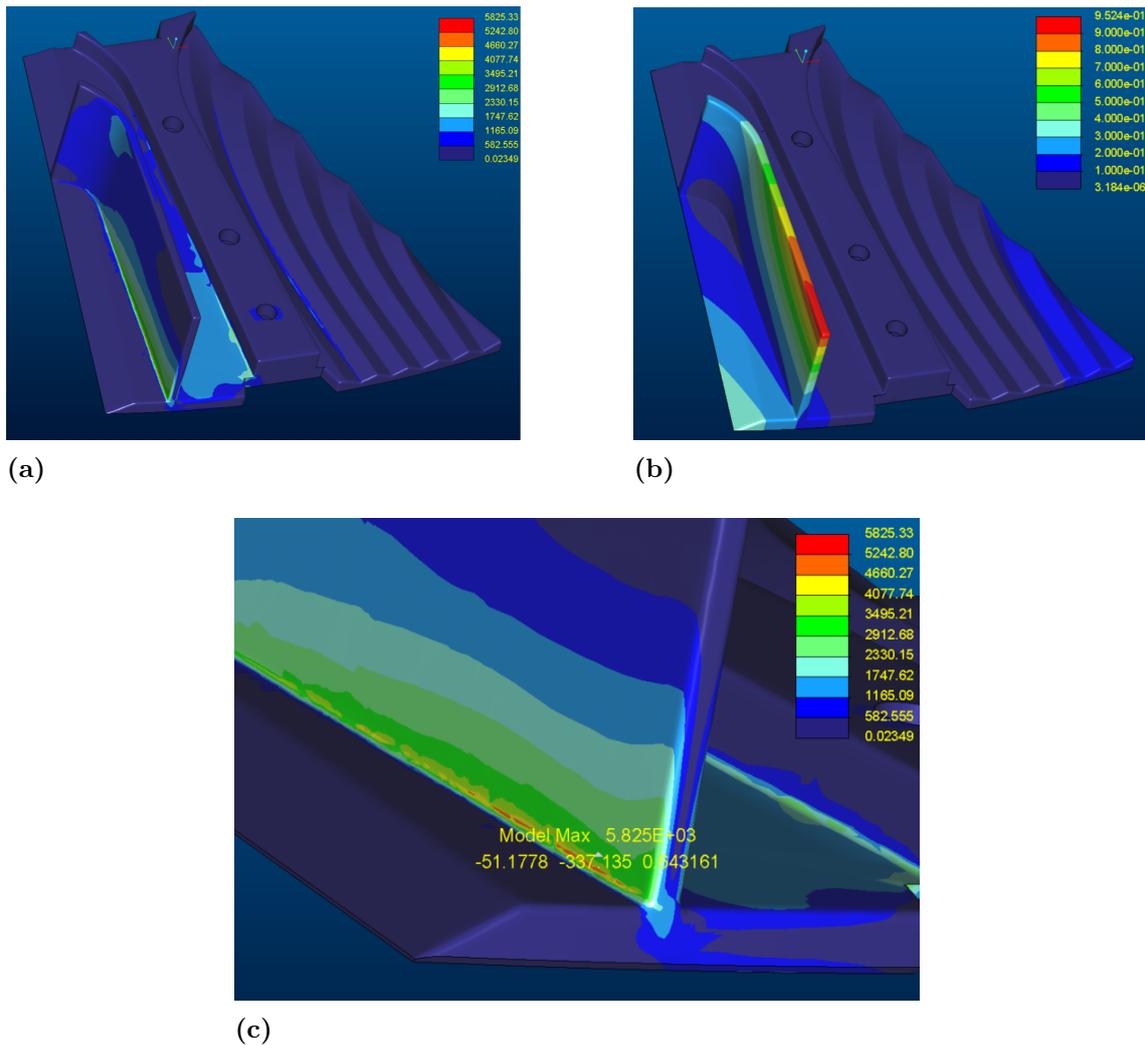
(a)

(b)

(c)

Figure 4.28: Results of von Mises stress in kPa (a) and displacement magnitude in mm is shown in (b). Close-up on stress concentration shown in (c).

The transition between the wall and the rest of the part was still thickened to lessen the stress concentration in this area and guard against the risk of layer separation in case of pressure from blockages of balls. The analysis was then redone with the same boundary conditions. As can be seen in figure 4.29, while the stress in this area remained, it was less concentrated and the maximum von Mises stress decreased from approximately 5600 kPa to 3900 kPa.
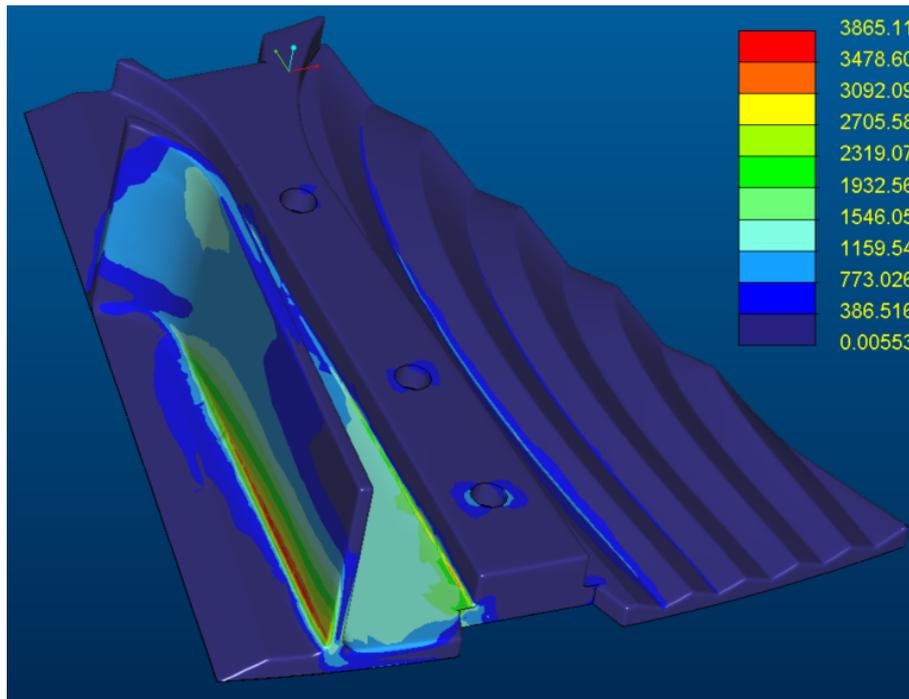
Figure 4.29: von Mises stress in kPa after adjustment on transition

To provide a clear overview of the remaining development work, a column was added to the final requirement specification which indicated what requirements were fulfilled, partially fulfilled and not fulfilled (see appended table D). As can be seen, the status of requirement no.16 related the functioning of the outlet was designated as not fulfilled as it remains to be checked through testing in the machine. This also applied to the requirement no.21 regarding the wear on the part. Requirements no.2, 6, 7 and 11, pertaining to the function of the inlet chute were designated as partially fulfilled as the accuracy of the test setup used was considered insufficient to fully verify the function. The proposed final designs were therefore 3D-printed in ASA to be sent to the production site in the United States for further testing in the complete machine. Proposals for future decisions on finalizing the design with regards to manufacturing and materials were proposed with a rough selection process made using the ANSYS Granta Selector software (see Appendix F.1). However, these decision would also be dependant on the results from further testing.

