Gamification for technology enhanced mineral value chain teaching and learning: serious gaming for geometallurgy concept

Lilian Schleret

Master Programme in Georesources Engineering
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Luleå University of Technology
Department of Civil, Environmental and Natural Resources Engineering
Abstract

The concept of gamification is being increasingly explored and applied to offer new teaching or training tools to teachers, students or employees. The field of geology and geometallurgy wasn’t particularly discussed in the topic of gamification. With the objective of creating a synthetic geometallurgical database and a game structure for a gamified simulation of a metal mine, the eastern part of the Malmberget deposit in Sweden was simplified and modelled. The geological model was obtained with assumptions of continuity and proximity, and the lack of data was reconciled using targeted randomization and regular statistics to achieve a smoother and realistic result.

A rule book was created to establish the framework that a geometallurgy game should follow, using a slightly adapted version of the Desing thinking framework by the Nielsen group, which consists of elaborating ideas and concepts, implementing them and testing the results before integrating feedbacks to the creation of future elements. The accent was put on obtaining an interactive experience where the player can try various things with a reasonable difficulty, and an accessibility to feedbacks.

The purpose of this project is to elaborate a mining simulation game, that could be a valuable tool in the understanding of the interdisciplinary concept of geometallurgy, as well as raising the awareness about sustainable development and how mining can be a part of it. The starting point of this project is another attempt at gamifying geometallurgy by P. Lamberg.

The simulation of mineral processing was done using the HSC Sim utilizing 8 different flowsheets that were designed to offer a variety and enable strategic choices. The events occurring at a real mine and beneficiation plant were translated into simple rules. The outcome is a realistic geological and processing model, which through the addition of mining, economics and market strategy, becomes a comprehensive geometallurgy database.

Keywords: Gamification, Malmberget, Geometallurgy, Synthetic model.
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I - Introduction

Universities and schools are always looking for more optimized and more adapted tools for teaching purposes. Social evolutions influence the students which requires evolving teaching methods. The teachers themselves also change through time and are influenced by the same parameters as well as political decisions. The development of advanced technologies enables new approaches and higher education requires to keep students motivated and involved. As a result, a learning method using gamification appears to be a good and innovative solution.

Gamification can be defined as the action of adapting the principles of a real activity into one that provides positive experiences, training, and rewarding mechanics like serious games. Gamification can be either intentional, for example when a studio aims to develop a simulation, or emergent, when referring to a cultural and social evolution linked to the growing importance of games. The positive outcome of using gamification in teaching can improve participation, time on teaching task and motivation. Gamification appeared beneficial in 26% of studied cases, while 64% of the other cases were inconclusive: to be efficient, the gamified subject should be properly adapted to the target and their specific learning objectives. (J. Hamari, 2019; C. Dichev, D. Dicheva, 2017)

Examples of gamification for learning include Minecraft (E. Rader et al., 2021) or Challenges of Geometallurgy (P. Lamberg, 2018). In particular, Challenges of Geometallurgy was developed by P. Lamberg for Luleå University of Technology to apply geometallurgical concepts for mineral processing students. The geological model of the game consists of a flat and square area of 100 cells, each containing a specific mineral composition, chemical composition and other processing related properties. The game consists of mining this area to extract the iron ore, and integrates the basic notions of transport, costs of mining and processing time. The groups of students have to make process mineralogical analyses of the area, elaborate a model, and take important decisions, such as their economic strategy. Eventually, the students could access economic analyses of their decisions, and write a report in order to properly explain their decisions and assess their efficiency.

This game has several beneficial aspects: It is rather concise, and the groups of students can analyze, decide on a production strategy, and mine according to their plans within a few hours. The game contains several elements that are element of decisions, such as the possibility to obtain a precise composition for most minerals. It was also technically simple, and even if a few bugs were detected, it proved successful and efficient.

The game implied a few limitations:
- The area is only 2-dimensional, involving on layer of 100 cells;
- There are only two potential processing lines that the player can use;
- Some mechanics are underused;
- There is not much importance in mine-organization;
- The player cannot decide on the mining or the transport methods.
As a result, the idea of a more complex game with similar game idea but with a larger area and the possibility to mine in a 3D environment emerged.

The topic of geometallurgy, or mining in general, is not often present in regular games and serious games. Most games or mining simulations are focused on the miner as a worker, i.e. at an individual scale instead of a company scale. As a result, the potential uses of these games in teaching high-level geometallurgy are reduced.

In order to provide an efficient geometallurgy learning tool for students who specialize in mineral processing, a simplified geological database is required. The main objective of this project is therefore to provide a realistic geometallurgical database using simplified parameters and available data. The selected inspiration for the developed database is the iron ore deposit in Malmberget, Northern Sweden. The second objective is to provide a conceptual framework for the development of the game by the software company EcoSim (based in Budapest, Hungary), in charge of programming and implementing the final game. This framework should explain the mechanics of a mining and geometallurgy game.

The following questions have been formulated from these objectives:

- How can a realistic and functional geometallurgy database be generated using a limited amount of initial parameters and simplified process models?
- Which mechanics can be used to adapt mining operations in a game?
II - Literature review

II.1 Gamification - definition and efficiency

II.1.1 Principles and related works

The term “gamification”, which methodology consists in the application of game-concepts in serious situations, was first used as a methodology in 2002, and started to spread after 2010 (E. Villegas et al., 2019). This term can be related to two different phenomena (J. Hamari, 2019):

- Intentional gamification, where an activity, product or service is transformed by the addition of game-related mechanics for interactivity or entertainment purposes;
- Emergent gamification, which is a social and cultural transformation induced by the engagement with games.

