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Specialty: Mining Mechanization

Study and design of a ball mill for artisanal mines

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QUOTE

“The mechanical design process is a complex dance between technical precision and creative problem solving.”

—Karl T. Ulrich, Product Design and Development

DEDICATION

I dedicate this work to:

My parents, for their unwavering support, patience and encouragement throughout this academic journey. Their faith in me has been a constant source of motivation.

My mentors and professors, whose wise advice and passion for research have enriched this study and guided me throughout my journey.

My friends, whose camaraderie, support and encouragement have been essential throughout this journey.

All those who, through their hard work and commitment, contribute to improving conditions in artisanal mines and to finding suitable technical solutions.

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ABSTRACT

This thesis focuses on the study and design of a ball mill adapted to the needs of artisanal mines in Burkina Faso. Faced with the challenges faced by artisanal miners, such as premature wear and inefficiency of existing mills, this work aims to develop a more durable and efficient ball mill, capable of effectively grinding local ores to improve the productivity of artisanal mines. The study analyzes the specific characteristics of these ores, evaluates existing grinding technologies and proposes a customized ball mill design that optimizes essential variables such as rotation speed, filling level and choice of materials. Modeling and simulation of the design under various loading conditions confirm the structural robustness and its effectiveness for the intended application. The results suggest that a specially designed ball mill can significantly improve the ore processing efficiency and durability. Future work could explore automation and advanced technologies to further optimize the grinding process and increase productivity.

Keywords: ball mill, artisanal mining, efficient grinding, durability, optimization.

RESUME

Ce mémoire porte sur l'étude et la conception d'un broyeur à boulets adapté aux besoins des mines artisanales aux Burkina Faso. Face aux défis rencontrés par les mineurs artisanaux, tels que l'usure prématurée et l'inefficacité des broyeurs existants, ce travail vise à développer un broyeur à boulets plus durable et efficace, capable de broyer efficacement les minerais locaux pour améliorer la productivité des mines artisanale. L'étude analyse les caractéristiques spécifiques de ces minerais, évalue les technologies de broyage existantes et propose une conception de broyeur à boulets personnalisée qui optimise des variables essentielles telles que la vitesse de rotation, le niveau de remplissage et le choix des matériaux. La modélisation et la simulation de la conception sous diverses conditions de charge confirment la robustesse structurelle et son efficacité pour l'application avisée. Les résultats suggèrent qu'un broyeur à boulets spécialement conçu peut améliorer significativement l'efficacité du traitement des minerais et la durabilité. Les travaux futurs pourraient explorer l'automatisation et des technologies avancées pour optimiser davantage le processus de broyage et augmenter la productivité.

Mots clés : broyeur à boulets, Mines artisanales, Broyage efficace, durabilité, optimisation.

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List of Acronyms and Abbreviations

BIT: Burkina Institute of Technology

CAD: Computer Aided Design

C: Carbon

Cr: Chromium

FAST: Function Analysis System Technique

HB: Brinell Hardness

HV: Vickers Hardness

HP: Engine power Horsepower

KW: kilowatt

LSMV: Leroy-Somer Motor Variable

m: meter

MEF: Finite Element Method

mm: millimeter

Mn: Manganese

MPa: Megapascal

n: rotation speed

n_{cr}: Critical rotation speed

Ni: Nickel

Pa: Pascal

RPM: Revolutions Per Minute

R: reduction ratio

SCADA/DCS: Supervisory Control and Data Acquisition / Distributed Control System

TPH: Ton per hour

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GENERAL INTRODUCTION

Burkinabe artisanal mining, defined as any operation of extraction, concentration and recovery of mineral substances using traditional or manual methods and processes[1], is essential for the local economy in Burkina Faso. It provides livelihoods for many people and is an important source of income at the local level. Burkina Faso currently has more than 600 active artisanal gold mining sites and more than a million people living directly from this activity.[2]. However, this form of mining often faces major challenges, particularly with regard to the equipment used. Among these equipment's, the ball mill, used for grinding ores, occupies a central place. The ball mill is a key equipment in the ore processing process in Burkina Faso, but the mills currently used in Burkinabe artisanal mines present significant challenges. In particular, most of these mills are not equipped with an internal lining, which leads to premature wear and reduced grinding efficiency. In addition, these mills are often of rudimentary design, which limits their capacity to efficiently process ores.

Faced with these challenges, **it becomes imperative to design a ball mill adapted to the needs of artisanal mines in Burkina Faso**. A mill that is both efficient in grinding ores and durable over time, taking into account the constraints of cost and availability of local materials.

This thesis therefore proposes to study and design such a ball mill, with an emphasis on optimizing its design for the specific conditions of artisanal mines in Burkina Faso. By exploring innovative solutions, this study aims to contribute to the development of more efficient and sustainable artisanal mining in the country.

This paper will be divided into five chapters. The first chapter will provide an overview of the study, including the research objectives and hypotheses. The second chapter will focus on grinding and gold ore, detailing the principles of crushing and the specificities of gold ore. The third chapter will cover the functional analysis, while the fourth will focus on sizing and calculation. Finally, the fifth chapter will cover modeling and simulation, before concluding on the entire study.

Chapter I: Research objectives and hypothesis

Introduction

This introductory chapter establishes the foundations and expectations of our study by presenting the objectives and hypotheses of our research on the study and design of a ball mill for artisanal mining. First, the general objective and specific objectives of this study will be outlined in order to clearly define the expectations of this study. Then, the research hypotheses will be formulated, thus providing a theoretical framework for the research.

I.1. Objectives of the study

I.1.1. General objective

The general objective of this study is to design a ball mill adapted to the needs of artisanal mines in Burkina Faso, in order to improve the efficiency of ore processing and increase gold production, while taking into account the specific constraints of this context.

I.1.2. Specific objectives

To achieve the general objective of designing a ball mill suitable for artisanal mines in Burkina Faso, this study sets three specific objectives.

- The first specific objective is to analyze the characteristics of the ores processed in artisanal mines, this analysis involves a detailed study of the physical properties of local ores, with the aim of acquiring an in-depth understanding of their characteristics.
- The second specific objective is to study existing grinding mill technologies and their adaptation to the constraints of artisanal mines, in order to demonstrate why the ball mill is the most appropriate technology.
- The third specific objective is to design a ball mill that will efficiently meet the requirements of ore grinding in artisanal mines in Burkina Faso. This involves sizing the mill components for optimum performance in artisanal mining conditions, choosing materials that are resistant to the specific stresses encountered in this context, and integrating technologies such as the use of special liners to ensure maximum mill efficiency and durability.

I.2. Research hypotheses

In order to guide our research and predict the expected results of our study, we formulate the following hypotheses:

- Local ores from artisanal mines in Burkina Faso have specific physical properties that require the use of mill with suitable technology.
- Among the various grinding technologies available, ball mill is the most suitable for artisanal mining due to its ability to provide efficient grinding.
- A custom-designed ball mill for artisanal mining in Burkina Faso, taking into account the characteristics of local ores and operating variables such as mill rotation speed, filling level, dimensions and materials used for its design will improve the efficiency of ore grinding.

Conclusion

This chapter laid the foundations of our study by presenting its general and specific objectives, as well as the hypotheses on which it is based. The following chapters will detail our methodology and results, with a view to proposing an innovative solution to improve the grinding process in artisanal mines in Burkina Faso.

Chapter II: General information on the grinding process and grinders.

Introduction

The grinding process plays a central role in mineral processing and the selection of an appropriate grinding mill is crucial to ensure the efficiency and profitability of the grinding operation. This chapter provides an in-depth analysis of the grinding process, highlighting the different modes of fragmentation and the characteristics of the local gold ore that influence the selection and design of grinding mills. We will also examine the main types of grinding mills used in the mining industry, detailing their operation, advantages and disadvantages and discuss the criteria for choosing a grinding mill in an artisanal mining context, in order to choose the most suitable grinding mill for artisanal mines in Burkina Faso.

II.1. General information on the grinding process

II.1.1. Grinding

Grinding is an operation consisting of dividing a solid, to increase its specific surface area, thus improving its reactivity.[3]. It aims to reduce the material obtained during crushing into small fragments or powder by wet or dry method.[4], in order to liberate useful minerals from sterile minerals, or to obtain products of the necessary granulometry. For this, the material is subjected to stress forces greater than its resistivity.

In mineral processing, grinding is carried out down to the liberation mesh, which is the size below which a mineral particle is considered perfectly liberated.[3]. This release mesh is essential for useful minerals such as gold, as it allows their recovery by subsequent processes such as flotation or cyanidation.

Depending on the intensity of the grinding operation, we can also speak of comminution or attrition.[3], thus highlighting the different methods used to achieve grinding objectives. Comminution refers to a more intense grinding, involving a more thorough fragmentation of the material, while attrition refers to a gentler grinding process, focusing on wear and abrasion of the particles. These two terms illustrate the variety of approaches and energy levels applied during grinding, thus highlighting the importance of choosing the right method for the characteristics of the ore and the processing objectives.

Grinding, whether comminution or attrition, wet or dry, plays a crucial role in optimizing mineral processing processes and in the overall efficiency of mining operations.

II.1.2. Fragmentation Modes

The fragmentation of a material can be achieved in different ways depending on its physical properties and the type of mill used.

Fragmentation can be achieved in four main fragmentation modes:

- Compression, or crushing, which consists of reducing the material by crushing it between two rigid surfaces. This method allows for relatively coarse fragmentation, with fragments measuring between 0.5 and 5 mm.
- Impact or percussion which consists of subjecting the material to shocks in order to reduce it to the order of 5 µm. The different types of fragmentation by impact include percussion by shock, percussion by grinding body and percussion between particles
- Shearing that involves cutting or tearing material by applying shear forces. It results in relatively fine fragmentation.
- Attrition is the process of reducing the size of materials by rubbing or striking them against each other or against rigid surfaces.

These different modes of fragmentation are illustrated in Figure 1.

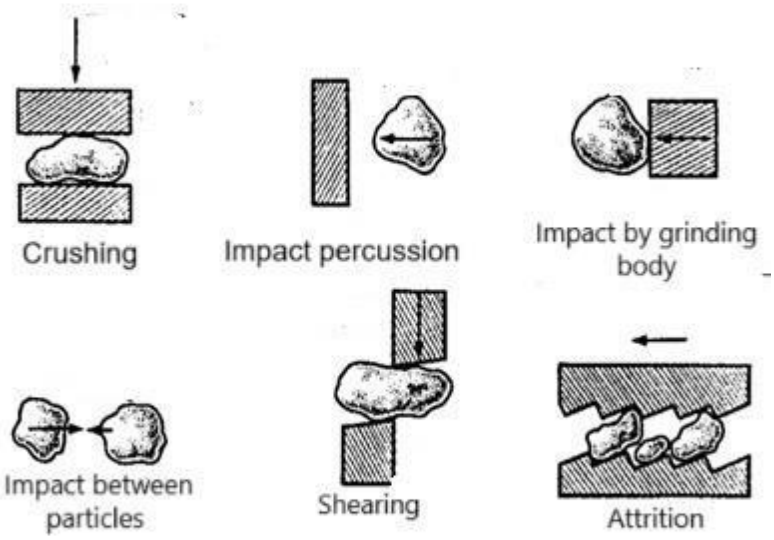


Figure 1 : Diagram of the different fragmentation modes[5].

II..1.3. Characteristics of local gold ore.

The behavior of a batch of particles in a grinding process will be closely linked to the nature of these particles[6]. We provide below a quick inventory of the main properties relating to the grindability of gold ore, which must be taken into account when choosing the type of grinder to use.

II.1.3.1. Hardness

The hardness of a mineral is determined by its resistance to being scratched.[7]This property is classically represented on the Mohs scale (figure 2), which classifies different materials from the most brittle to the hardest.

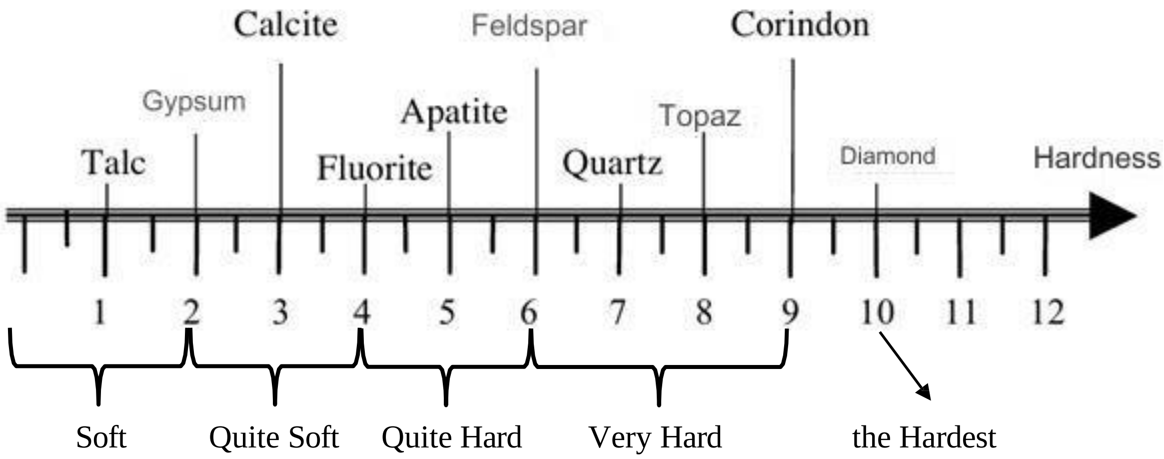


Figure 2 : Mohs hardness scale of different materials[8].

In Burkina Faso, gold is frequently associated with minerals such as quartz, pyrite and arsenopyrite, which are very hard minerals, measuring between 6 and 7 on the Mohs scale. This hardness of the ore requires powerful mills and specific grinding parameters.

II.1.3.2. Abrasiveness

Abrasiveness is the ability of a material to wear or erode other materials by friction (the grinding tools), it is closely related to hardness, because in general, hard materials tend to be more abrasive. The local ore, with a hardness between 6 and 7, highlights its abrasiveness, which can lead to rapid wear of the grinding tools and increase maintenance costs. This abrasiveness is a crucial factor in the selection of materials for grinding liners and parts.

II.1.3.3. Adhesiveness

Adhesiveness refers to the tendency of a material to stick to the surfaces with which it comes into contact. In the context of ore grinding, it is the tendency of ore particles to adhere to mill walls and tools. It is influenced by several factors, including the mineralogical composition, humidity and texture of the particles. Local ore, often associated with hard minerals such as quartz, can exhibit increased stickiness, thus reducing grinding efficiency.

II.2. General information on mills

II.2.1. Definition of the grinding mill

A grinding mill is an equipment used to reduce the size of solid materials by grinding processes. It consists of two main parts: a mechanical part and an electrical and control part.

II.2.1.1. Mechanical part

The mechanical part of a mill varies depending on the type of mill used, it includes the essential elements for the size reduction of the material. These elements include a grinding chamber such as the drum or cylinder, the shafts and bearings, the grinding media (such as balls, hammers or bars), the feed and discharge hoppers, the transmission system (gears, belts, pulleys), and the support structure that ensures the stability and alignment of the components.