5

Discussion

This chapter includes reflection on the process and outcome of the development project. Recommendations for future studies and further development of the feeding chute is also included.

5.1 Reflection

This chapter provides a detailed reflection on a thesis project centered around designing and developing a feeding chute for the lapping machine. The initial objective of the project was to optimize the inlet taper of the top plate in addition to addressing the feeding problem. However, due to time limitations the team made the decision to prioritize resolving the feeding issue as it was deemed more critical. This along with the shift from simulation to physical testing, constituted major changes to the project plan. This could have been better prepared for during the planning phase by for example performing a risk analysis on the steps of the project and preparing alternative approaches. It is worth mentioning that involving the BEAST team in consultations during the project's initial phase would have been beneficial as it could have provided the team with valuable insights into potential difficulties and assisted in strategic project planning.

The study that was conducted to understand the project's significance and identify needs and problem relied on observations of the process and consultations with experts. However, a firmer basis for this could have been established through the collection of quantitative data on current lapping process. This could then have been used as a baseline for further testing of concepts. Key questions were formulated to address the problem and establish the scope of the thesis. Various systematic and creative methods were used, such as external idea exploration and brainstorming sessions, to generate a wide range of solutions. The team faced challenges in creating the initial morphological matrix, as the project had a wide scope that included the possibility of re-designing the machine. To overcome this, a function-means tree was found to be a better method at the early stage.

The initial scope of the concept generation was kept wide with the intention of covering as much of the solution space as possible early, to later converge on a specific solution type. However, to evaluate and screen the varying solution types proved time-consuming and thus delayed the detailed design, testing and refinement stages. Further development of the chute designs could have been achieved with a more

focused and constrained initial scope as more test iterations could have been accommodated.

For concept evaluation, Pugh's matrix was employed, which provided a comprehensive overview of the concepts' performance and identified areas for improvement. It was easier to navigate and compare concepts compared to Kesselring's matrix, making it effective for early-stage evaluation. The Pugh's matrix could have been further iterated to reach a convergence in the selection. However, the Kesselring's matrix was considered more suitable for scoring concepts with weights and taking the importance of criteria into account.

During the testing phase, the team faced challenges due to limited access to the actual lapping machine. To overcome this limitation, a simulated setup was created for testing purposes. However, it is important to acknowledge that simulated testing inherently had limitations in terms of obtaining accurate results. As a result, it was deemed necessary to conduct testing on the actual machine to evaluate the performance of the two final solution proposals before making a conclusive decision. Nevertheless, the tests conducted on the simulated setup contributed to the identification of issues with the early designs and allowed for some refinement. It is worth noting that the outlet chute concept could not be tested in the same setup and, therefore, could not be iteratively refined like the inlet. Consequently, future research should prioritize validating the concepts by conducting tests on the actual machine, including evaluating the outlet chute.

During the testing of the concepts on the simulated setup, certain parameters were not able to be replicated, which are crucial for assessing the feasibility of the concepts. For instance, in the actual machine setup, there is a height difference between the magazine and the lapping plate which is used in the final design to aid in feeding process. Additionally, the presence of residual lapping fluid as seen in the images in chapter 4.1 would reduce the friction within the ball flow, resulting in smoother movement compared to the simulated testing setup. Another important difference is the force exerted by the larger quantity of balls in magazine of the actual machine, which provides additional propulsion for the balls compared to what could be achieved during the testing. Despite these parameters not being accounted for during the simulated testing, the concepts still indicated potential in enhancing the feeding of balls.

The project used an agile development process of short prototype and test cycles, which proved useful in the refinement phase to handle the uncertainty regarding the chute performance. The rapid prototyping, enabled by the availability of 3D printers afforded great flexibility in design changes which proved essential when using this agile approach.

Overall, the team faced challenges in various aspects of the project, such as limitations of simulated testing. However, the team were able to overcome these challenges by utilizing alternative methods and maximizing the available resources. The

methodology and outcomes of the project contribute valuable insights into the design and development of a feeding chute for the lapping machine. It also highlights the importance of future research and testing in a realistic manufacturing environment to validate the concepts.

5.2 Materials and Manufacturing Proposals

As the chute would experience both contact with the hard silicon nitride balls and abrasive particles from the lapping process, it was expected that the chute printed in ASA polymer, would experience significant wear in the machine. One way to solve this, should the material prove sufficient in all other aspects such as strength and stiffness, would be a abrasion resistant coating in epoxy for example. The other way to solve the problem of wear would be to a metallic material which would also have the added benefit of less friction between balls and chute. Two materials were proposed based on a coarse selection in Granta Selector using price per mass and abrasion-resistance as indices for a cost effective choice. The material index for abrasion-resistance $\frac{E^2}{H^3}$ was provided in the software, with E being Young's modulus and H the Vickers hardness. In the plot in Appendix F.1 the cheaper and resistant materials are found towards the lower left corner.

As indicated by the plot, cast iron would be a cheap and durable option with the added benefit of being already present since the lapping plates are milled from the same material. The chute parts could then also be milled from the material available. This would however require some design changes such as having the dividing walls of the chute as separate pieces to avoid excessive material waste when machining it from a solid block.

Another would be low alloy steel which, while being slightly more expensive, would enable other manufacturing methods. Due to the better formability, the chute could be produced using sheet metal forming. This would require some design changes for a uniform thickness of the chute's cross-section but would minimize material waste in production compared to milling.

It is important to note that these recommendations were derived from a coarse analysis performed using Granta Selector. When finalizing the material selection, practical considerations must be taken into account. These aspects include evaluating the feasibility of manufacturing the chosen materials into the desired shape, size and quantity for the feeding chute. Additionally, it is essential to consider the specific requirements of the feeding chute, encompassing factors such as the operating environment, loads and stresses, and temperature range of lapping machine. By incorporating both the recommendations obtained from Granta Selector and practical considerations related to manufacturing feasibility and specific requirements, a comprehensive and well-informed material selection for the feeding chute can be achieved. This approach ensures that the chosen materials not only align with the theoretical analysis but also address real-world considerations, resulting in an opti-

mized and effective feeding chute design.

5.3   Future Recommendations

This section presents recommendations for the future development of the feeding chute concept for the silicon nitride lapping machine, as well as the integration of other promising concepts through machine redesign. While initially designed for silicon nitride balls with a 25.4 mm diameter, the use of this chute could be extended to different ball sizes, machine models and materials as needed which only minor resizing.

Through tests conducted on a simulated setup, the feeding chute concept has exhibited promising results in enhancing the efficiency of ball supply and distribution within the machine area. Therefore, it is strongly advised to proceed with the further development of this concept by subjecting it to testing on the existing machine. This approach would yield quantitative data, including changes in machining cycle time, ball surface quality, and chute wear rate, enabling a comprehensive evaluation of the impact on the lapping process in terms of time and cost. Specific areas of interest that should be studied during these tests are:

- How are the balls distributed to the lapping grooves at the inlet before and after application of the chute?