II.2.1.2. Electrical part

The electrical and control part of a mill includes the electric motor, often coupled with a frequency inverter to control the rotation speed, the control panel to monitor and control the parameters, the sensors and measuring instruments (temperature, speed, vibration, material level), the automated control system (SCADA/DCS) for automation of operations, the protection and alarm systems (overload relays, circuit breakers, alarms), and the cooling systems to dissipate heat and ensure reliable performance.

II.2.2. Types of grinding mills

In the field of mineral processing, there are several methods for classifying mill, including by the mode of fragmentation (compression, impact, shear, abrasion) and by the size of the fragments (coarse, intermediate, fine). However, these methods can be ambiguous, because some mills use several modes of fragmentation, and the size of the fragments obtained depends on various factors such as operating conditions and equipment settings. On the other hand, classification by the nature of the grinding media, distinguishing between mills with free and non-free grinding media, is more precise and reliable, because it is based on clear and distinct technical criteria.

II.2.2.1. Non-free grinding body mill

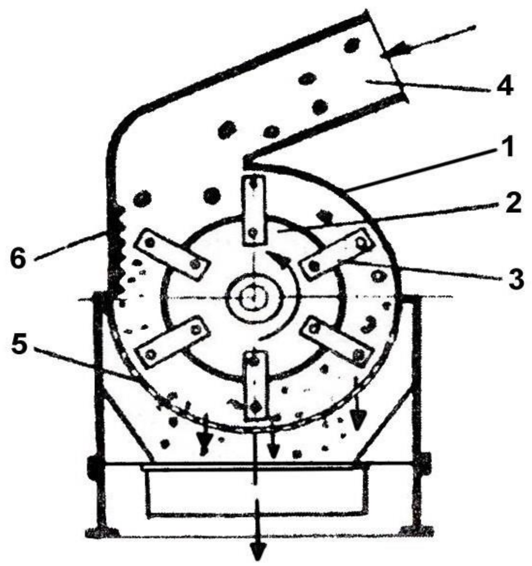
In this category of mill, the grinding bodies are fixed to rotors or shafts and exert a compressive, impact or shearing force on the material to be crushed. Some of these mills are only crushers adapted to advanced fragmentation and others on the other hand are of original design. They are all designed to operate dry[9],except the millstone grinder.

II.2.2.1.1. The hammer mills

This mill consists of an axially assembled rotor on which hammers (bars) are fixed, hence the name hammer mill, which rotates inside a grinding chamber. The lower part of this chamber is equipped with a sieve. This device allows coarse and medium reductions, but is not suitable for hard and abrasive materials. It is appreciated for its simplicity and versatility.

- Operating principle

Its principle is to pulverize the material by projecting it at high speed against the chamber reinforced with a shield. The material to be ground is introduced into the grinding chamber where it is struck by the hammers which rotate at 20 to 60 ms-1 peripheral speed.[10]. The impact of the hammers and the projection of the materials against the armor plates or grids allow the particle size to be reduced. The crushed material is then evacuated through the perforated grids (sieves).



Legend: 1-Carcass 2- Rotor 3- Hammer 4- Power supply 5- Sieve 6- Armor plate

Figure 3 : Diagram of a hammer mill[11].

- Benefits

- Simplicity and versatility
- Low cost

- Inconvenience

- Limiting particle sizes
- Dust product
- Not suitable for hard and abrasive materials like gold ore

II.2.2.1.2. The millstone mills

Grinding mills are traditional grinding equipment but modernized to be used in various industries, especially in some semi-mechanized mines. They are composed of one or two grinding wheels rotating on a table. Robust and versatile, they allow to obtain fine and uniform particles.

- Operating principle

This type of mill works on the principle of pressure grinding[12],that is to say by compression. The material to be ground is introduced between the grinding wheels where it is crushed by compression between the grinding wheels and the circular track (table). Different arrangements are adopted depending on the products, the table can be either fixed, with the grinding wheels rotating around the axis of the grinder while rolling on the circular track or rotating, with the grinding wheels rotating on themselves and around their own axis while rolling on the circular track[13]. The grinding pressure is obtained either by gravity requiring very heavy grinding wheels, or by the centrifugal force of the grinding wheels rotating in a track with vertical or steeply inclined walls. The evacuation is done through a mesh trapdoor on the table.

- Benefits

- Very fine and uniform particles
- Versatile

- Disadvantages

- Limited processing capacity
- Complex

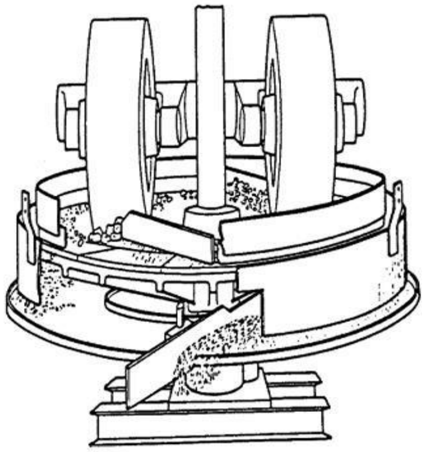


Figure 4 : Millstone diagram[9].

II.2.2.2. Free grinding body mills

Free grinding media mill are the most widely used in industry due to their high processing capacity and fragmentation efficiency. They are cylindrical or cylindro-conical machines rotating around their horizontal axis and containing grinding media that can be balls, bars, pebbles or the ore itself[7].

II.2.2.2.1. Ball mills

Ball mills are the most used in the mining sector. Efficient and versatile, they are able to process a wide range of materials to obtain very fine particles. Their particularities are that they use balls as grinding bodies and their drums are cylindrical or cylindro-conical in shape.

- Operating principle

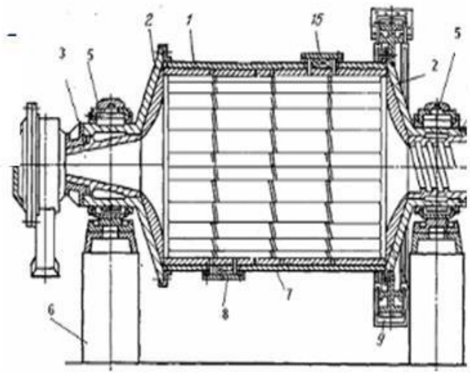
Ball mills are usually loaded with ore by a loading trunnion, they operate by rotating a drum partially filled with steel balls and the material to be ground. As the drum rotates, the balls are lifted by the drum wall covered by a lining to a critical height, then cascade back to the bottom where they start their course again. Grinding is carried out by the impact of the grinding media on the pieces of material to be ground as they fall to the bottom of the drum, and by crushing as they rise. The rotation of the drum, combined with a slight inclination of its longitudinal axis relative to the horizontal plane and the transport medium which can be air for dry grinding or water for wet grinding, drives the material to be ground and the grinding products (the materials reduced in size) along the drum. The grinding products are then discharged from the mill through the discharge trunnion by various methods, such as overflow (Figure 5), where the ground material passes over the edge of the drum, or by grate (Figure 6), where it passes through a perforated grate at the end of the drum allowing for more precise control of the final particle size. The diameter of the discharge trunnion is usually larger than that of the loading trunnion larger than that of the discharging trunnion which also facilitates the movement of the ground material to the discharge trunnion. The balls are steel balls that can vary in diameter from 12.7 to 2.2 cm. These mills generally have a length to diameter (L/D) ratio of 1.5. When this ratio is greater than 1.5, they are called tube mills. These mills can operate continuously or batchwise.

- Benefits

- Fine grinding
- Produces uniform fragments
- Flexible
- High production capacity compared to other mills

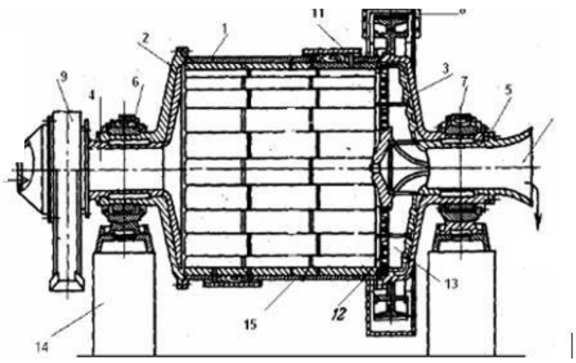
- Disadvantages

- Production of heat.
- Wear of components such as bullets and armor plates[14].



Legend: 1 - drum; 2 - covers;
3 – loading trunnion; 4 – unloading trunnion; 5 – bearings; 6 – foundation;
7 – wear plates (liner); 8 – hatch.

Figure 5 : Ball mill with central discharge (overflow) [14].



Legend: 1 – drum; 2, 3 – side covers;
4, 5 – hollow journals; 6, 7 – bearings; 8 – toothed ring; 9 – feeder; 10 – discharge throat; 11 – hatch; 12 – grid; 13 – blade (lifting vane); 14 – foundation; 15 – wear plates (liner); 15 – wear plates (liner).

Figure 6 : Ball mill with grid discharge. [14]

II.2.2.2.2. Autogenous mills*

Autogenous mills are mining grinding equipment whose particularity lies in the fact that they use the ore itself as grinding media. Thus, eliminating the need for steel grinding media (balls or bars). They are characterized by their large diameter and short length compared to ball mills.[15].

- Operating principle

Autogenous grinding relies on the ore to be ground containing fragments that are large and hard enough to perform the grinding. They work by rotating a cylindrical drum partially filled with the ores to be ground. As the drum rotates the ores are lifted to a critical height before cascading down, creating impact, compression and friction forces on the ore. These combined forces progressively reduce the particle size. They have the same loading and unloading system as ball mills.

- Benefits

- Less steel consuming than other mills with free grinding bodies (balls, and bars)
- Less contamination
- Less expensive
- Less wear and tear

- Disadvantages

- Incomplete grinding as grinding may be inefficient;
- The larger the grain size, the more work the mill does on the ore;
- Bulky;
- Produces fewer fine fragments than ball mills.

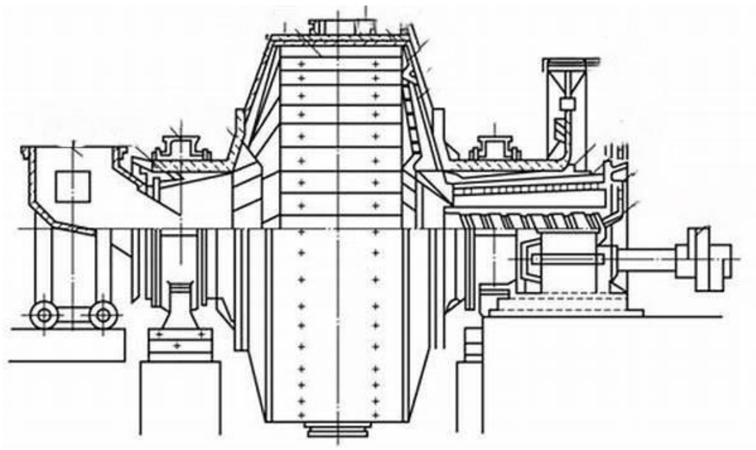


Figure 7 : Autogenous mill diagram[16].

II.3. Choosing a grinding mill

As mentioned above, there are several types of grinding mill and carrying out a study to choose a mill is not a waste of time. On the contrary, it allows us to target our needs, avoid going back and forth to different markets, and optimize expenses. A good selection in the industry translates into an economic gain by avoiding unnecessary expenses. Therefore, a choice study is essential to choose an appropriate mill in an artisanal context and ensure optimal efficiency of the gold ore processing process.

II.3.1. Selection criteria

To choose a mill suitable for processing gold ore in an artisanal mine, several criteria must be considered. These criteria include:

- The nature of the ore

The mill chosen must be capable of processing the specific type of gold ore being mined as seen in 1.3, with adequate particle size to liberate the gold particles efficiently.

- Processing capacity

The mill must have sufficient capacity to process the volume of ore extracted daily.

- Energy efficiency

The mill must be energy efficient to minimize operating costs, a particularly important criterion in artisanal mines where resources may be limited.

- Durability and maintenance

mill durability and ease of maintenance are essential to ensure continuous operation with minimal interruptions.

- Initial and operational cost

It is important to consider both the acquisition cost of the mill and the operational costs to ensure that the investment is profitable in the long term.

II.3.2. Interest in choosing a ball mill

Ball mill is an optimal choice for ore processing in an artisanal mine due to its grinding efficiency, flexibility, robustness, and cost-effectiveness. Capable of grinding ore to a very fine particle size, it allows for efficient liberation of gold particles, which is crucial for gold recovery. In addition, its high production capacity coupled with its ability to be adjusted to process different types of ores and operate in harsh conditions makes it a sustainable and cost-effective solution. Although its initial cost is a bit high, its energy efficiency helps reduce operational costs, making it a cost-effective solution in the long run.

Conclusion

The in-depth analysis of the grinding process, fragmentation methods and characteristics of local gold ore has highlighted the importance of the selection and design of mills in the mining industry. After examining in detail, the main types of mills and then discussing the selection criteria, it appears that the ball mill is the most appropriate choice for artisanal mines in Burkina Faso.

Chapter III: Functional analysis

Introduction

This chapter is devoted to the functional analysis of the mill. Functional analysis is a methodical approach that aims to identify the essential functions of the system, taking into account user needs and required performance. This analysis will make it possible to propose technical improvements in order to optimize the efficiency, reliability and durability of the mill in the context of artisanal mines.

III.1. Horned beast diagram

The horned beast diagram is a visual used to formalize the expectations and needs related to the product to be designed. It is about consistently expressing the goal or need to be satisfied by the system by answering the following three questions:

1. Who does the product serve?
2. What does the product act?
3. What is its purpose?

The answers are presented in a diagram called “Horned Beast.”

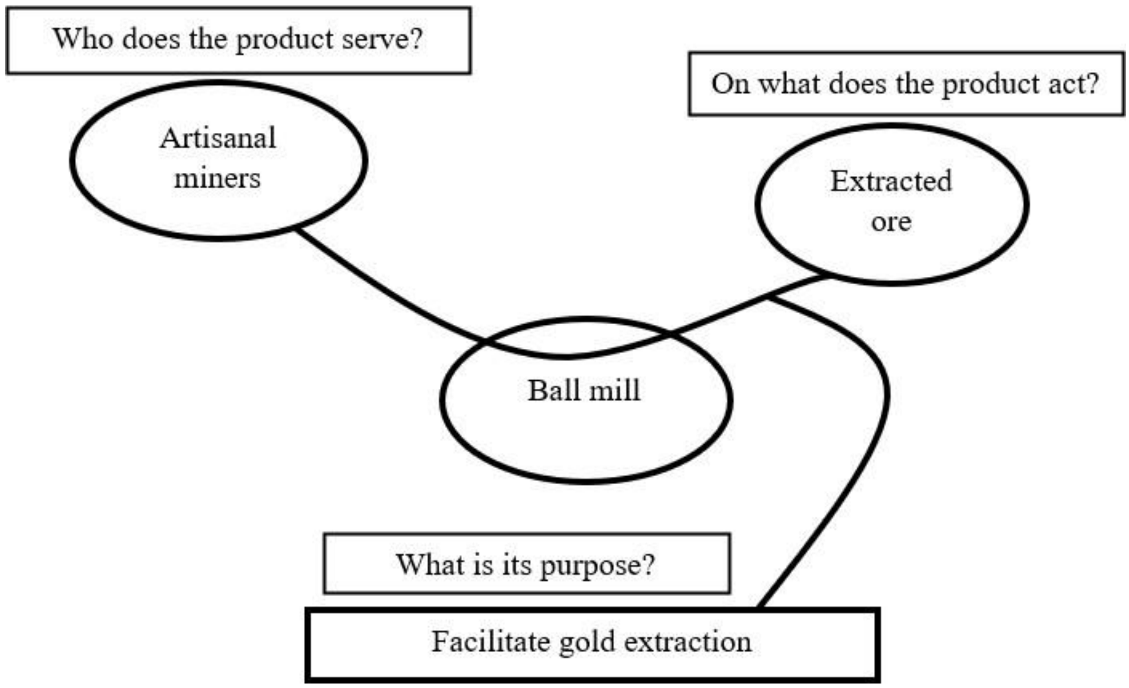


Figure 8 : Horned Beast Diagram.

III.2. Validation of the need

After capturing and stating, it is crucial to move on to the validation step to ensure that the ball mill will actually meet the expectations of the end users. This validation is done by asking and answering the following three questions[17]:

- Why does this need exist?

The need to design a ball mill for artisanal mining exists with the aim of improving the efficiency and productivity of artisanal miners.

- How can it evolve?

This need can evolve by integrating more advanced automation and control technologies. Such as the implementation of sensors for real-time monitoring of grinding parameters (speed, temperature, etc.).

- What could make it disappear?

The need for this type of mill could disappear if new gold extraction technologies, not using ore crushing, were developed and implemented. For example, innovative chemical or biological methods for extracting gold directly from ore without the need for crushing could make ball mills obsolete.

III.3. Census of service functions

A service function is an action or set of actions performed by a product to meet a specific need. This designed product must function effectively under the imposed external and internal conditions. These conditions include the human environment, the economic environment, the technical environment and the physical environment.

The figure below shows the list of service functions that affect the ball mill.

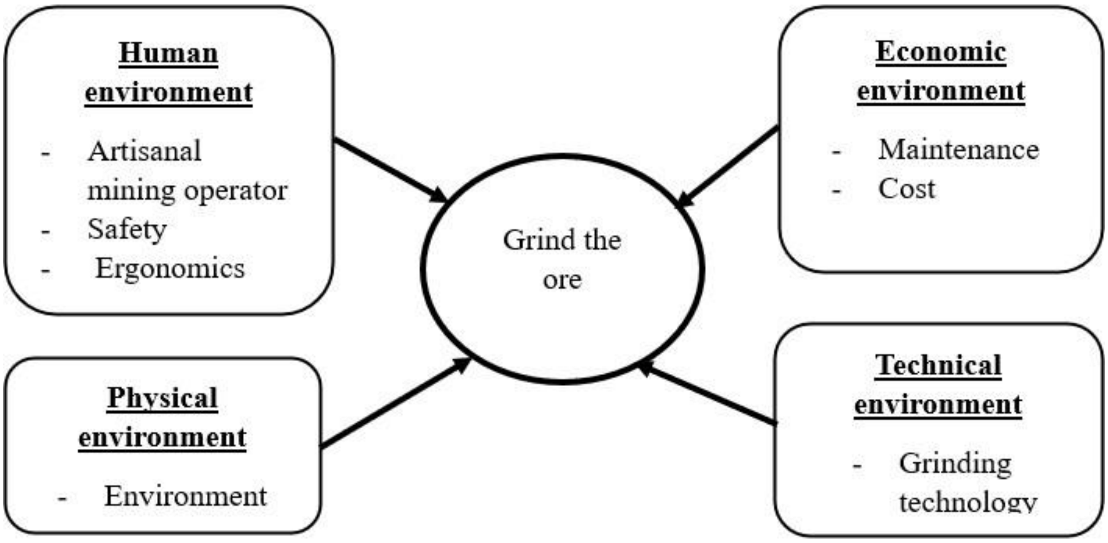


Figure 9 : Census of service functions.

III.4. Octopus diagram

The “octopus diagram” tool, used to analyze needs and identify the service functions of a product, highlights the interactions between the various elements of the environment and the product. These interactions, called service functions, make it possible to meet the identified need.

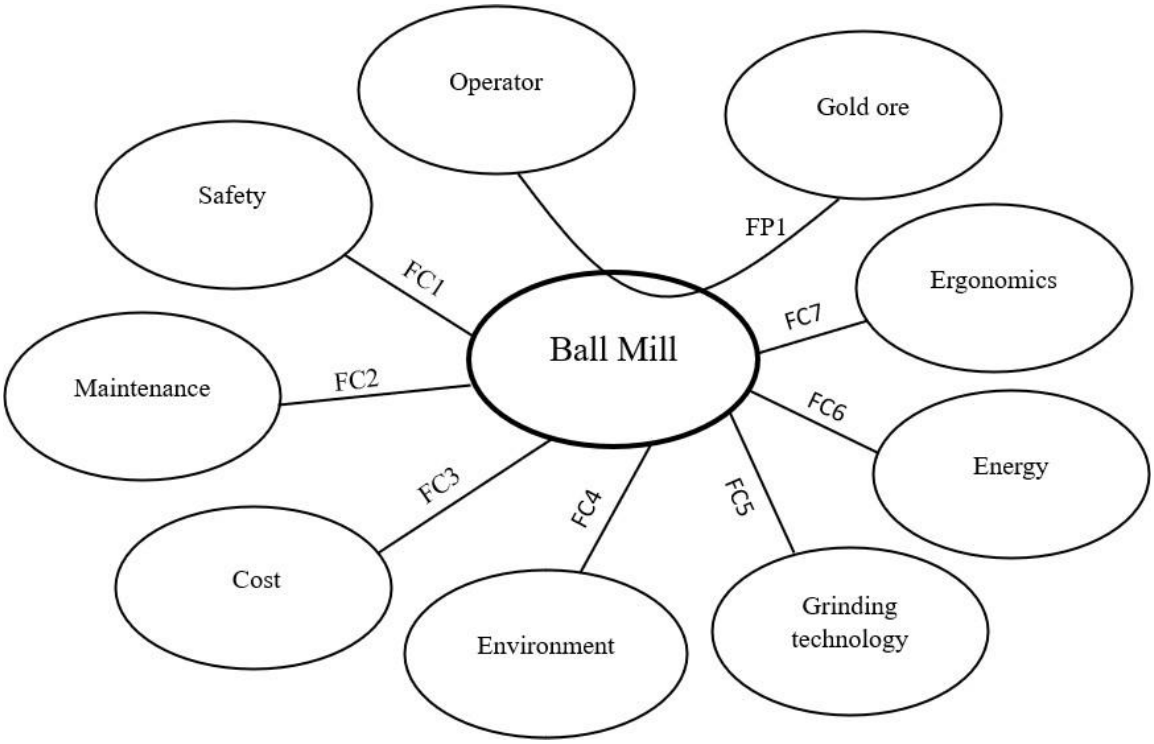


Figure 10 : Octopus diagram

The list of service functions is listed in the following table:

Table 1 : List of service functions.

FP1	Grinding gold ore
FC1	Do not present any harm to the operator and his environment
FC2	Have easy and affordable maintenance
FC3	Have an affordable cost
FC4	Respect environmental conditions
FC5	Be efficient, reliable and durable
FC6	Be optimal and save energy
FC7	Allow easy and adequate use

III.5. Prioritization of service functions

To ensure an efficient and focused design, we will prioritize service functions by prioritizing the mill's essential needs.

III.5.1. Cross-sorting

In order to prioritize the service functions of our mill, we will use the “Cross Sort” sorting tool, a table listing the different functions and their relative importance.

The grades awarded are as follows:

0: No superiority; 1: Slightly superior; 2: Moderately superior; 3: Clearly superior

Table 2 : Cross sort.

	FP1	FC1	FC2	FC3	FC4	FC5	FC6	FC7	Points	%
FP1	-	2	2	3	3	2	2	2	16	18.82
FC1	1	-	2	2	2	2	2	2	13	15.29
FC2	1	1	-	2	1	1	2	1	10	11.76
FC3	0	1	1	-	2	1	2	2	9	10.59
FC4	0	1	2	1	-	2	2	2	10	11.76
FC5	1	1	2	2	1	-	2	2	11	12.94
FC6	1	1	1	1	1	1	-	2	8	9.41
FC7	1	1	2	1	1	1	1	-	8	9.41
Total									85	100

The table above shows the ranking of main functions and constraints based on the previously assigned scores.

III.5.2. Service function diagram

This involves representing the main functions and constraints in decreasing order of their importance using a diagram.

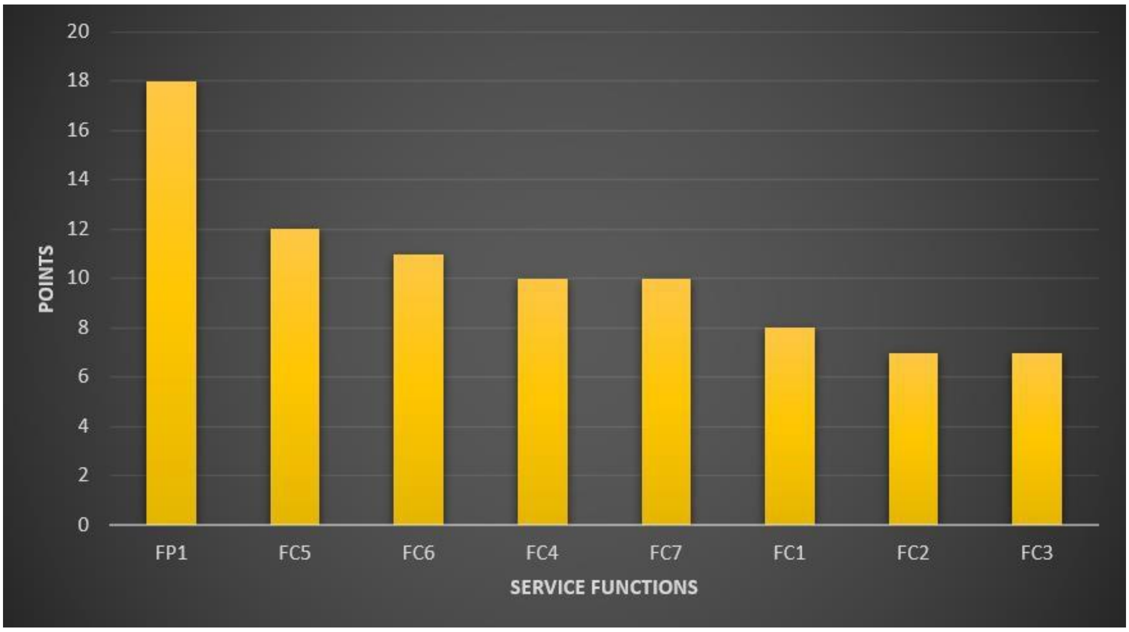


Figure 11 : Service function diagram.

III.6. functional specifications

In order to determine the qualitative and quantitative requirements of service functions, we must precisely characterize each service function.

Table 3 : Functional specifications.

Reference	Function	Criteria	Level
FP1	Grinding gold ore	- Ore size at entrance - Ore size at outlet	Input: 5 to 20 mm Output: 75 to 20 microns
FC1	Does not present any danger to the operator or those around him.	Operation without risk for the operator and without negative impact on those around him.	Safety standards
FC5	Be efficient, reliable and durable.	High availability rate	
FC2	Have easy and affordable maintenance.	- Easy maintenance with a cost - Easy disassembly - Standard parts	

FC4	Respect environmental conditions.	Environmental compliance	Respect local and international standards
FC3	Have an affordable cost.	Affordable price	
FC6	Be optimal and save energy.	Low energy consumption	
FC7	Allow easy and adequate use.	Ease of use	

III.7. FAST (Function Analysis System Technique) diagram

Once the service functions have been identified, the FAST method allows us to organize them and break them down into technical functions.

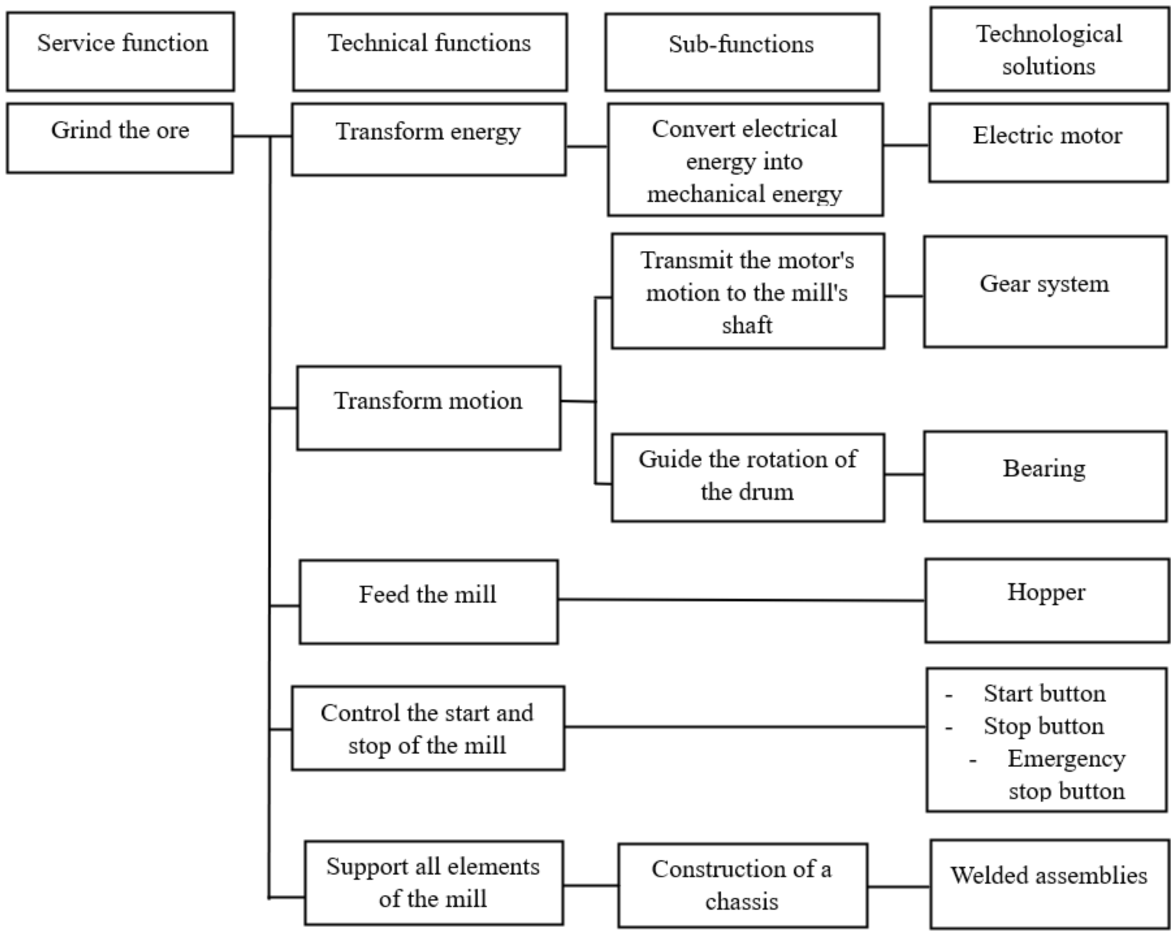


Figure 12 : FAST diagram.