- At what rotation speed of the magazine are pile-ups beginning to occur, before and after application of the chute?

- Are there any balls stuck at the outlet area after application of the chute?

Due to the uncertainty regarding the functioning of the outlet design, a backup solution was proposed. This involved widening the gap of the top plate. This would leave enough space for balls from all six lapping grooves to exit in a row between the divider and top plate (see figure 5.1). It was however deemed appropriate to first test the non-intrusive solution of the dividing wall as the other option would entail a slight decrease of the machining area. It would also require changes to the inner wall of the magazine a shown in figure 5.2.
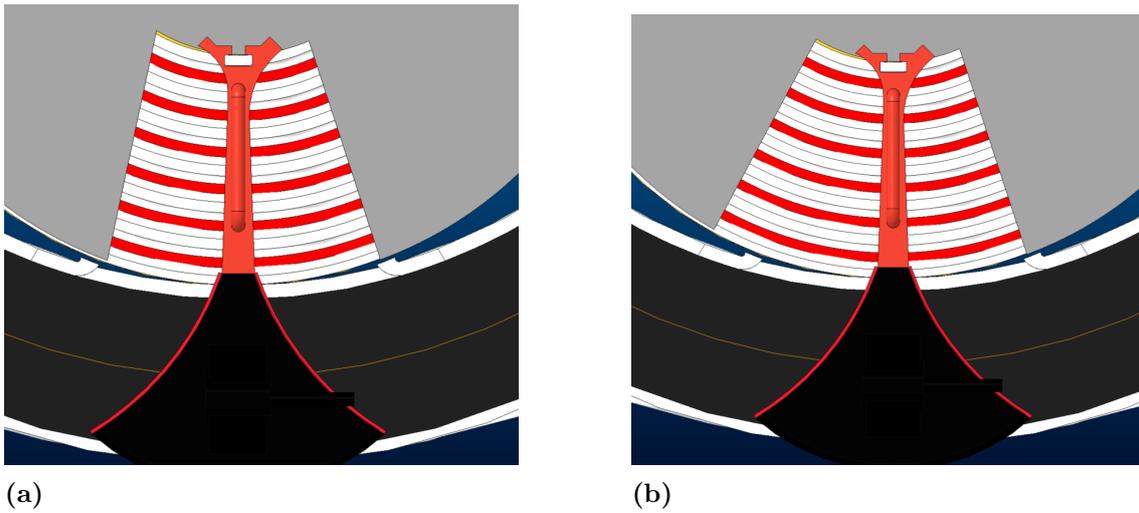
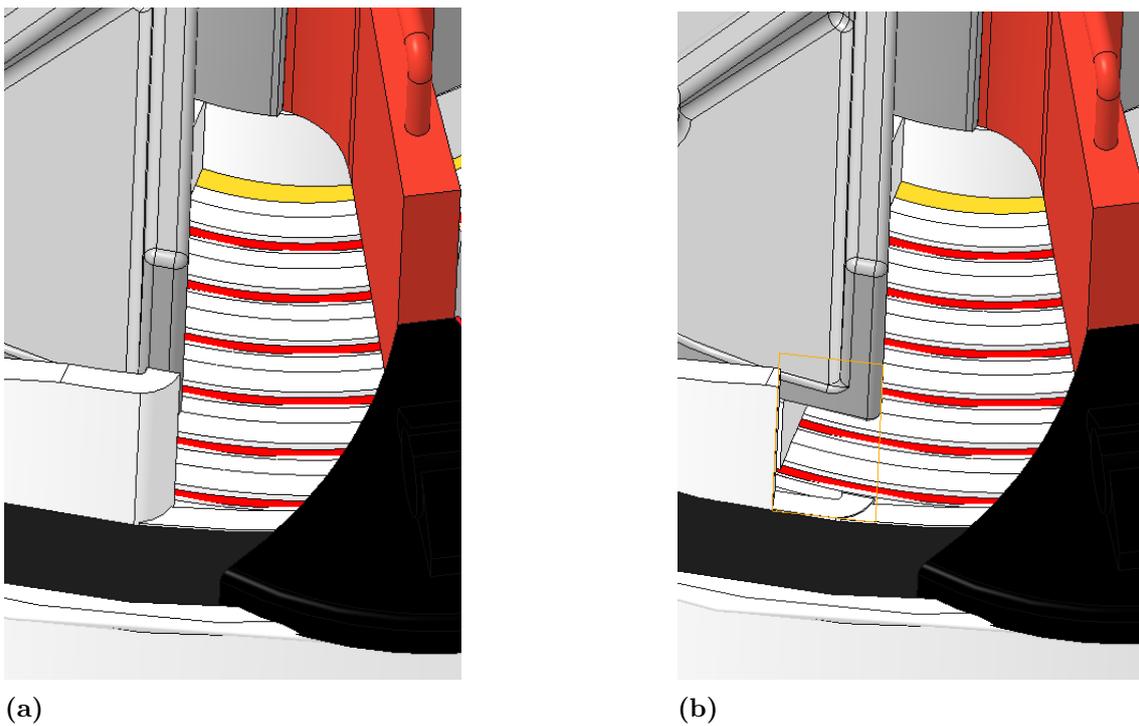**Figure 5.1:** Expanding the outlet gap of the top plate.

Figure 5.2: Modification to the magazine wall in the form of a cut.

While several other promising concepts were developed during the thesis, their implementation is currently unfeasible within the existing machine design. Thus, it is recommended to to study alternative lapping configurations, primarily with angled lapping discs. Examples of this setup can be seen in the expired patent JPH0557602A by Sato [37]. From a pure feeding perspective, this could simplify the issue considerably as the direction could be perpendicular to the lapping grooves, thereby removing the need for the bending and narrowing flow into the gap of the

top plate. In addition, the height difference between the inlet and outlet would aid the circulation to and from the magazine. However, the impact an angled setup would have on the abrasive process would have to be studied first to ensure that the desired machining performance can be achieved.

Considering that SKF develops the BEAST software in-house, it would be highly advantageous to expand the software to enable the simulation of flows of balls. A related feature currently exists, used for fluid simulations with the soft particle method [38, p. 524]. This is however currently limited to small diameter spherical particles for modelling dynamic lubrication flow. Expanding this function to model the macroscopic behaviour of large spheres could expedite the development of components for ball processing. This could involve both fine-tuning of design details, parameter optimization as well as assessment of the feasibility and performance of completely new designs. Another alternative would be using software such as ANSYS LS-DYNA to model the flow using discrete element method as done by Kabir et al. [39] . Considerable work would be required to validate this type of model but if successful, could accelerate the innovation process and ensure SKF remains at the forefront of technological advancements within the industry.

6
Conclusion

The objective of this master thesis was to improve the productivity of lapping larger silicon nitride balls, by addressing two key issues: pile-ups in the flow of balls and uneven distribution between the lapping plate's grooves. To achieve this, a feeding chute was designed and developed to handle silicon nitride balls and ensure their even distribution.