Conclusion

This chapter has allowed us not only to identify and prioritize the different functions required in the design of the mill but also to understand in detail the requirements and expectations of such a design in order to develop a high-performance, reliable and competitive system

Chapter IV: Sizing and Calculations

Introduction

After completing the functional analysis of the mill, we will focus on the sizing and calculations required for its design. In this chapter, we will cover the detailed technical aspects, including component specifications, dimensional calculations, determination of the required power and the selection of suitable materials to meet the requirements established in the functional analysis.

IV.1. Block diagram

The synoptic diagram provides a clear and concise overview of our mill, facilitating the understanding of the process and the interactions between its various main parts.

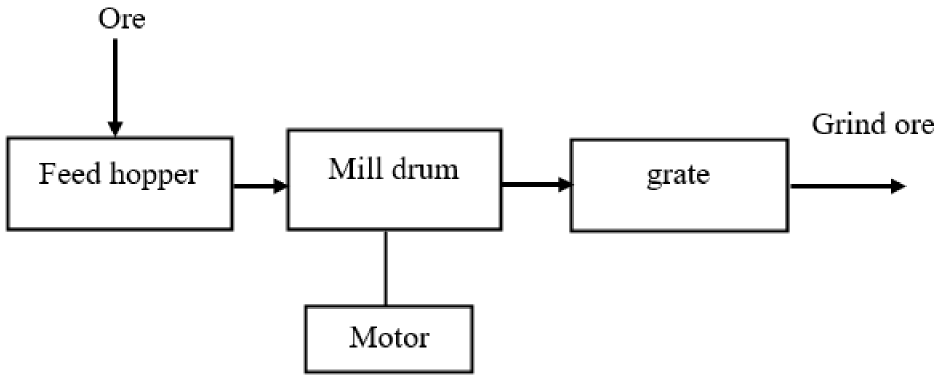


Figure 13 : Block diagram.

IV.2. Kinematic diagram

To better understand the internal mechanism of the mill, it is essential to establish a kinematic diagram that represents as faithfully as possible the relationships between the different groups of parts.

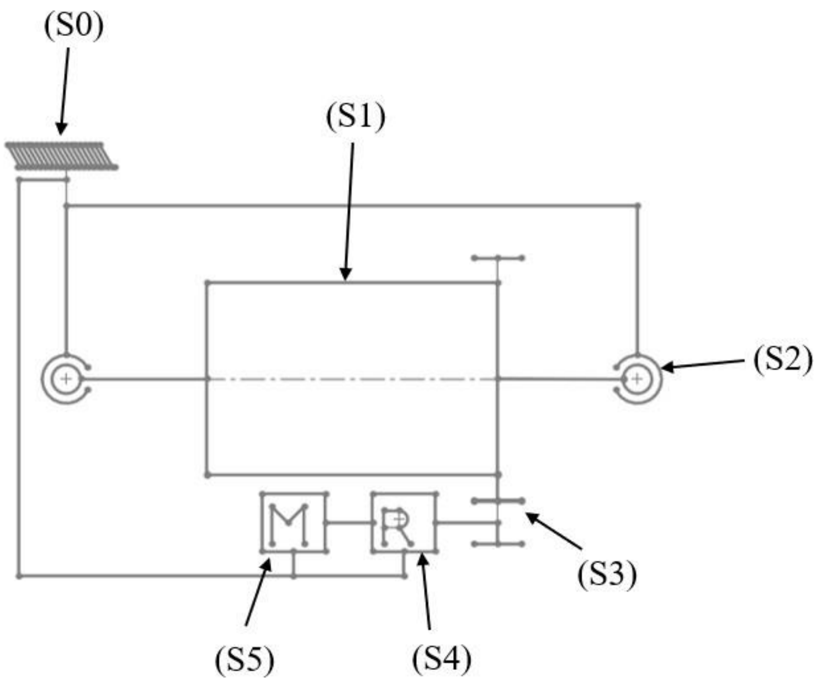


Figure 14 : Kinematic diagram.

Table 4 : Designation of the elements of the kinematic diagram.

Number	Designation
S0	Built
S1	Drum
S2	Rolling
S3	Gear
S4	Reducer
S5	Engine

IV.3. Determination of certain technical characteristics necessary for the design of the mill

Determining the dimensions of a ball mill is a complex process that relies heavily on the application of empirical equations or factors based on accumulated experience. Different mill manufacturers use different methods for these calculations, making it difficult to verify the validity of sizing estimates when they diverge considerably between sources. This disparity also complicates the teaching of sizing to engineering students, due to the apparent lack of a logical engineering basis for these empirical equations.[18]. However, given the challenges and uncertainties associated with computational sizing, we have taken a pragmatic approach by selecting the mill dimensions from the standard data sheets in Tables 5 and 6.

Table 5 : Sheet of standard dimensions of ball mills and their approximate capacities[18].

Dimensions Diameter x Length (ft)		Diameter x Length (m)	Approx. speed (rpm)	Ball load (T)	Capacity (T/h)	Engine power (kW)	mill weight (T)
3 x 6	3 x 6	0.9 x 1.8	37	1.5	0.65-2	18.5	4.6
3 x 10	3 x 10	0.9 x 3	36	2.7	1.1-3.5	22	5.6
4 x 8	4 x 8	1.2 x 2.4	36	3	1.5-4.8	30	12
4 x 10	4 x 10	1.2 x 3	36	3.5	1.6-5	37	12.8
4 x 15	4 x 15	1.2 x 4.5	32	5	1.6-5.8	55	13.8
5 x 10	5 x 10	1.5 x 3	30	7.5	2-5	75	15.6
5 x 15	5 x 15	1.5 x 4.5	27	11	3-6	110	21
5 x 19	5 x 19	1.5 x 5.7	28	12	2.5-6	130	24.7
6 x 10	6 x 10	1.83 x 3	25	11	4-10	130	28
6 x 15	6 x 15	1.83 x 4.5	25	15	4.5-12	155	32
7 x 10	7 x 10	2.1 x 3	24	15	6.5-36	155	34
7 x 15	7 x 15	2.1 x 4.5	24	24	8-43	245	42
8 x 10	8 x 10	2.4 x 3	21	23	7-45	245	54
8 x 15	8 x 15	2.4 x 4.5	21	30	8.5-60	320	65
9 x 13	9 x 13	2.7 x 4	21	40	12-80	400	94
10.5 x 15	10.5 x 15	3.2 x 4.5	18	65	12-100	800	137

Table 6 : Standard dimensions sheet for internal diameters[18].

Effective Internal Dimensions (foot)	Effective Internal Dimensions (m)	Approximate Capacity TPH	Avg Engine Power (HP)	Approx. Weight (Tons)
3 x 3	0.8 x 0.8	0.5	10	5
3 x 4	0.8 x 0.8	0.75	15	5
4 x 4	1.0 x 1.0	0.8-3.6	25	10
4 x 5	1.0 x 1.3	1.0-4.5	30	11
5 x 5	1.3 x 1.3	1.7-7.9	50	15
5 x 6	1.3 x 1.5	2.1-9.5	60	16
6 x 6	1.5 x 1.5	3.8-17.4	125	29
6 x 8	1.5 x 2.0	5.1-23.2	150	32
7 x 7	1.8 x 1.8	6.9-30.5	200	42
7 x 9	1.8 x 2.3	7.9-34.9	250	46
8 x 8	2.0 x 2.0	11.1-50.2	300	61
8 x 9	2.0 x 2.3	12.5-56.3	350	64
9 x 9	2.3 x 2.3	17.5-79.6	450	80
9 x 10	2.3 x 2.5	19.4-88.5	500	84

These sheets provide standard ball mill dimensions and their approximate capacities, facilitating the sizing process without involving complex calculations.

IV.3.1. Determination of length and diameter

We consider that the mine extracts 16 t/day and the mill must process these 16 tons in 10 hours. To use the technical sheet (table 5), we must determine the hourly capacity of the mill.

Equation 1 : $$\text{hourly capacity} = \frac{\text{total capacity (t)}}{\text{number of operating hours (hours)}}$$

NA: $$\text{hourly capacity} = \frac{16}{10}$$

$$\text{hourly capacity} = 1{,}6\ \text{T/h}$$

So, our mill must have a processing capacity of 1.6 tons per hour.

By consulting the standard dimensions sheet of ball mills and their approximate capacities (Table 5), we identify several options that can meet this requirement. However, to minimize costs and optimize efficiency, we must select the smallest mill that has a footprint of 0.9x1.8m or 3x6 feet with a capacity between 0.65 - 2 tons per hour, which is sufficient for our need of 1.6 tons per hour.

Therefore, the mill will have a length of **1.6 m** and a diameter of **0.9 m**.

IV.3.2. Calculation of the thickness of the mill linings

Based on the standards in Table 6, we found that the effective diameter inside the liners is 0.8m. Since the overall diameter before the liners are applied is 0.9m, we can deduce the total thickness of the liner.

Equation 2 : $$\text{liner thickness} = \frac{\text{overall diameter} - \text{effective diameter}}{2}$$

NA: $$\text{liner thickness} = \frac{0.9-0.8}{2}$$

$$\text{liner thickness } 0.05\text{m}$$

So, the thickness of the liner is **50mm**.

IV.4. Calculation of factors affecting mill efficiency

The efficiency of a ball mill depends on several key factors that we will detail in the following sub-points.

IV.4.1. Drum rotation speed

The management of the rotation speed of the mill is very important because it determines different grinding modes: cascade (50-70% of the critical speed), mixed (70-90% of the critical speed), and cataract (80-90% of the critical speed). At low speed, the load cascades, producing increased wear of the liner, at normal speed, the load cataracts, leading to efficient grinding and reduced wear. Too high a speed causes excessive wear, reaching a critical speed where the load remains against the wall. Thus, to determine the speed of the drum (n) of the mill we must know its critical speed (n_{cr})

The critical speed of a ball mill is the speed at which the grinding body (balls) remains pressed against the wall by centrifugal force.

- Critical rotation speed $\mathrm{n_{cr}}$

The expression for the critical speed is:

Equation 3 : $$\mathrm{n_{cr}} = \frac{42.3}{\sqrt{D}} \quad [4]$$

With D the inner diameter of the drum

$\mathrm{n_{cr}}$ The critical rotation speed

NA: $$\mathrm{n_{cr}} = \frac{42.4}{\sqrt{0.9-0.05}}$$

$$\mathrm{n_{cr}} = 46{,}09 \text{ rpm}$$

- Rotation speed n

The rotation speed of the drum is determined by the following relationship:

Equation 4 : $$\mathrm{n} = \psi . \mathrm{n}_{cr} \quad [4]$$

With walking value, we chose 0.85 or 85% to have an optimal speed ψ

$$\mathrm{n} = 0.85 * 46{,}09$$

$$\mathrm{n} = 39{,}17 \text{ rpm}$$

Hence our mill must have a rotation speed of around **39 revolutions per minute**.

IV.4.2. Ball dimensions

The size of the balls in the ball mill directly influences the grinding efficiency because it depends on the fineness of the powder that is to be obtained. The Starke formula (empirical formula) establishes a relationship between the diameter of the grains (d) to be ground and the diameter of the balls (D) expressed in micrometers µm according to the following formula:

Equation 5 : $$D = \frac{\sqrt{d}}{25{,}4.10^{-4}} \quad [10]$$

With d a grain diameter of 20 mm or 20,000µm

$$D = \frac{\sqrt{20000}}{25{,}4.10^{-4}}$$

$$D = 55677{,}7 \ \mu m$$

$$D \approx 56 \text{ mm}$$

So, the diameter of the balls will be of the order of **56mm.**

IV.4.3. Ball charge quantity

In order to make the ball in a rolling state, in addition to the rotation speed of the grinding drum, it also depends on the amount of ball charge and the friction between the balls and the drum wall. Although theoretically this calculation is complex, the amount of ball charge is often determined empirically due to the difficulty in measuring the friction coefficient. According to experience, the critical load is between 40% and 50% of the drum volume. This ratio of ball volume to drum volume is called the filling factor. A filling factor of less than 30% results in ball slippage and low grinding efficiency. On the other hand, a factor greater than 50% reduces the moment of inertia near the center of rotation, thereby decreasing the grinding efficiency. A filling factor is between 40% and 50%.

Therefore, we will choose a filling factor of **45%** to ensure maximum grinding efficiency.

IV.4.4. The quantity of loading

The loading quantity in a ball mill is generally expressed by the ratio of balls to the material to be ground. And in theory, when the material just fills the space of the ball, the grinding efficiency and production efficiency are ideal.

IV.4.5. Wet grinding environment

Since the further processing of the ore takes place in an aqueous environment, we have chosen wet grinding. This method keeps the particles suspended in the liquid, thus reducing dust production and minimizing health risks for workers. In addition, it improves grinding efficiency and facilitates further processing.

IV.5. Selection of materials for mill components

The selection of materials for components is crucial, as it determines the durability and overall performance of the mill. In this section, we will choose suitable materials based on the operational conditions and specific grinding requirements.

IV.5.1. mill body

The mill body must be made of durable materials that can withstand high loads and temperatures. Nickel-chromium alloy steel 16NiCr4 is our choice because it is known for its good mechanical properties, corrosion resistance and temperature resistance (See Appendix 1).

IV.5.2. liners

The liner protects the inside of the mill from wear. They must be made from highly abrasion resistant materials. A commonly used material for this application is manganese steel X120Mn12, this choice of material will be adapted to the crushing conditions of our mill (See Appendix 1).

IV.5.3. The Balls

For the balls, the material must offer a combination of hardness, abrasion resistance and durability to ensure efficient grinding. In order to simplify the manufacturing and material sourcing process, we will choose the same material as the one used for the lining, namely X120Mn12. This material perfectly meets these requirements (See Appendix 1).

IV.6. Selection of transmission elements

IV.6.1. Electric motor

IV.6.1.1. motor selection criteria

The choice of motor depends on the available power supply and the intended mechanical use. The table below shows the main characteristics and areas of use of electric motors.

Table 7 : Features and areas of use of electric motors.

Category	types	Properties	Use
Direct Current	Permanent magnets	Low power easy control	Computer hardware, robotics, electric vehicles
	Independent excitement	Important couple	Lifting, machine tools
	Series excitement	High starting torque	Car starter

Alternating current	Single-phase asynchronous	Low power, very economical	Household appliances
	Three-phase asynchronous	Economical, powerful	Most widely used industrial engine
	Synchronous magnet	Low power, speed variator required	Robotics (brushless motor), computer hardware
	Synchronous with electromagnets	High and very high power, expensive	mill, ship propulsion, pumping, turbines,

Our choice highlighted in green, is for a three-phase AC motor, economical, powerful and widely used in industry.

IV.6.1.2. Motor Characteristics

According to the standard dimensions sheet of ball mills and their approximate capacities (Table 5), the motor power required for the proper operation of the mill is 18.5 KW. Referring to the LEROY-SOMER motor catalogs presented below, the LSMV 180 M should be chosen.

Table 8 : LSMV 180 M motor characteristics[19].

Type	Power supply 400V 50 Hz Delta connection		Power supply 400V 87 Hz Star connection					
	Rated power	Rated torque	Rated power	Rated torque	Intensity	Speed at 50hz	Speed at 87hz	Power factor
	P_N kW	C_N N.m	P_N kW	C_N N.m	I_{MOTEUR} A	N min^{-1}	N min^{-1}	Cos φ
LSMV 80 LG	0,75	4,9	1,3	4,9	3,5	1445	2533	0,71
LSMV 90 SL	1,1	7,2	1,9	7,2	4,1	1445	2533	0,81
LSMV 90 LU	1,5	9,9	2,6	9,9	5,6	1450	2540	0,8
LSMV 100 LR	2,2	14,4	3,8	14,4	8,1	1450	2540	0,79
LSMV 100 LG	3	19,6	5,2	19,6	11,7	1460	2554	0,81
LSMV 112 MU	4	26,1	6,9	26,1	16,5	1465	2561	0,78
LSMV 132 SM	5,5	36,1	9,5	36,1	19,1	1455	2547	0,86
LSMV 132 M	7,5	49,1	13,0	49,1	25,7	1455	2547	0,85
LSMV 132 MU	9	58,7	15,6	58,7	33,7	1465	2561	0,8
LSMV 160 MR	11	71,4	19,1	71,4	39,2	1460	2554	0,83
LSMV 160 LUR	15	97,6	26,0	97,6	50,7	1466	2551	0,86
LSMV 180 M	18,5	120	32,0	120	65,1	1469	2556	0,82
LSMV 180 LUR	22	143	38,1	143	74,4	1470	2558	0,85

IV.6.2. Speed reducer

The purpose of the speed reducer is to change the speed ratio between the input and output of the transmission system. In our case, the rotation speed of the motor is 1469 rpm while the mill drum must rotate at a speed of 39 rpm, so it is necessary to reduce the speed of the motor to achieve the required speed of the drum.

The choice of reducer will depend on the reduction ratio between the motor and the drum, this ratio is calculated as follows:

Equation 6 : $$R = \frac{n_e}{n}$$

With motor speed n_e and drum speed n

NA: $$R = \frac{1469}{39}$$

$$R \approx 38$$

So, we need a reducer with a reduction ratio of 38 that will support the power of the engine. Based on the Bonfiglioli catalog below, we chose the VF 250_40 with a ratio of 40.

Table 9 : Characteristics of the VF 250_40 reducer[20].

18.5 kW									
n_2 min-1	M_2 Nm	S	i	R_{n2} N				IEC	
19.2	6717	0.9	50	50000	—	VF 250_50	P200	BN200LA6	166
24.0	5595	1.2	40	48700	—	VF 250_40	P200	BN200LA6	166
29.2	4598	1.0	50	47000	—	VF 250_50	P180	BN180M4	166
32	4472	1.2	30	45200	—	VF 250_30	P200	BN200LA6	166

IV.6.3. Choosing a Transmission System

The mill uses a gear system to transmit the rotational motion from the motor to the drum. A gear is a mechanism composed of two toothed wheels moving around axes of fixed position and one of which drives the other by the action of teeth successively in contact.

There are three categories of gears: parallel, concurrent and left gears.

Figure 15 : The different types of gear[21].

For our mill, we opted for straight-toothed parallel gears because of their simplicity of manufacture, low cost and power transmission efficiency.

IV.6.4. Method used for the selection of the guidance system

IV.6.4.1. The different guidance technologies

In the case of our ball mill, it is essential to guide the drum in rotation.

There are various technologies for guiding pivot link rotation as shown in the figure below.

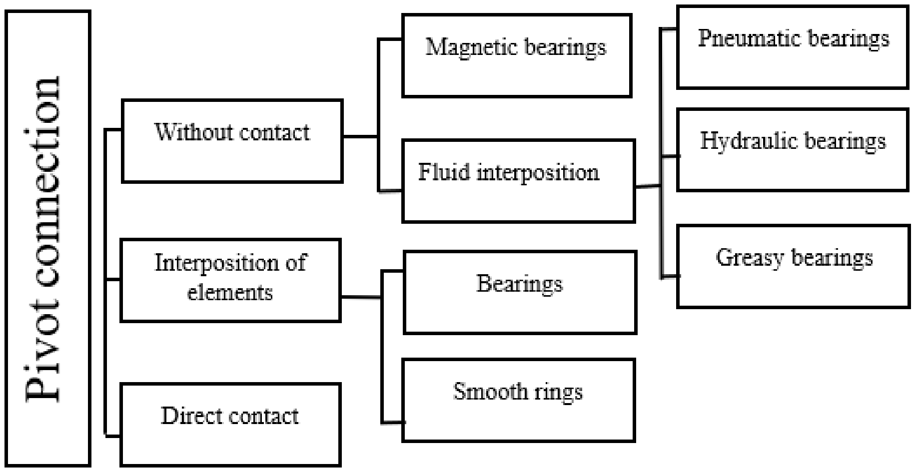


Figure 16 : Classification trees of the different pivot links.

Among these different technologies for guiding the rotation of pivot links, the solution most suited to our mill is the use of bearings.

In mechanics, a bearing is a device designed to guide a rotating assembly, that is, to allow one part to rotate relative to another along a defined axis of rotation. The bearing thus plays the role of a bearing.

IV.6.4.2. Choice of bearing

The choice of the type of bearings to be used depends on the specific technical requirements of each application, such as the required service life, the importance of the applied loads, the available space, the rotation speed. It is therefore essential to know the technical characteristics of each type of bearing to make an appropriate choice.

The figure below shows the types of loads supported by the different types of bearing.

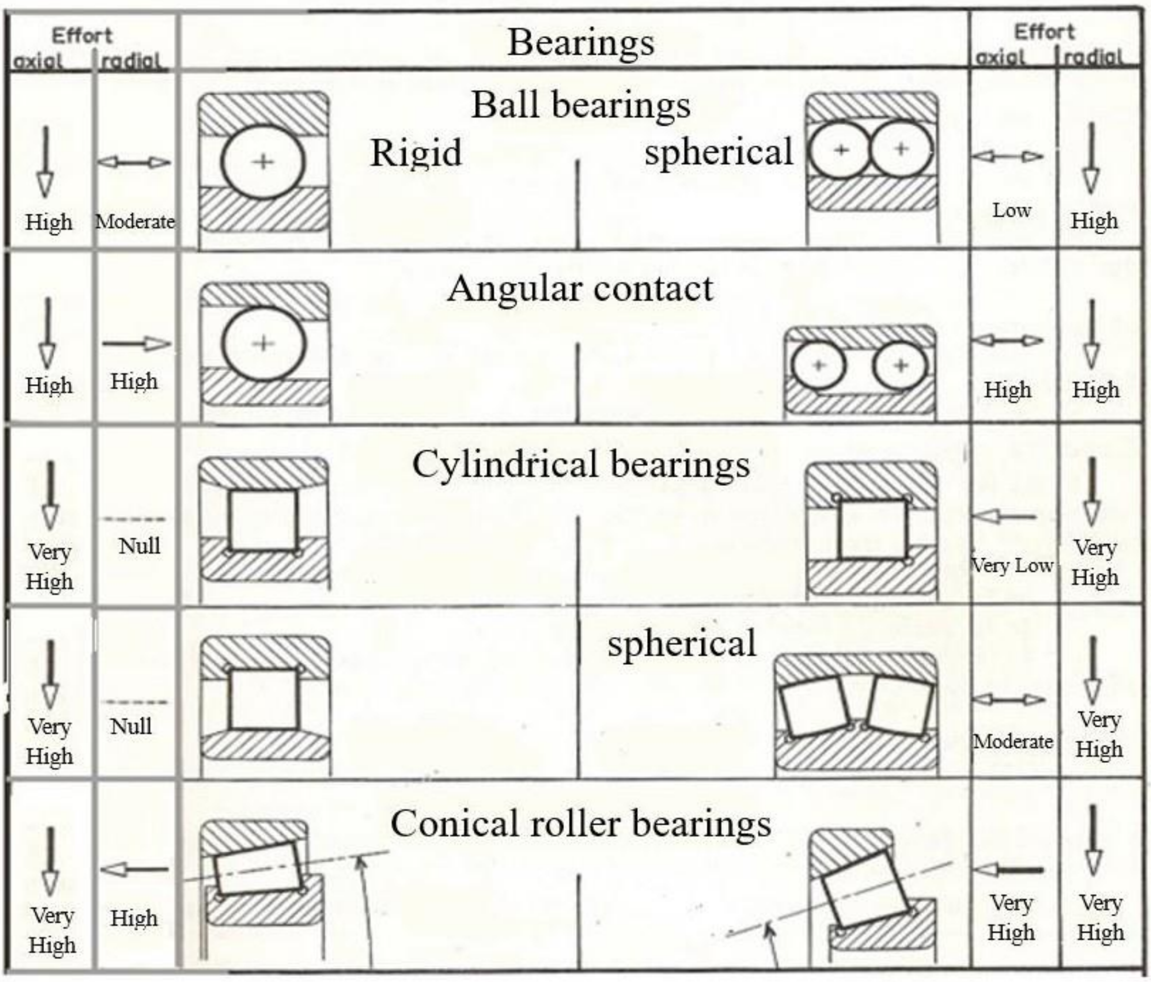


Figure 17 : The different types of bearing and their supported loads[22].

In the case of our mill, we opted for the use of spherical roller bearings. This choice is motivated by the exceptional capacity of these bearings to support high radial loads while accommodating potential misalignments, which is essential in the demanding and variable environments of artisanal mining sites.

Conclusion

This chapter has established the numerical values necessary for dimensioning the different elements of the mill. This prepares us to approach, in the next chapter, the design and simulation of the different parts of it.

Chapter V: Modeling and simulation

Introduction

After having dimensioned and calculated the main parts of the mill, it is now crucial to assign values to the results of the previous chapter and verify them through Computer Aided Design CAD and simulation. This gives this chapter its major importance in the whole project.

V.1. Definition of CAD

Computer Aided Design (CAD) is a set of software and hardware that allows the creation of a geometric representation of an object in order to simulate and virtually test its behavior before its actual manufacture.

V.2. Principle and use of CAD

CAD allows you to have a complete vision of the behavior of an object before its creation, both aesthetically and structurally and functionally. Objects can be modeled in two or three dimensions (2D or 3D), with a wireframe, volumetric or surface appearance, and even a texture simulation.

V.3. Advantages and disadvantages of CAD

V.3.1. The advantages of CAD

CAD has revolutionized product design by replacing traditional paper drawing with digital tools that offer unmatched accuracy and the ability to work in three dimensions. CAD software, based on vector images, eliminates errors associated with scaled drawings and allows designs to be modified without loss of accuracy. In addition, these tools facilitate the creation of realistic 3D models, allowing designers to visualize and explore products from different angles, improving the customer experience and simplifying the detection and correction of problems.

V.3.2. Disadvantages of CAD

Although computer-aided design (CAD) has brought many benefits to the design field, some remain skeptical about its overall impact. They argue that traditional paper drawing "remains a fundamental tool for accelerating visual problem solving." Hand sketching stimulates the designer’s creative thinking and helps him or her develop innovative solutions to the challenges he or she faces.

V.4. Software used

Industrial programs, such as SOLIDWORKS, CATIA, ABAQUS, ANSYS, are designed to solve complex problems involving thousands to hundreds of thousands of variables. These software programs offer many features, such as static and dynamic analysis, consideration of complex behavior laws, and processing of various phenomena (elasticity, thermal, etc.).
For our case we will use SolidWorks because of its robustness, its ability to model 3D objects with precision, as well as its advanced features to perform complex simulations and analyses, such as static and dynamic analysis, which are essential to optimize the design and operation of the ball mill.

V.5. Geometric modeling of the main components of the mill

Geometric modeling consists of representing the main components of the mill in 3D.

V.5.1. Geometric modeling of the drum

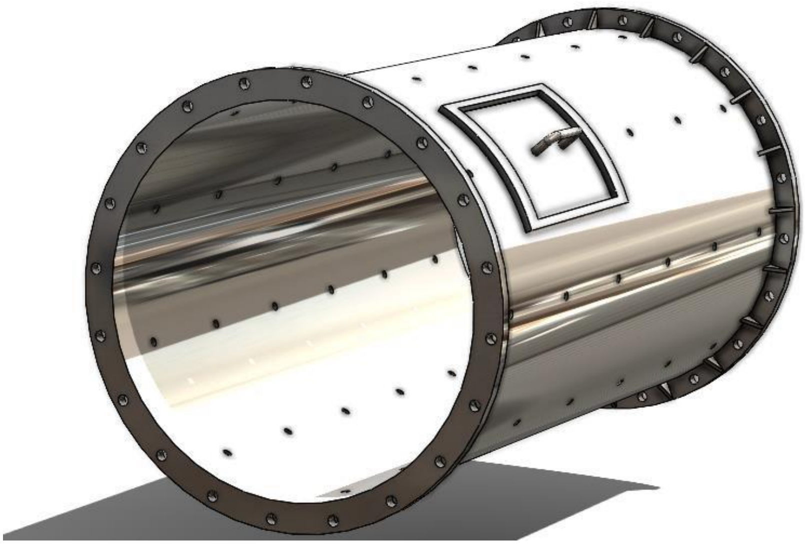


Figure 18 : 3D Model of mill Drum.

Figure 18 shows the 3D model of the mill drum, a key component of the mill. This drum is distinguished by its cylindrical structure made of alloy steel, with perforations all around, facilitating secure assembly with the side closures and armor plates. A rectangular opening is also integrated on the drum, providing convenient access for loading the balls and for maintenance operations.

V.5.2. Geometric modeling of side closures

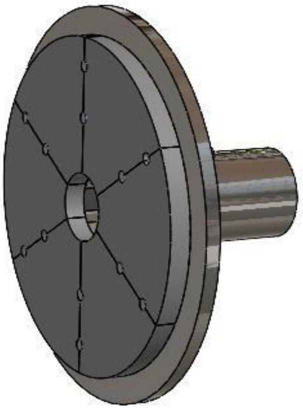


Figure 20 : 3D model Side closure drum entrance.

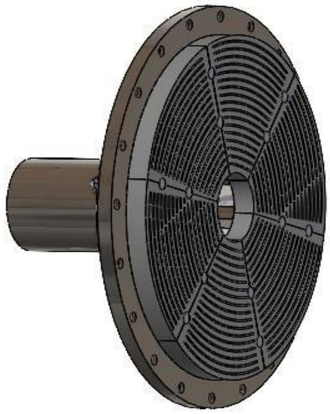


Figure 19 : 3D model Side closure Drum outlet.