Incorporating sustainability into the design process aimed to minimize material waste and energy usage. The efficient distribution of balls across all grooves of the lapping plate helps reduce the need for maintenance and additional processing, resulting in resource savings and a reduced environmental impact. By enhancing the machine's efficiency, overall energy consumption during the manufacturing process can be reduced, contributing to a more sustainable production approach. Moreover, this project has economical benefits that extend beyond technical considerations in the from of shorter manufacturing lead times and increased product availability. This benefits consumers who rely on the machine's products, as market demands can be met more effectively and timely. Additionally, the cost savings achieved through enhanced operational efficiency can contribute to affordability and accessibility, encouraging the wider adoption of low friction and long lasting bearings.

In conclusion, the successful design and development of a feeding chute capable of handling silicon nitride balls and ensuring their even distribution would result in significant improvements in the efficiency and productivity of the lapping process. This advancement aligns with sustainability objectives by reducing waste and optimizing energy consumption. Moreover, the project's ethical benefits are reflected in improved product availability, affordability, and accessibility. By considering sustainability and ethical aspects, this project not only brings technical advancements but also contributes to a more sustainable and socially responsible manufacturing process. Before fully implementing the feeding chute concept and incorporating other promising concepts into the lapping machine, it is recommended to subject the chute concept to testing on the existing machine and carefully plan the re-design process to integrate new components while maintaining desired performance, considering feasibility, cost, and implementation time. Additionally, a more detailed material selection process needs to be conducted to ensure the compatibility of the chosen materials with the intended application regarding wear, cost, manufacturing method and sustainability.

Bibliography

[1] F. He, G. Xie, and J. Luo, "Electrical bearing failures in electric vehicles," *Friction*, vol. 8, pp. 4–28, 2020. Url: `https://doi.org/10.1007/s40544-019-0356-5`.

[2] 360 Market Updates, "Global and united states silicon nitride ceramic bearing balls market." `https://www.360marketupdates.com/global-and-united-states-silicon-nitride-ceramic-bearing-balls-market-20990808`, 2021.

[3] J. Kang and M. Hadfield, "A study on the lapping of ceramic balls," *WIT Transactions on Engineering Sciences*, vol. 25, 1970.

[4] R.-T. Lee, Y.-C. Hwang, and Y.-C. Chiou, "Lapping of ultra-precision ball surfaces. part i. concentric v-groove lapping system," *International Journal of Machine Tools and Manufacture*, vol. 46, no. 10, pp. 1146–1156, 2006. Url: `https://doi.org/10.1016/j.ijmachtools.2005.08.003`.

[5] B. Zhang, T. Uematsu, and A. Nakajima, "High efficiency and precision grinding of si3n4 ceramic balls aided by magnetic fluid support using diamond wheels," *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing*, vol. 41, no. 3, pp. 499–505, 1998. Url: `https://doi.org/10.1299/jsmec.41.499`.

[6] N. Umehara and K. Kato, "Magnetic fluid grinding of advanced ceramic balls," *Wear*, vol. 200, no. 1-2, pp. 148–153, 1996. Url: `https://doi.org/10.1016/S0043-1648(96)07297-3`.

[7] J. Kang and M. Hadfield, "A novel eccentric lapping machine for finishing advanced ceramic balls," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 215, no. 6, pp. 781–795, 2001. Url: `https://doi.org/10.1243/0954405011518728`.

[8] SKF, "Decarbonizing in progress update 2022." `https://investors.skf.com/sites/default/files/library/Decarbonizing%20in%20progress%20update%202022.pdf`. Accessed: June 1, 2023.

[9] S. Thomke and D. Reinertsen, "Agile product development: Managing development flexibility in uncertain environments," *California management review*, vol. 41, no. 1, pp. 8–30, 1998. Url: `https://doi.org/10.2307/41165973`.

[10] L. Wang, R. Snidle, and L. Gu, "Rolling contact silicon nitride bearing technology: a review of recent research," *Wear*, vol. 246, no. 1, pp. 159–173, 2000.

[11] SKF, "Hybrid ceramic ball bearings." `https://www.skf.com/us/products/mrc/hybrid-ceramic-ball-bearings`, 2023. Accessed: 2023-04-17.

[12] SKF, "Xl hybrid bearings – protect your turbine from electric currents." `https://www.skf.com/in/industries/wind-energy/drivetrain/generator/skf-xl-hybrid-bearings`, 2023. Accessed: 2023-04-17.

[13] E. Jisheng, T. Stolarski, and D. Gawne, "Tribochemically assisted wear of silicon nitride ball," *Journal of the European Ceramic Society*, vol. 16, no. 1, pp. 25–34, 1996. Url: `https://doi.org/10.1016/0955-2219(95)00109-3`.

[14] J. Kang and M. Hadfield, "Parameter optimization by taguchi methods for finishing advanced ceramic balls using a novel eccentric lapping machine," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 215, no. 1, pp. 69–78, 2001. Url: `https://doi.org/10.1243/0954405011515145`.

[15] T. A. Otitoju, P. U. Okoye, G. Chen, Y. Li, M. O. Okoye, and S. Li, "Advanced ceramic components: Materials, fabrication, and applications," *Journal of industrial and engineering chemistry*, vol. 85, pp. 34–65, 2020. Url: `https://doi.org/10.1016/j.jiec.2020.02.002`.

[16] B. Zhang, J. Wang, F. Yang, and Z. Zhu, "The effect of machine stiffness on grinding of silicon nitride," *International Journal of Machine Tools and Manufacture*, vol. 39, no. 8, pp. 1263–1283, 1999. Url: `https://doi.org/10.1016/S0890-6955(98)00083-2`.

[17] J. Kang and M. Hadfield, "Examination of the material removal mechanisms during the lapping process of advanced ceramic rolling elements," *Wear*, vol. 258, no. 1-4, pp. 2–12, 2005. Url: `https://doi.org/10.1016/j.wear.2004.09.017`.

[18] SpezialMaschinenfabrik Schonungen GmbH, "Ball processing machines." `https://www.sms-schonungen.de/kugelbearbeitungsmaschinen_en.html`.

[19] S. Si, "Ball grinding machine," (2011, November 17). Patent WO2011140693A1 [Online]. Url: `https://worldwide.espacenet.com/patent/search?q=pn%3DWO2011140693A1`.

[20] S. Messerschmidt, "Apparatus for lapping and grinding balls," (1967 October 24). Patent US3348338A [Online]. Url: `https://worldwide.espacenet.com/patent/search?q=pn%3DUS3348338A`.

[21] K. Kunio and Y. Hajime, "Polishing device for spherical body," (2001 September 25). Patent JP2001260008A [Online]. Url: `https://worldwide.espacenet.com/patent/search?q=pn%3DJP2001260008A`.

[22] T. Okura, "Spherical body supply chute device," (2000, November 21). Patent JP2000318814A [Online]. Url: `https://worldwide.espacenet.com/patent/search?q=pn%3DJP2000318814A`.