Figure 19 shows the side closure located at the outlet of the ball mill. It shows circular shield plates with a grid pattern. This design helps control the particle size of the crushed ore exiting the drum while keeping the balls inside and protecting the drum. In the center of these shield plates, there is a circular opening that serves as an outlet to evacuate the finely ground ore out of the drum.

Figure 20 shows the side closure located at the entrance of the ball mill drum. There we can see circular shielding plates that serve to contain the balls inside the drum and also to protect the drum. In the center of these plates, we can see a circular opening that allows the introduction of the ore to be ground into the drum.

V.5.3. Geometric modeling of the internal liner

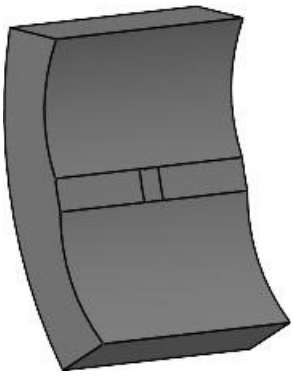


Figure 21 : 3D model of the inner drum liner.

Figure 21 shows the inner liner of the ball mill, it shows a structure with a curved shape and a hole for its attachment to the drum. This plate has the role of protecting the inside of the drum from wear and damage caused by the movement of the balls.

V.5.4. Geometric modeling of balls

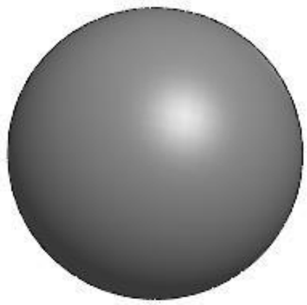


Figure 22 : 3D model of the balls.

Being the grinding body of the mill, they play an essential role in the grinding process. Their movement in the rotating drum of the mill allows the introduced ore to be reduced to powder. The spherical shape optimizes their movement and impact for maximum grinding efficiency.

V.5.5. Geometric modeling of the Ball Mill

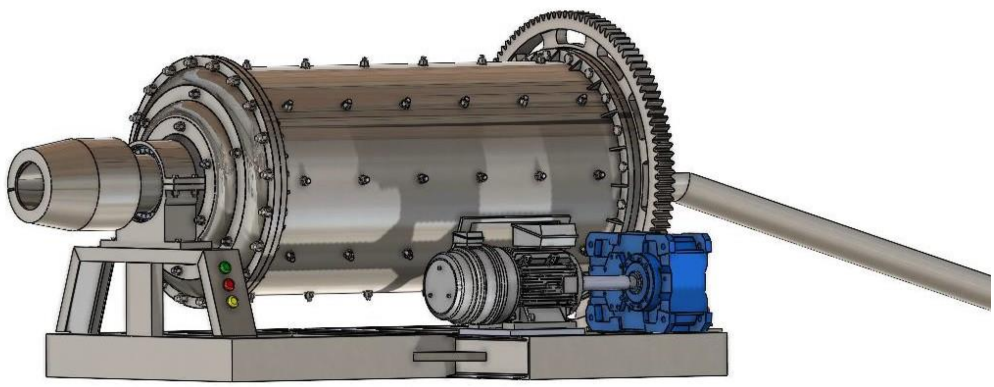


Figure 23 : Ball Mill Overview.

Figure 23 provides a clear and precise overview of our ball mill, highlighting the components and their arrangement.

V.6. Numerical modeling of the elements stressed in the mill structure

Numerical modeling (simulation) of the main components of the ball mill allows us to simulate their behavior under various conditions. This approach provides us with a detailed analysis of the stresses and deformations of the components. In the context of this numerical modeling, we will use the finite element method (FEM).

V.6.1. Finite element method (FEM)

The finite element method (FEM) is a numerical analysis technique used to solve partial differential equations that describe the behavior of complex physical systems, such as mechanical structures, fluid flows, or thermodynamic phenomena. This method consists of decomposing a model into a mesh made up of small elements where mathematical operations are applied to precisely simulate the stresses, strains, and other dynamic behaviors of the system under various loading conditions. The FEM thus makes it possible to numerically model complex objects while guaranteeing a solution faithful to real physical phenomena, provided that these objects are continuous and described by linear equations.

V.6.2. Meshing

The finite element method is based on the division of space into a mesh, the mesh consists of dividing a complex domain into a set of small regions called elements, which form a network or "mesh". This mesh serves as a basis for the analysis, allowing to solve the equations that describe the physical behavior of the system. The quality and density of the mesh directly influences the accuracy of the results: a finer mesh adapted to critical areas allows to obtain more precise solutions and close to reality.

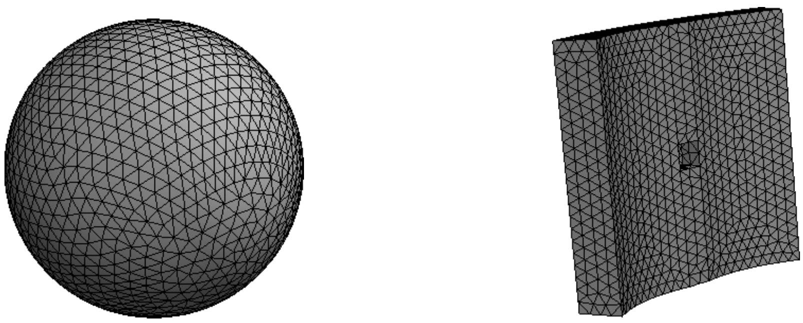


Figure 24 : Mesh of the ball and the inner liner.

V.6.3. Von Mises constraints

In the context of simulating the components of the ball mill designed using SolidWorks, the use of Von Mises stress was essential for accurately predicting the mechanical behavior of materials subjected to complex loads, such as compression, torsion, and bending. This criterion, used to assess the strength of isotropic materials like metals, helps predict plastic deformation or failure under multiaxial stresses. It is based on the idea that a ductile material begins to yield when the Von Mises stress reaches a critical threshold, typically set at the yield strength[23]. This ensures that the components do not exceed this threshold under expected loads, thereby guaranteeing their durability and reliability in operation.

V.6.4. Drum simulation

Boundaries Conditions

Material	Study type	Constraint type	Charge applied	Min	Max
16NiCr4	Static	Von mises	2 Tons	4.973e-11 (Pa)	1.159e+04 (Pa)

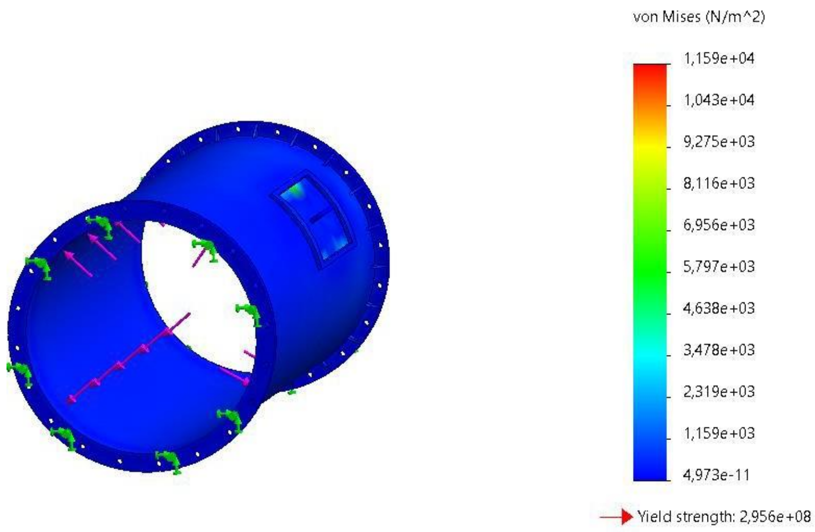


Figure 25 : Drum deformation graph.

Figure 25 shows the results of the finite element simulation applied to the ball mill drum. The drum appears entirely in blue, which corresponds to a Von Mises stress range from 4.973e-11 (Pa) to 3.478e+03 (Pa), well below the material yield stress of 2.956e+08 (Pa). This uniform stress distribution demonstrates that the drum, under the simulated loading conditions of 2 tons, is designed to withstand the applied forces without risk of permanent deformation.

V.6.5. Inner liner simulation

Boundaries Conditions

Material	Study type	Constraint type	Charge applied	Min	Max
X120Mn12	Static	Von mises	800 Kg on 1 liner	3.364e+03 (Pa)	2.429e+04 (Pa)

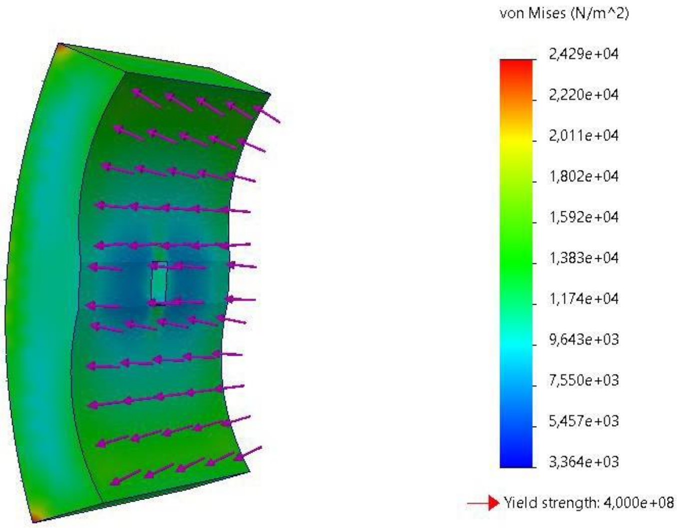


Figure 26 : Inner liner deformation graph.

The figure 26 shows that most areas of the liner are colored green and blue, indicating stresses between 3.364e+03 Pa and 1.802e+04 Pa. These values are well below the yield stress of the material, which is set at 4.000e+08 Pa, as indicated by the red arrow on the scale. This relatively homogeneous and low stress distribution suggests that the liner is well designed to withstand the applied forces without exceeding the yield stress.

V.6.6. mill Frame Simulation

Boundaries Conditions

Material	Study type	Constraint type	Charge applied	Min	Max
16NiCr4	Static	Von mises	5 Tons	3.369 (Pa)	7.492e+08 (Pa)

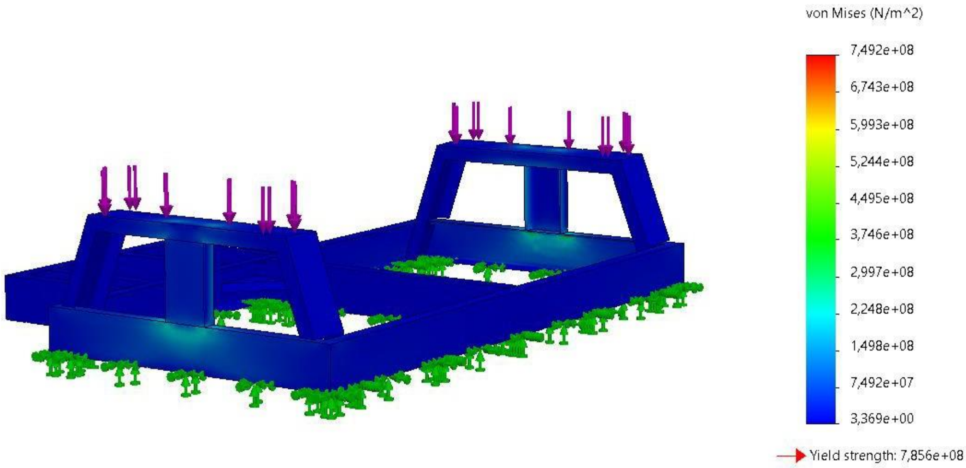


Figure 27 : Frame Deformation Graph.

The simulation results in Figure 27 show the von Mises stress distribution on the ball mill support under a simulated load of 5 tons. The highest stress regions, shown in orange and red, reach about 7.492e+08 Pa. Although some regions are subjected to high stresses, these remain slightly below the elastic limit of the material, suggesting that the support, under the specific conditions, can support the applied load without undergoing plastic deformation.

Conclusion

This chapter validated the design and verified the performance of critical components under various loading conditions. The results show that stresses and strains remain well below the elastic limits of the materials used, indicating sufficient structural robustness for the intended applications.

GENERAL CONCLUSION

This thesis focused on the study and design of a ball mill for artisanal mines. The literature review revealed that local ores require the use of mills with suitable technologies. This research also made it possible to compare the different existing grinding technologies and to conclude that the ball mill is the most appropriate solution for this context, due to its ability to ensure efficient grinding. The design of this mill was therefore focused on the optimization of essential variables such as rotation speed, filling level, dimensions and materials used, in order to improve performance and grinding. Thus, the objectives set were achieved and the research hypotheses validated.

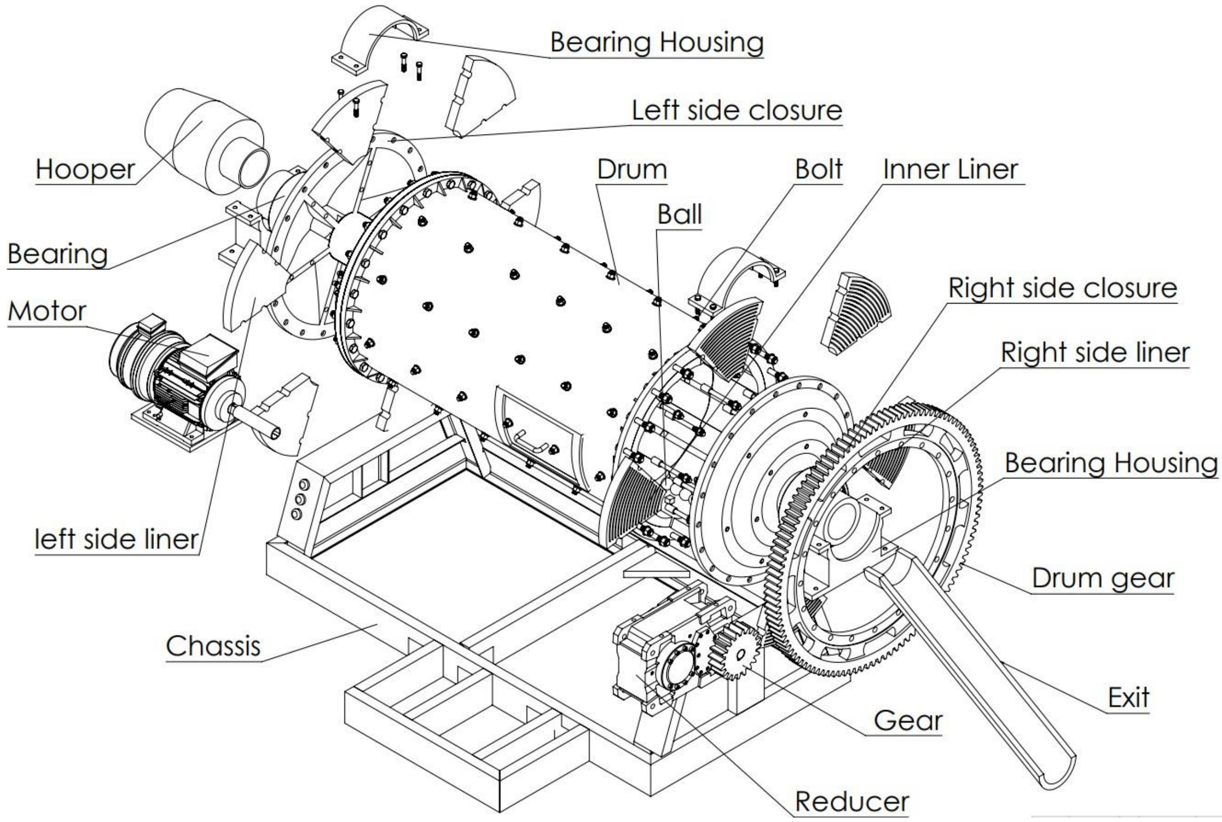
Despite this advancement, the current design of the mill can be improved and optimized. One area of improvement that we have identified is to automate the crushing process by integrating advanced technologies, such as installing sensors to monitor key parameters such as drum rotation speed, filling level, flow rate and particle size in order to maximize crushing efficiency and increase the productivity of artisanal mines.