[23] T. Suzuki, K. Tonooka, K. Kawashima, C. Sato, M. Shinomoto, and H. Nojima, "Sphere polisher," (1999, July 13). Patent US5921851A [Online]. Url: `https://worldwide.espacenet.com/patent/search?q=pn%3DUS5921851A`.

[24] A. Pinders, "Improvements in ball grinding machines," (1911, June 21). Patent GB191100408A [Online]. Url: `https://worldwide.espacenet.com/patent/search?q=pn%3DGB191100408A`.

[25] G. F. Matteson, "Feeding mechanism," (1933, February 21). Patent US1898979A [Online]. Url: `https://worldwide.espacenet.com/patent/search?q=pn%3DUS1898979A`.

[26] K. Ulrich, S. Eppinger, and M. Yang, *Product Design and Development (7th ed.)*. New York : McGraw-Hill Education, 2020.

[27] E. Hull, K. Jackson, and J. Dick, *Requirements engineering (4th ed.)*. Cham: Springer, 2017.

[28] Y. Kitamura, R. Mizoguchi, *et al.*, "Organizing knowledge about functional decomposition," in *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm*, pp. 55–56, 2003.

[29] J. Malmqvist, "Improved function-means trees by inclusion of design history information," *Journal of Engeering Design*, vol. 8, no. 2, pp. 107–117, 1997. Url: `https://doi.org/10.1080/09544829708907955`.

[30] G. Pahl, W. Beitz, J. Feldhusen, and K. Grote, *Engineering Design: A systematic Approach (3rd ed.)*. Springer London, 2007.

[31] B. Camburn, V. Viswanathan, J. Linsey, D. Anderson, D. Jensen, R. Crawford, K. Otto, and K. Wood, "Design prototyping methods: state of the art in strategies, techniques, and guidelines," *Design Science*, vol. 3, p. e13, 2017. Url: `https://doi.org/10.1017/dsj.2017.10`.

[32] D. D. Frey, P. M. Herder, Y. Wijnia, E. Subrahmanian, K. Katsikopoulos, and D. P. Clausing, "The pugh controlled convergence method: model-based evaluation and implications for design theory," *Research in Engineering Design*, vol. 20, pp. 41–58, 2009. Url: `https://doi.org/10.1007/s00163-008-0056-z`.

[33] D. Raudberget, "The Decision Process in Set-Based Concurrent Engineering - An Industrial Case Study," *DS 60: Proceedings of DESIGN 2019, the International Design Conference, Dubrovnik, Croatia*, pp. 937–946, 2010.

[34] SKF, "Dynamic Simulation – Building Knowledge in Product Development," 2013. Url: `https://evolution.skf.com/dynamic-simulation-building-knowledge-in-product-development/`.

[35] D. Raudberget and G. Gustafsson, "From DDB to TDB - A New Approach to Design-Build Projects," *3:e Utvecklingskonferensen för Sveriges ingenjörsutbildningar*, pp. 119–112, 2012. Url: `https://www.diva-portal.org/smash/record.jsf?pid=diva2:548348`.

[36] ANSYS Inc, "Granta selector." Version 2021 R1,[Software], Url: `https://www.ansys.com/products/materials/granta-selector`.

[37] C. Sato, "Ball lapping machine," (1993 March 09). Patent JPH0557602A [Online]. Url: `https://worldwide.espacenet.com/patent/search?q=pn%3DJPH0557602A`.

[38] C. Sandström, "Beast, bearing simulation tool, 14.9 user's manual," 2022. Unpublished.

[39] M. Kabir, M. R. Lovell, and C. F. Higgs III, "Utilizing the explicit finite element method for studying granular flows," *Tribology Letters*, vol. 29, no. 2, pp. 85–94, 2008. Url: `https://doi.org/10.1007/s11249-007-9285-y`.
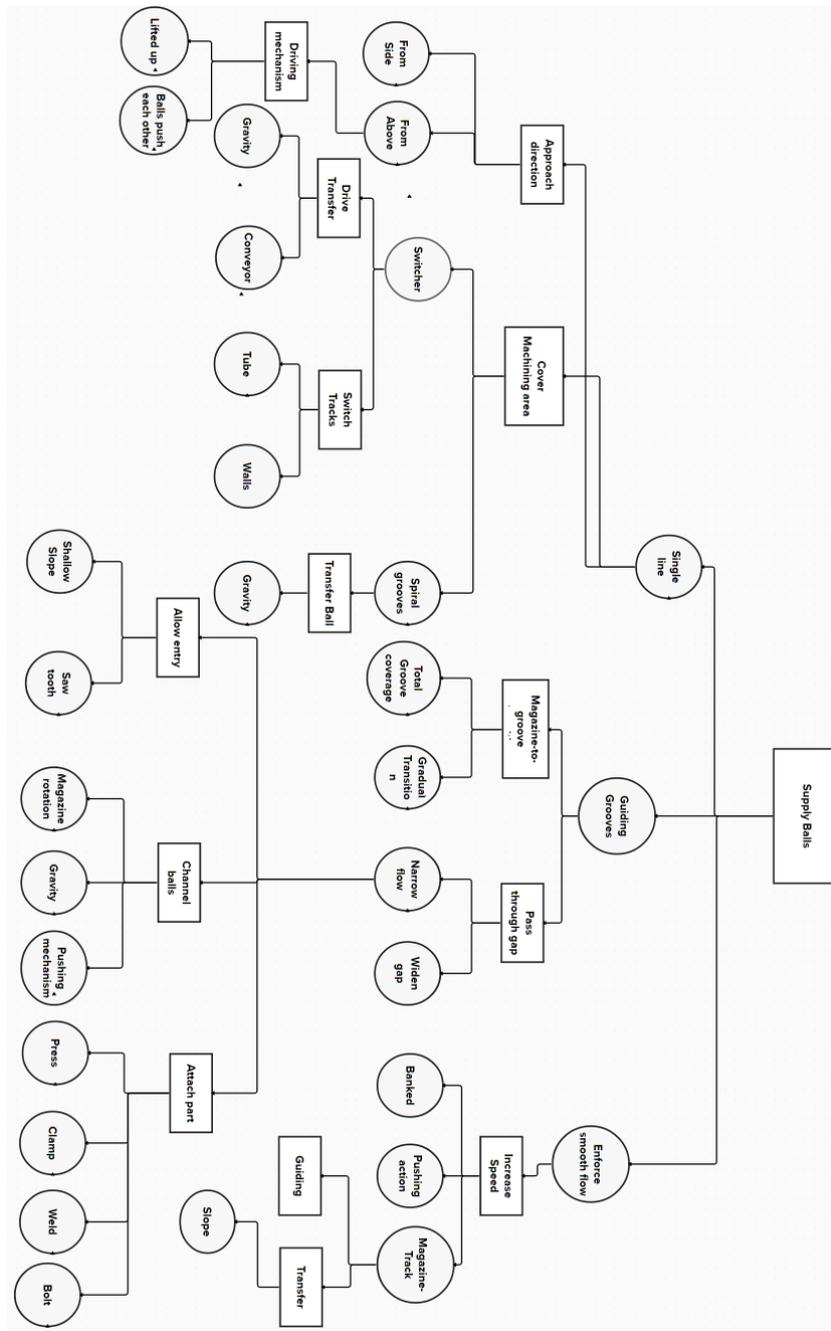
A

Function-Means Tree

Figure A.1: Function-means tree. Square shapes represents functions and circles means for solutions.