ANNEXES

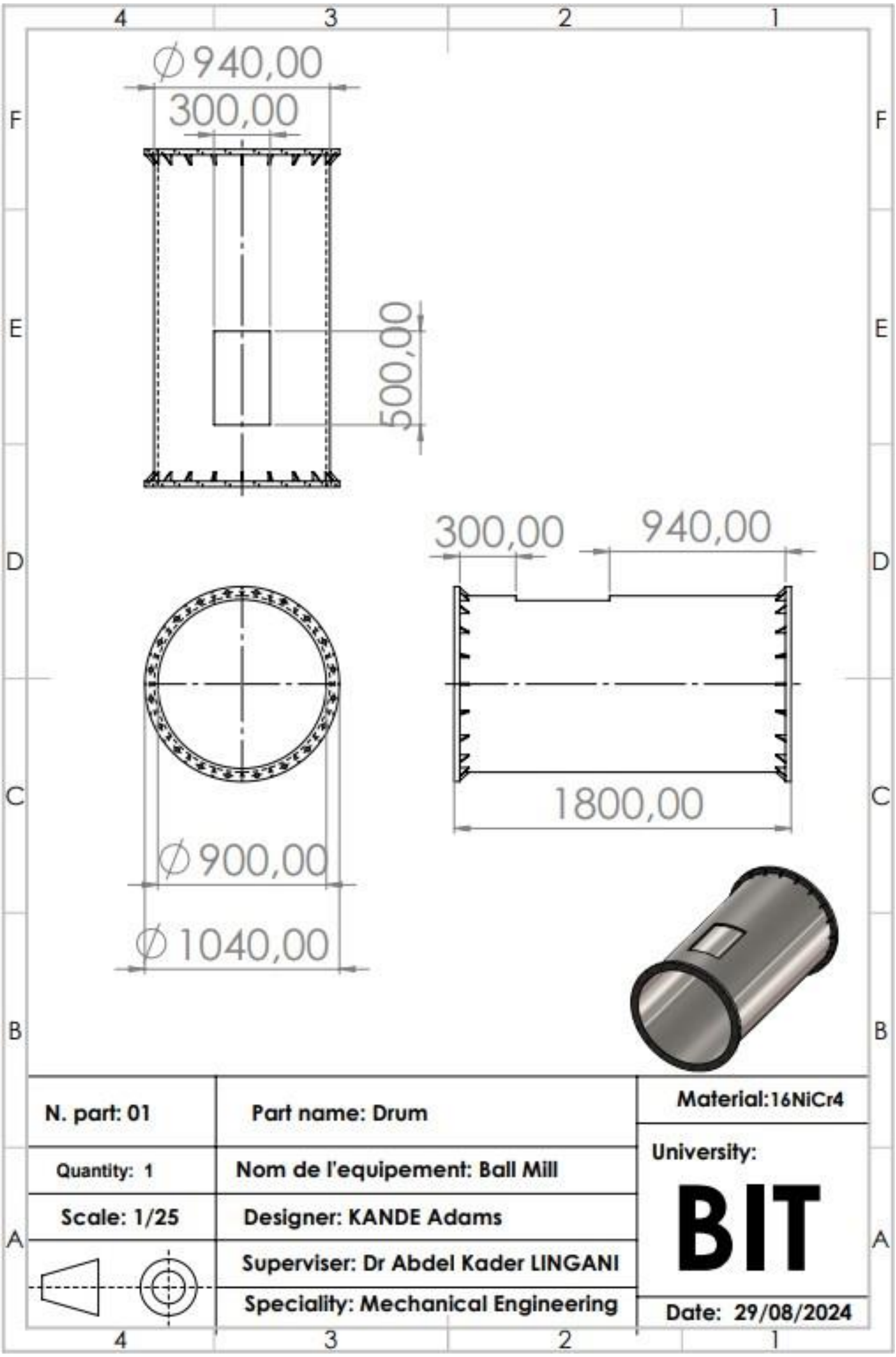
Annex 1: Physical properties of 16NiCr4 and X120Mn12 steels.

Properties	**16NiCr4**	**X120Mn12**
Steel type	Low alloy steel for carburizing	High manganese steel
Composition	0.12-0.18% C, 0.4% Mn, 0.4% Cr, 1.6% Ni	11-14% Mn, 0.8-1.2% C
Density	About 7.8 g/cm³	About 7.8 g/cm³
Elastic limit	Up to about 1000 MPa after carburizing	800-1000 MPa (depends on hardening)
Hardness	600-700 HV after carburizing and quenching	200-250 HB at initial state, can increase significantly under stress
Elastic limit	Typically, between 350 and 550 MPa, depending on the heat treatment applied (e.g. after carburizing and quenching).	In general, the yield strength of this steel is relatively low in the initial state, around 300 MPa, but it increases considerably under repeated mechanical stresses or impacts, due to its hardening by work hardening.
Typical usage	Gears, shafts, cemented components	mills, shields, wear parts
Wear resistance	Moderate, increased after cementation	Very high thanks to work hardening

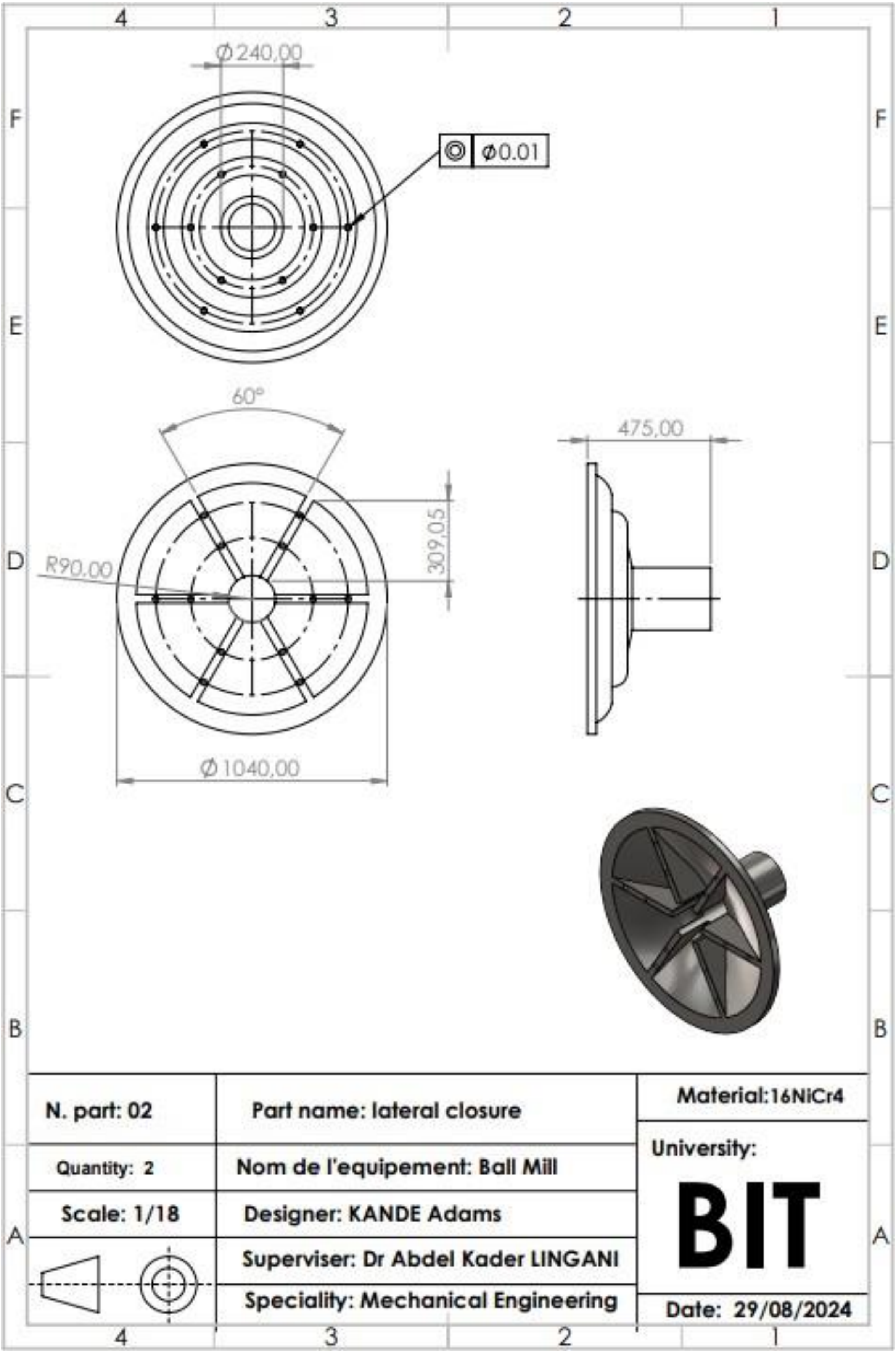
Annex 2: Ball mill layout.



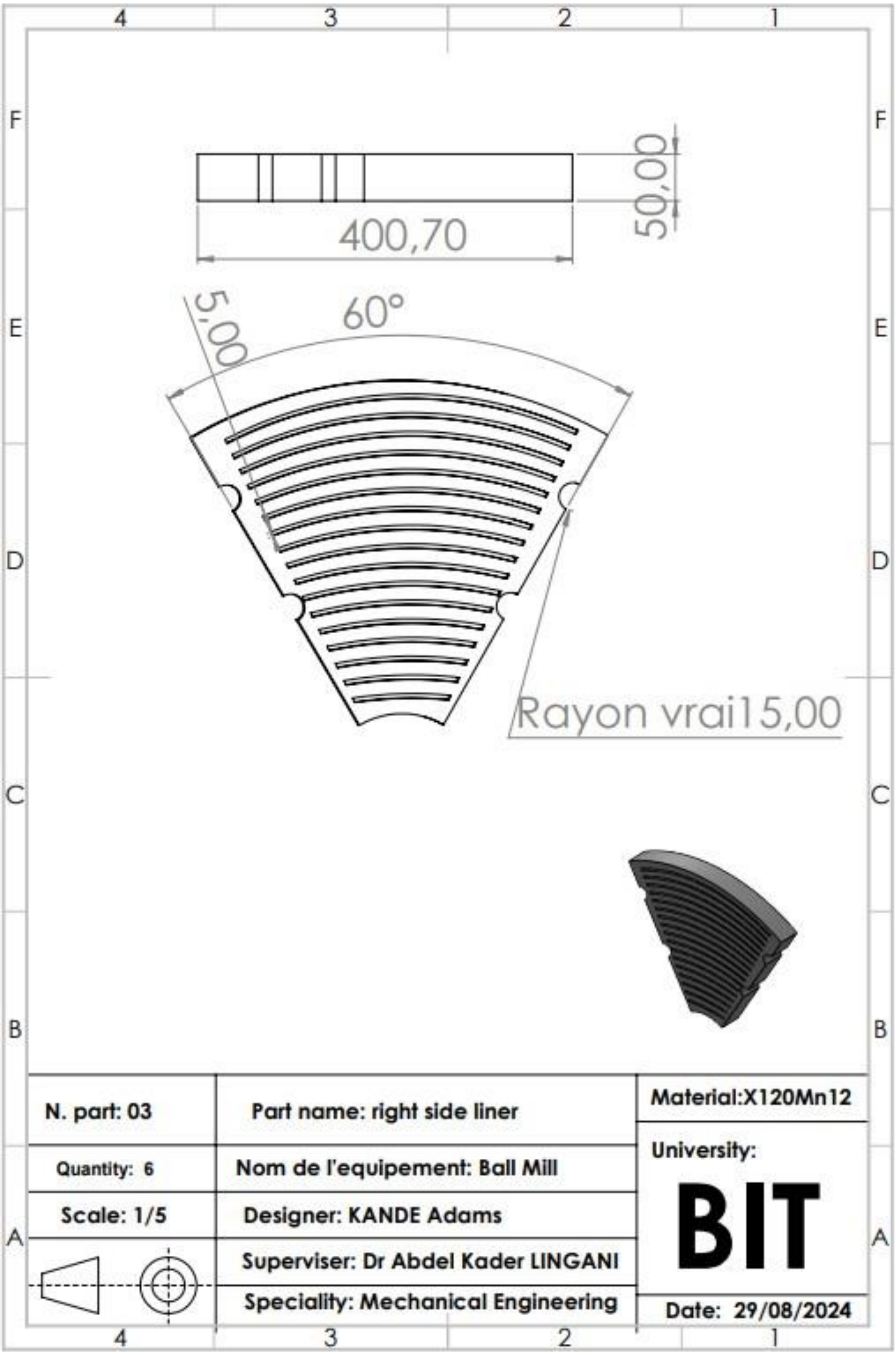
Annex 3: Drum layout.



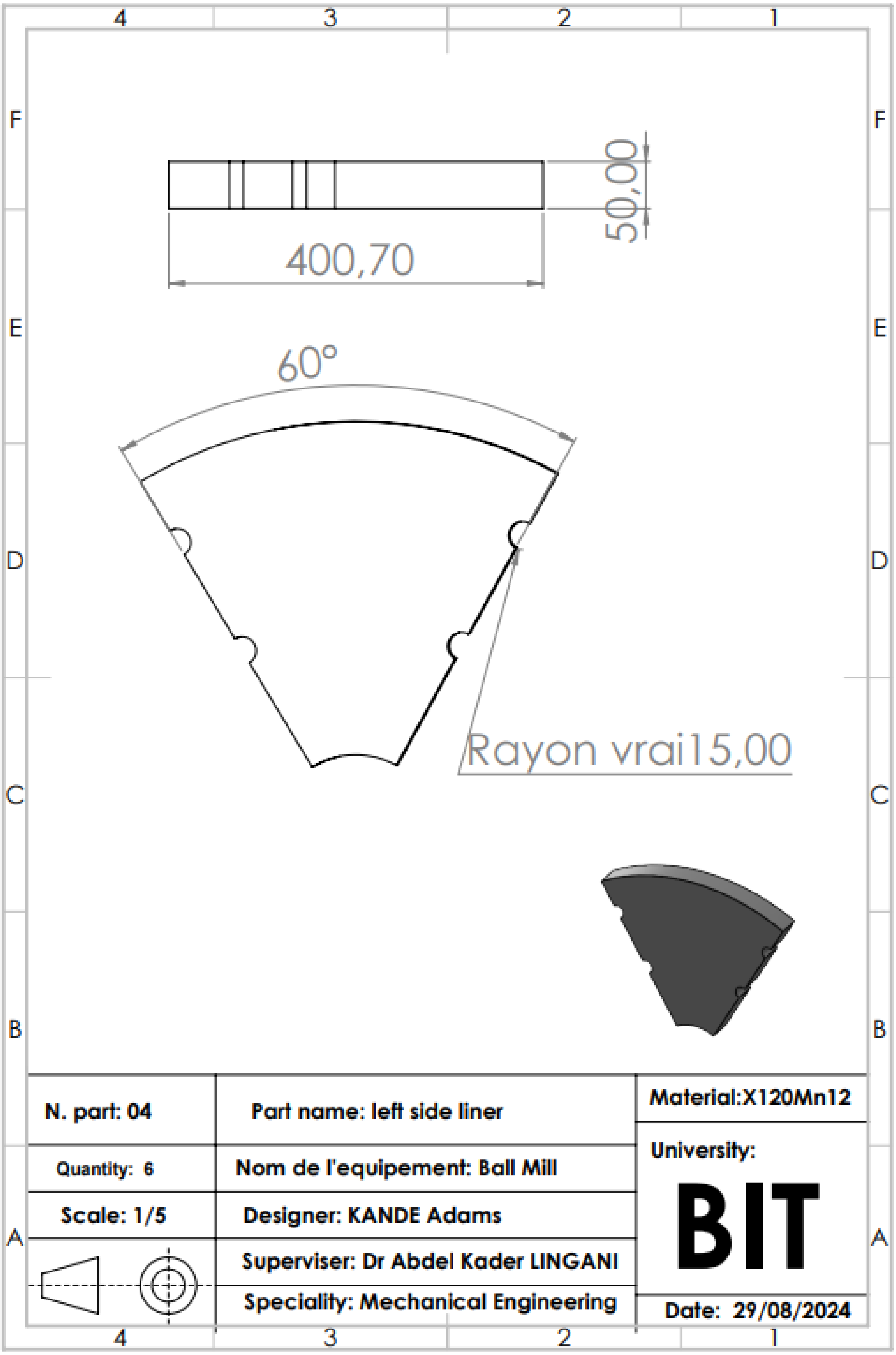
Annex 4: Side closure layout.



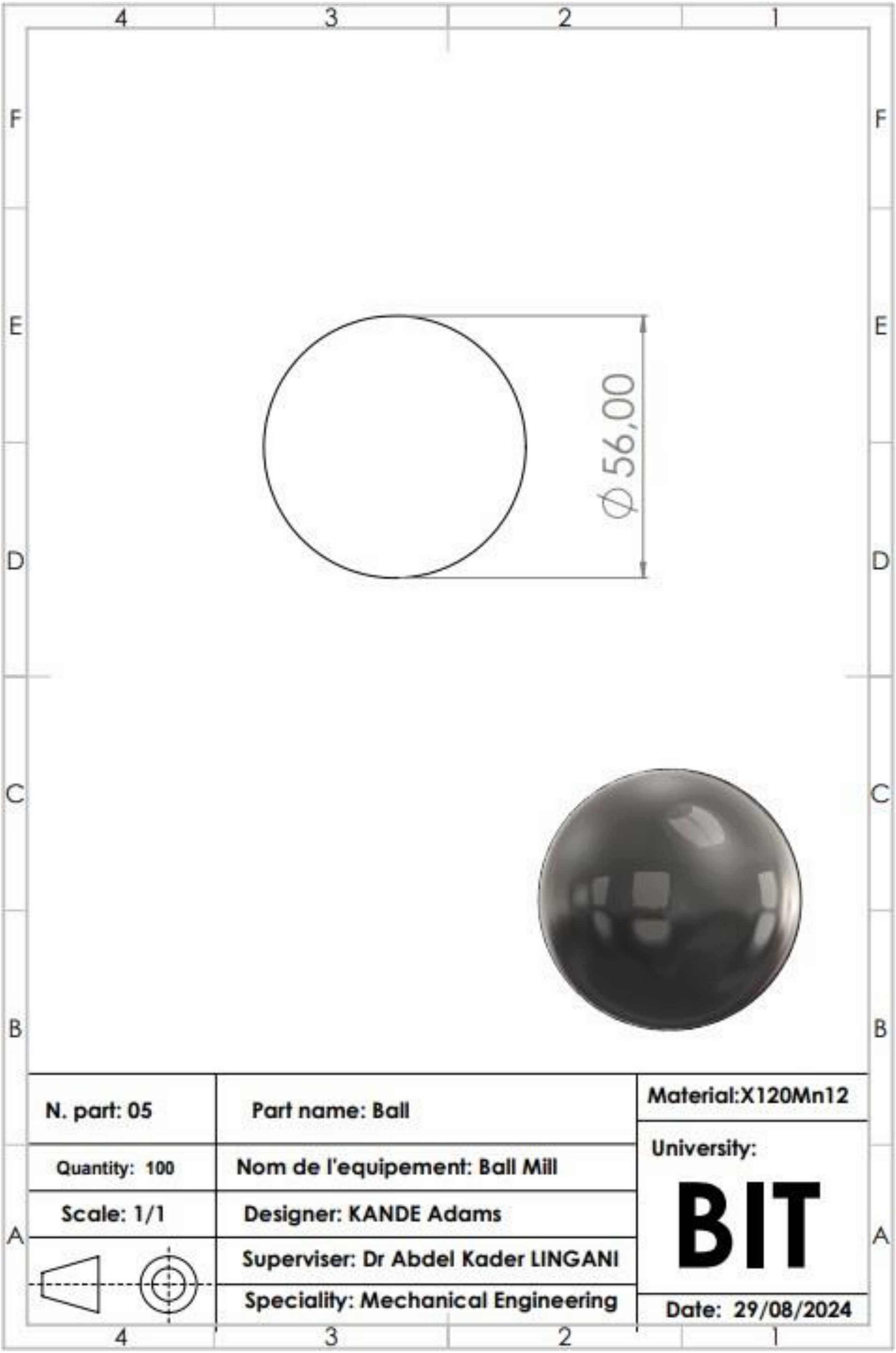
Annex 5: Right side liner.



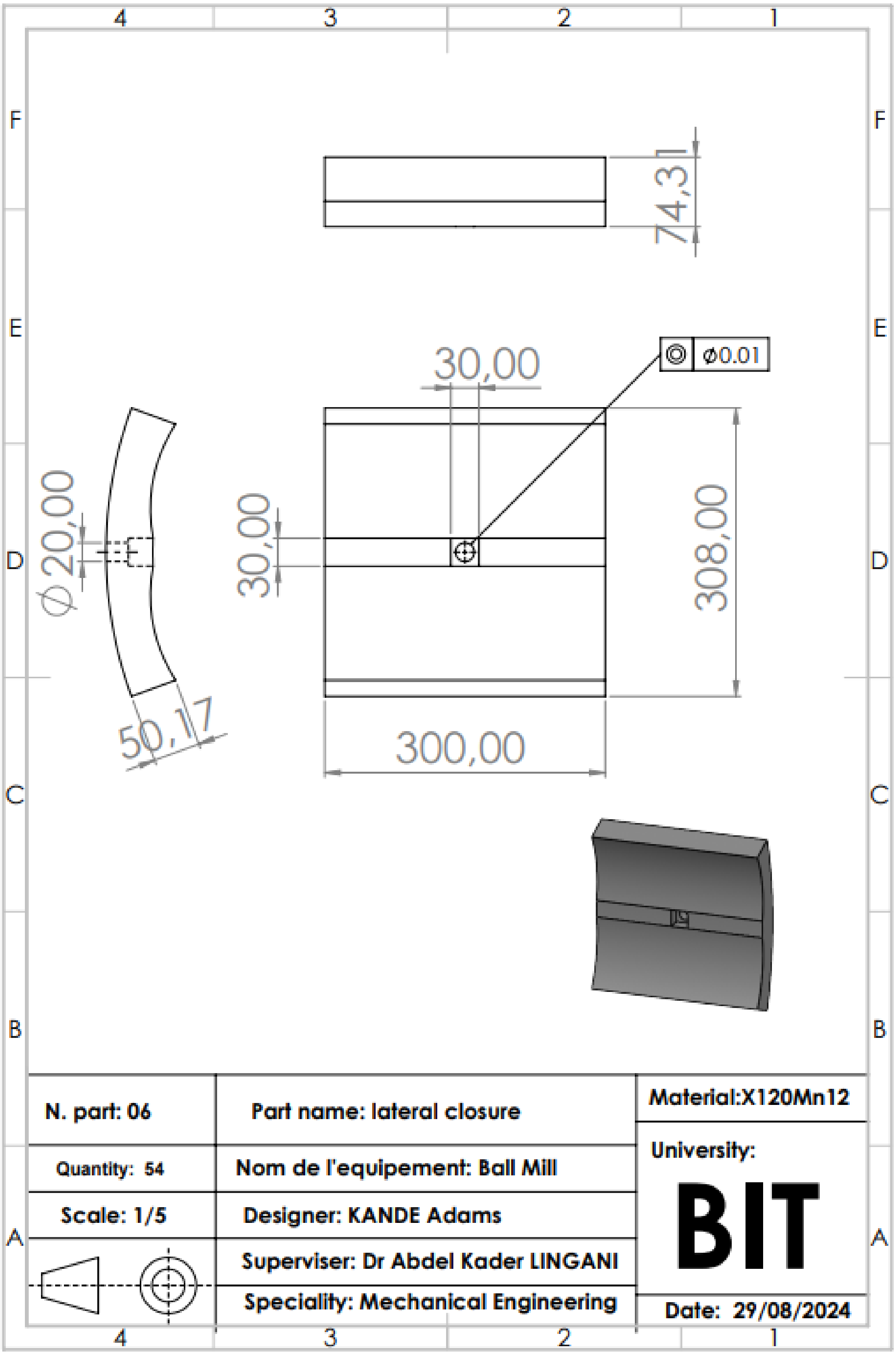
Annex 6: left side liner.



Annex 7: Drawing of the ball.



Annex 8: Internal liner layout.



BIBLIOGRAPHY

[1] "G00718.pdf". Accessed: May 7, 2024. [Online]. Available: https://www.iied.org/sites/default/files/pdfs/migrate/G00718.pdf

[2] "Burkina Faso: Over 600 artisanal gold mining sites identified in the country". Accessed: May 7, 2024. [Online]. Available: https://www.aa.com.tr/en/africa/burkina-faso-over-600-artisanal-gold-mining-sites-identified-in-the-country/2944980

[3] "Grinding," Wikipedia, June 25, 2020. Accessed: May 20, 2024. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Grinding&oldid=172322760

[4] "CD162.pdf". Accessed: May 24, 2024. [Online]. Available: https://ir.nmu.org.ua/bitstream/handle/123456789/161491/CD162.pdf?sequence=1

[5] "Fragmentation Course - Modes of Fragmentation". Accessed: October 5, 2024. [Online]. Available: https://www.azprocede.fr/Cours_GC/fragmentation_modes.html

[6] A. Chamayou and J. Fages, "Grinding in the agri-food industries," in *Powder Technology in the Food Industries*, J.-P. M. & J.-L. Ilari, Eds., in *Agri-Food Science & Technology*. Lavoisier, 2003, pp. 375–406. Accessed: June 17, 2024. [Online]. Available: https://hal.science/hal-00442390

[7] Abdoulaye OUEDRAOGO, "Geology and Mining Exploitation Course", Burkina Institute of Technology.

[8] Faculties: Engineering Sciences, Department: Mechanical Engineering, Domain: Sciences and Techniques, Field: Mechanical Engineering, Specialization: Mechanical Construction.

[9] D. O. H. Malek and B. Abdenacer, "Study of the Bond Index of a Ball Mill. Practical Approach".

[10] "PMM_KB.pdf". Accessed: May 27, 2024. [Online]. Available: https://www.univ-usto.dz/images/coursenligne/PMM_KB.pdf

[11] "Figure 9. Diagram of a Hammer Mill These devices cover a wide range...", ResearchGate. Accessed: October 5, 2024. [Online]. Available: https://www.researchgate.net/figure/Schema-dun-broyeur-a-marteaux-Ces-appareils-couvrent-un-large-domaine-de-distributions_fig5_280755839

[12] "Grinding Mill with Rotating Disc | Hosokawa Micron". Accessed: May 27, 2024. [Online]. Available: https://www.hosokawamicron.fr/technologies-traitement/broyage-compactage/broyeurs-selecteurs/broyeur-meules-awm.html

[13] L. Gendron, "Pulverizer-Grinders," *Practical Industrial Mechanics*, vol. 23, no. 5, pp.

99–103, February 1941, doi: 10.1051/mattech/194123050099.

[14] "CD162.pdf". Accessed: May 25, 2024. [Online]. Available: https://ir.nmu.org.ua/bitstream/handle/123456789/161491/CD162.pdf?sequence=1

[15] "Semi-autogenous (SAG) Mill for Sale, Sag Mining | CIC", Citic Ic Luoyang Heavy Machinery Co., Ltd. Accessed: June 3, 2024. [Online]. Available: https://fr.cicemech.com/products/sag-mill/

[16] "Structure and Pros and Cons of Dry and Wet Autogenous Mills". Accessed: October 5, 2024. [Online]. Available: https://www.xinhaimining.com.cn/news_14_1266.html

[17] "7198-analysis-of-need-ensps.pdf". Accessed: July 17, 2024. [Online]. Available: https://eduscol.education.fr/sti/sites/eduscol.education.fr.sti/files/ressources/pedagogiques/7198/7198-analysis-of-need-ensps.pdf

[18] "Calculate Ball Mill Grinding Capacity". Accessed: August 2, 2024. [Online]. Available: https://www.911metallurgist.com/blog/calculate-ball-mill-grinding-capacity

[19] "4981_fr.pdf". Accessed: October 5, 2024. [Online]. Available: https://www.leroy-somer.com/documentation_pdf/4981_fr.pdf

[20] "Product Catalogue: Right-Angle Gearmotors - Units VF-W ATEX". Accessed: October 5, 2024. [Online]. Available: https://www.bonfiglioli.com/international/usefulDocuments/product-catalogue_right-angle-gearmotors---units_vf-w_atex_eng_r00_2.pdf

[21] "Power Transformation - Google Drive". Accessed: October 5, 2024. [Online]. Available: https://drive.google.com/drive/folders/1SkvLDUhI3x8eWfgFwBVHXzg_BXcShC9G

[22] E. de D. Techniques, "Choosing a Ball Bearing | Technical Files". Accessed: October 5, 2024. [Online]. Available: https://www.dossiers-techniques.fr/mecanique/choisir-un-roulement-a-billes.html

[23] "2021 SolidWorks - von Mises Stress Criterion". Accessed: October 14, 2024. [Online]. Available: https://help.solidworks.com/2021/english/SolidWorks/cworks/r_maximum_von_mises_stress_criterion.htm