B
Morphological Matrices

Table B.1: Morphological matrix from first idea generation

Morphological Matrix- Feeder Chute	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6
Distribution	Switch between grooves	Slope	Divide ball flow	Variable groove	Grooves on magazine	Stir up balls
Avoid pile-up	Widen gap	Increase speed	Separate balls	Brute force balls		
Feeding direction	Above gap	Level to gap				
Avoid Collisions	Separate balls	Direct balls away				
Driving mechanism	Rotation from magazine	Gravity	Flushing	Conveyor	Mechanical pushing force	

Table B.2: 2nd morphological matrix from the later idea generation and prototyping stage. Crossed out sub-solution indicate features deemed unsuitable

| Morphological Matrix- Feeder Chute	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Allow entry	Shallow slope	Saw tooth	Cutout		
Funnel to channel	From rotation of magazine	Fall into place			
Channel	Separated/wall	Grooves	Transition walls to grooves	~~Double stack~~	
Nr of channels	~~2~~	3	6		
Attachment	Clamp	Bolt	Integrate into divider	~~Welding~~	Split up + Integrated into divider
Exit	~~Flat~~	Ridge	Groove		
Material	Polymer	Metal			

C

Concepts Mock-ups
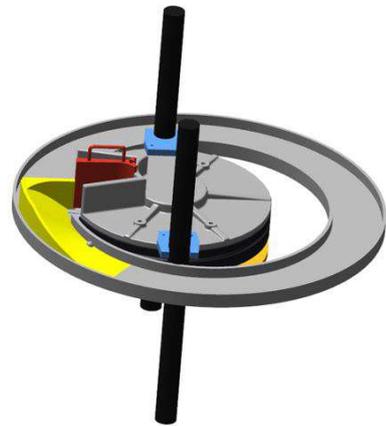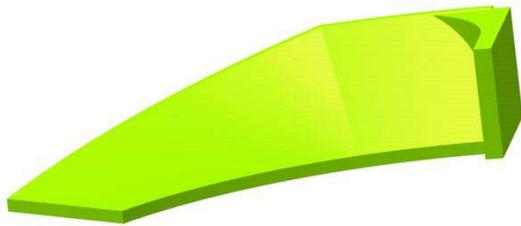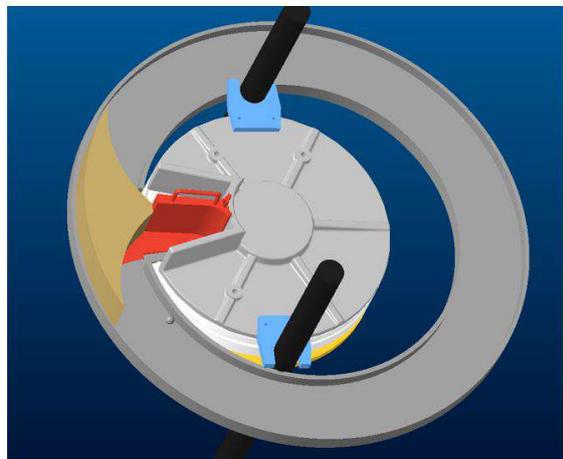

Figure C.1: Banked Concept
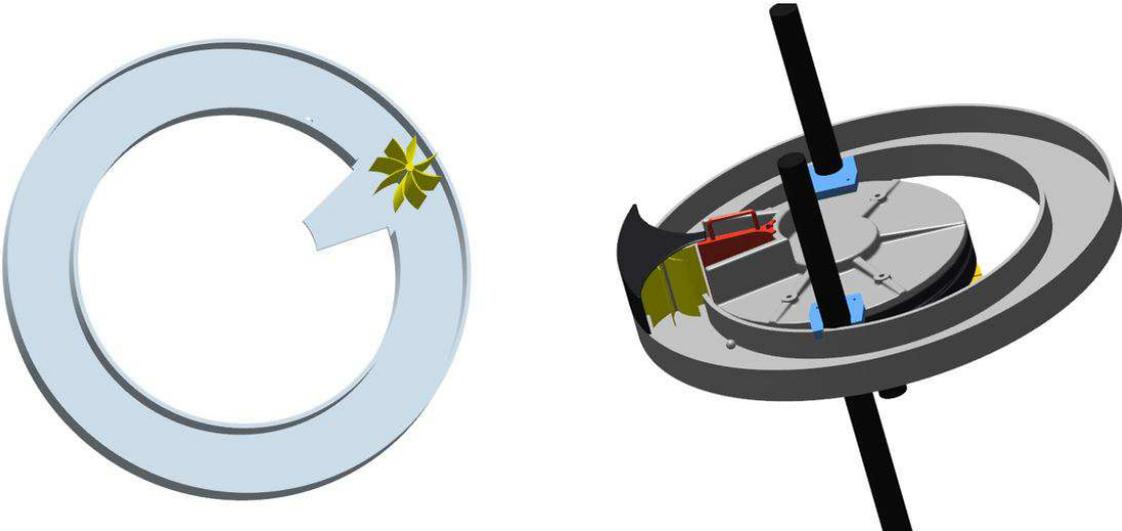

Figure C.2: Mini-Track

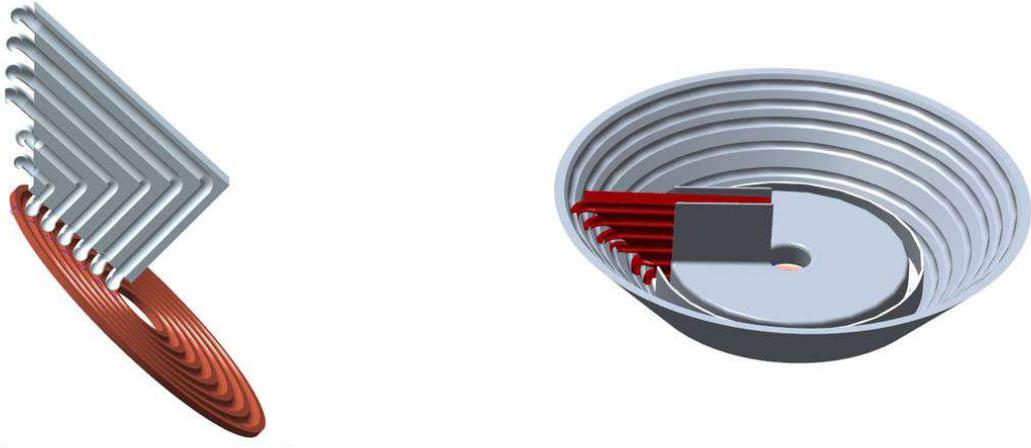**Figure C.3:** Paddle Wheel Concept

Figure C.4: Magazine-Track Concept

D

Full Requirement Specification

| Number	Category	Requirement	Value	Unit	Evaluation	Description	Justification	Fulfillment
1		Must accomodate balls with varying diameter	28 to 25.4	mm	CAD/Testing		Handle both blanks and machined	Fulfilled
2	Inlet Entry	Must allow balls to enter from magazine without slowing or backflow			Testing		high entry edge leads to pile-up without additional force	Fulfilled verified, testing in machine required
3		Must not obstruct the rotation of magazine			CAD		Magazine rotates underneath feeder	Fulfilled
4		Minimize length of entry zone			CAD		Long entry slows flow without additional force to drive balls	Fulfilled
5		Must fit inbetween magazine walls		mm	CAD		Machine constraint	Fulfilled
6	Inlet Channel	Must be able to transition flow from magazine width to gap width		mm	CAD/Testing		Need of regular flow	Fulfilled verified, testing in machine required
7		Minimize force required to channel balls			Testing		Enough to utilize magazine rotation	Fulfilled verified, testing in machine required
8		Minimize contact area between ball and channel			CAD	Convex or v-groove	Easier to roll along	Fulfilled
9	Inlet U-turn	Must fit within entry gap of top plate		mm	CAD		Avoid redesigns	Fulfilled
10		Minimize interference with surrounding components			CAD		Easier implementation	Fulfilled
11	Inlet Exit	Must transition flow into 6 grooves			CAD		Distribution need	Fulfilled verified, testing in machine required
12		Must not obstruct rotation of bottom plate			CAD/FEA		Machining function	Fulfilled
13		Must allow space for ball to fall into grooves		mm	CAD	Enough space between top plate and feeder	Reliable exit of balls	Fulfilled

Figure D.1: Final requirement specification part 1

| 14	Outlet	Must not obstruct rotation of lapping plate			CAD/FEA		Rotating plate underneath should not impact component	Fulfilled
15		Must accept balls from lower position in v-grooves			CAD		Balls must be lifted up from v-grooves	Fulfilled
16		Balls exiting from innemost grooves must not be blocked by outer ones			Testing	Outermost balls exiting at higher speed	Core function to avoid balls stuck in outlet area	Not fulfilled, testing in machine required
17		Minimize interference with surrounding components			CAD		Ease of implementation	Fulfilled
18	Attachment	Must be able to be firmly fixed			engineering assessment		Withstand ball flow	Fulfilled
19		Must be easily replaceable with basic tools			engineering assessment		Removable for maintenance of machine	Fulfilled
20	Safety	Must allow for feeler function			CAD, check assembly	Feeler shuts down magazine if pile-up too high	Automatic shutdown safety feature	Fulfilled
21	Durability	Must not wear out before at least one completed cycle			Material selection/Testing	Able to be tested in machine	Fulfill core function throughout lapping process	Not fulfilled, testing in machine required
22		Should withstand general rough handling			Material selection/FEA		Use in factory environment	Fulfilled
		Must resist greases, oil, water			Material selection		Handle chemicals present in process	Fulfilled
23	Production	Minimize required support material for 3D printing			avoid overhangs		Avoid long post-processing and material waste	Fulfilled
24		Must have thick enough sections to enable printing	2	mm	CAD + expert assessment		Ensure structural integrity	Fulfilled
25		Must fit within the build plate	305x305x600	mm	CAD		Low part count	Fulfilled
26		Minimize printing time			height in print direction		Enable faster prototyping	Fulfilled

Figure D.2: Final requirement specification part 2, values related to machine dimensions omitted

E

Test Results

(a) t=0

(b) t=1
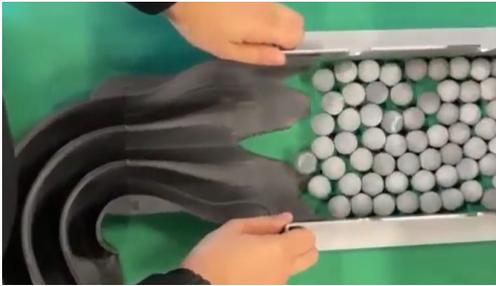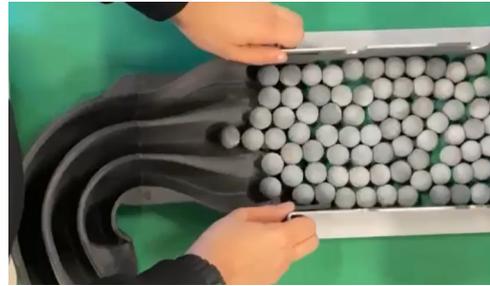
(c) t=2

(d) t=3

(e) t=4

Figure E.1: Four second time-lapse of an exploratory test with the Double stack prototype, t indicating elapsed time in seconds after conveyor start.

(a) t=0

(b) t=1

(c) t=2

(d) t=3

(e) t=4

Figure E.2: Four second time-lapse of an exploratory test with the Saw-tooth prototype, t indicating elapsed time in seconds after conveyor start.

X

(a) t=0

(b) t=1

(c) t=2

(d) t=3

(e) t=4

Figure E.3: Four second time-lapse of a test with the Cutout prototype, t indicating elapsed time in seconds after conveyor start.

(a) t=0

(b) t=1

(c) t=2

(d) t=3

(e) t=4

Figure E.4: Four second time-lapse of a test with the 6 Groove prototype, t indicating elapsed time in seconds after conveyor start.

(a) t=0

(b) t=0.5
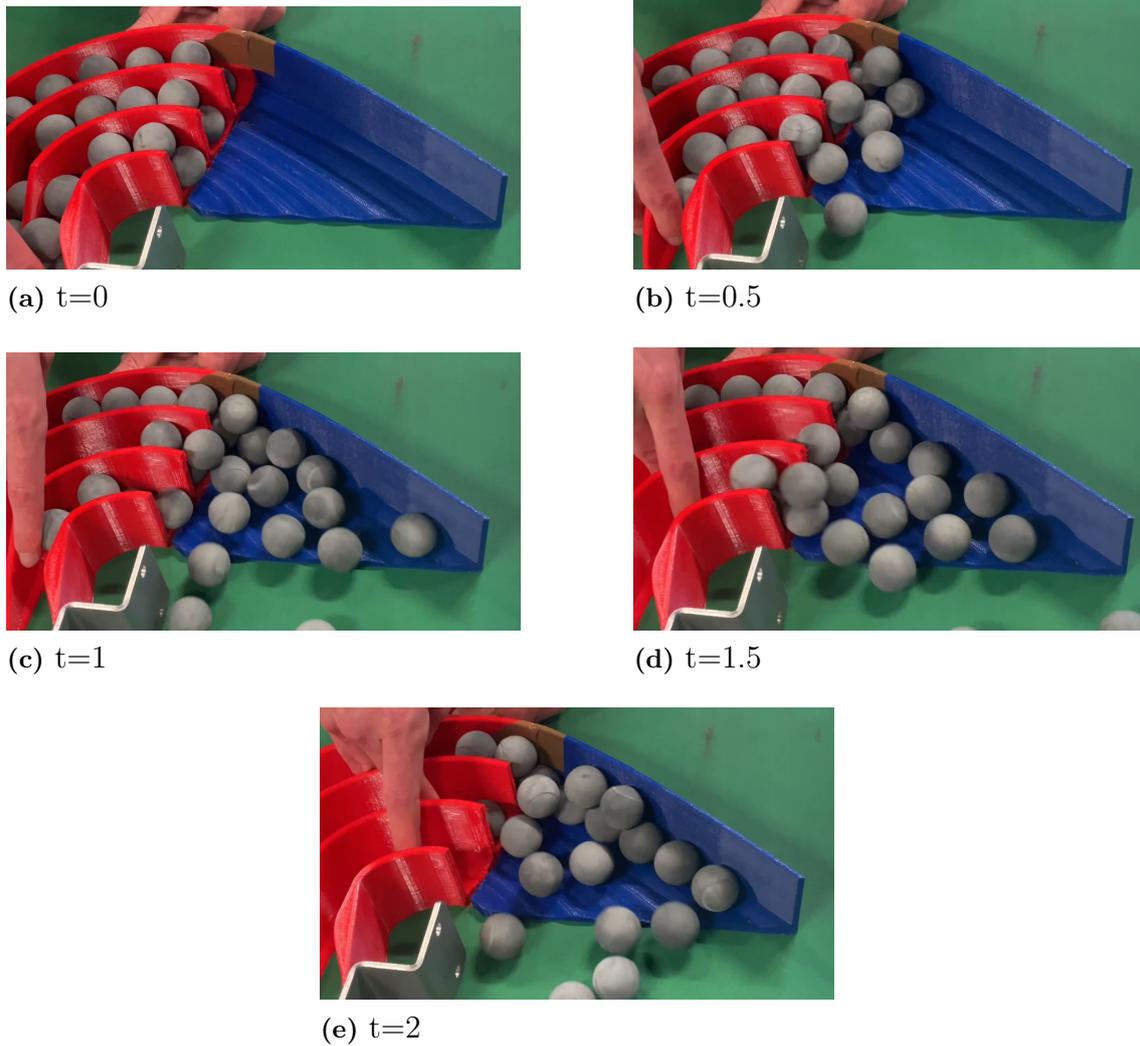
(c) t=1

(d) t=1.5

(e) t=2

Figure E.5: Two second time-lapse of a test with the merged prototypes. Balls were pushed by hand through the chute to inspect distribution. t indicates elapsed time in seconds.

(a) t=0

(b) t=0.5

(c) t=1

(d) t=1.5

(e) t=2

Figure E.6: Four second time-lapse of a test with the final 6 groove prototype. t indicating elapsed time in seconds after conveyor start.

(a) t=0

(b) t=0.5

(c) t=1

(d) t=1.5

(e) t=2

Figure E.7: Four second time-lapse of a test with the final 3 - 6 Transition proto-type. t indicating elapsed time in seconds after conveyor start.
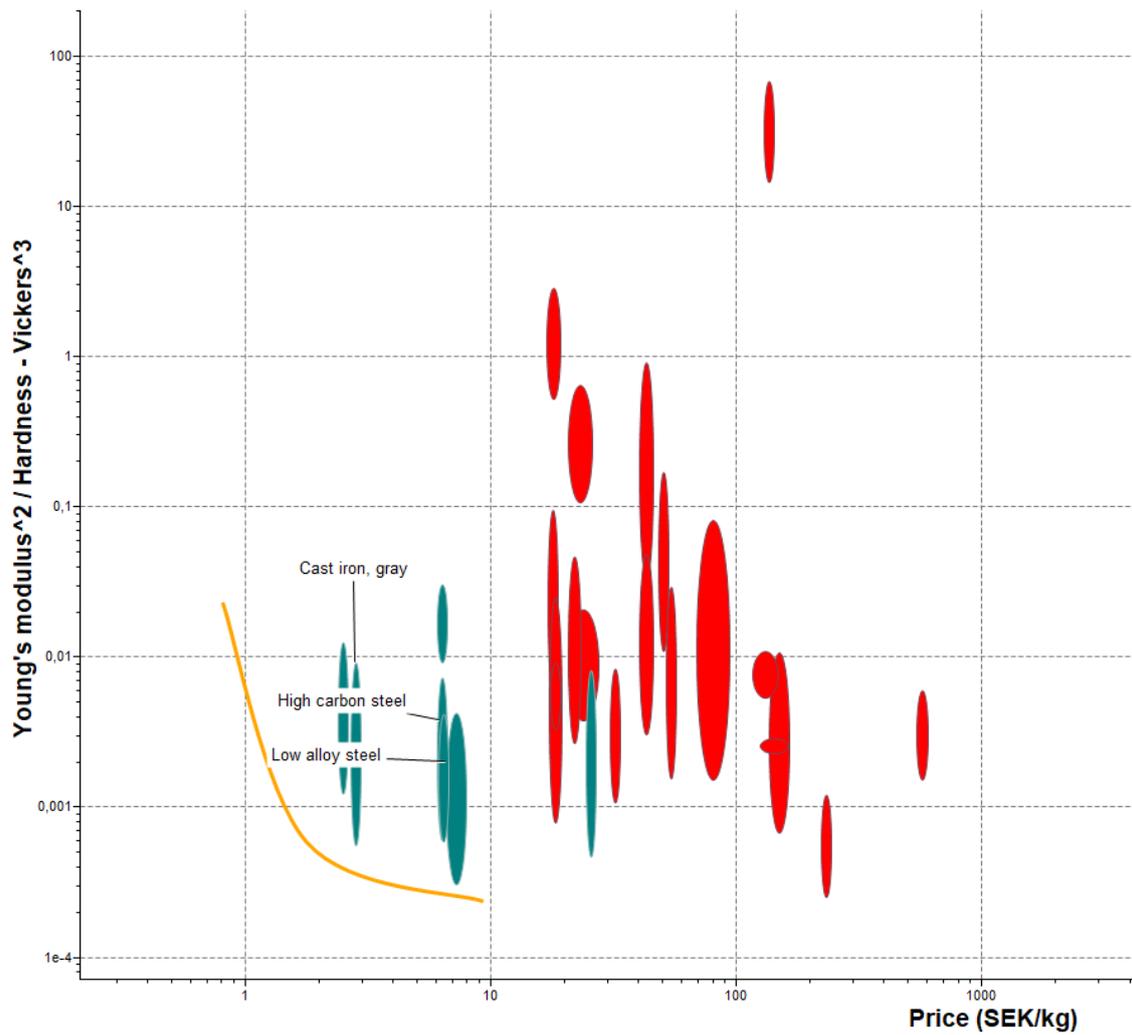
F

Material Selection Plot

Figure F.1: Material selection plot using Granta Selector. Selection index for abrasion resistance (to be minimized) on the y-axis and price per mass on the x-axis. Blue bubbles represent ferrous metals and red bubbles the non-ferrous.