In this study, the term “gamification” will be used to refer to intentional gamification. The interest around gamification grew after 2010, with a noticeable increase in the number of academic papers released on this topic every year (Figure 1) (J. Hamari, J. Koivisto, H. Sarsa, 2014). Gamification has been more recently integrated in enterprises too with various results (C. Busch, 2014). The recent impact of the CoVid-19 that forced online teaching is, for example, likely to cause an increased interest on the topic of gamification (P.A.S. Bergamo et al., 2022).

![Figure 1: Evolution of academic papers per year on Gamification between 2011 and 2022.](image)

Most academic papers released on Gamification (Figure 2) are focused on the topics of Computer science (33.1%), Social sciences (23.7% with the addition of Management and Decision Science), and Engineering (13.3%). Gamification can be beneficial for teaching at schools but also at higher education institutions and for management education. The game
Monopoly was the first game used in higher education as a teaching tool (R. J. R. da Silva, R. G. Rodrigues, Leal, C. T. P., 2019).

Gamification revolves around three main components, referred to as MDA (E. Villegas et al., 2019):

- Mechanics, i.e. the rules defining the studied system;
- Dynamics, i.e. the relation between the users and the system;
- Aesthetics, i.e. the perception of the system by the users.

The most important aspect of gamification is that it relates to “game” and not to “play”, where play refers to an activity designed mostly for entertainment, and game refers to an activity organized by rules where the user must fulfil an objective. Most critics expressed towards gamified applications state that the game aspect is too developed while the play aspect, like offering some liberties to the users, is less integrated. A balance between these two aspects could enable a better efficiency of gamification. (S. Deterding, 2014)

Gamification applied to simulation software could become a major aspect of teaching, insofar as computers are widely used in various fields of study. For example, when asked how often they integrate computer technology into their teaching activities, teachers in Information and Communication Technologies answered at 38% “Often”, at 6% “Almost always” and at 31% “All the time”. When the same teachers had to tell their preferred teaching methodology, 58% of them answered a more learner-oriented methodology. (A. Ktona et al., 2019)
An example of the application of a gamified geology system is the use of the videogame “Minecraft”, which contains several simplified geological structures. The efficiency of a serious use of Minecraft proved useful and raised interest for mining, which is a particularly positive outcome insofar as earth sciences are usually disregarded by younger students (E. Rader et al., 2021; J.P. Betzner, E.A. Marek, 2014). The developed countries also usually show hostility towards the mining industry, mostly for social and environmental concerns. The project Montagne D’or in French Guyana was indeed drastically slowed down after protests against the use of cyanides near a natural and protected area (A. Orsini, 2019). Developing the sense of responsibility and awareness of future engineers towards current and future concerns as well as highlighting the effort of the industry to these issues can be done by several ways, and gamification could be one of them.

II.1.2 Efficiency and systematic reviews

The gamification approach is subject to critics regarding its efficiency. Indeed, even if positive outcome can be observed mostly regarding engagement and motivation, most studies (64%) trying to distinguish these benefits are inconclusive (C. Dichev, D. Dicheva, 2017). This phenomenon can partially be explained by the fact that most studies focused on gamification outcomes rely on qualitative results (J. Hamari, J. Koivisto, H. Sarsa, 2014). It results in several studies not being repeatable, and another critic towards gamification is that the theories and psychologic principles are not often analyzed, resulting in numerous potential explanations without a scientific consensus. At least 106 concepts exist to explain the gamification principles, with 21 of them being more common and spread between Affect, Learning and Behavior related models (Figure 3) (J. Krath, L. Schürmann, H. F. O. von Korflesch, 2021). The application of gamification often lacks a methodological and technical support (F. Garcia et al., 2017).

A systematic review on several studies on gamification highlight the most important aspects that explain the results of gamified systems: clear and illustrated goals for the users through the use of score systems, guided paths to goal-oriented tasks, immediate feedbacks to improve performance, and simplified contents in order to make the tasks appear manageable. The users can decide whether they want to follow a regular path or impose themselves a personal goal in order to be able to adapt to the various tasks by themselves. (J. Krath, L. Schürmann, H. F. O. von Korflesch, 2021)
II.1.3 Previously established frameworks for gamification

The keys for a successful gamification were studied and several frameworks exist. The one proposed by Andrej Marczewski involves three definitions (Figure 4): First the problem, the users and the objectives should be precisely defined. The system then revolves around three phases that are Discovery, Design and Redefine. The first phase consists in explaining the aims to the user, the second phase consists in integrating the possible motivations and game mechanics into the session, and the last phase involves giving feedbacks to the player in order to offer ways of improvements. (E. Villegas et al., 2019)
The gamification model canvas developed by Sergio Jiménez is less centered on the user, though it is an important parameter (E. Villegas et al., 2019). The model implies an equal integration of the defining parameters that are: platforms, mechanics, components, dynamics, aesthetics, behaviors, players, costs and revenues. An evolution of this model also integrates the difficulty perception as a base (Figure 5), and involves the types of motivators and the dynamics afterwards. (E. Villegas et al., 2019)

![Figure 5: A representation of a framework involving difficulty, from Villegas et al., 2019.](image)

Another methodology proposed is the fun experience design framework (E. Villegas et al., 2019). This model involves 4 phases: Exploration, that seeks to offer first-hand knowledge of the concerns and needs of the game, Creation of the gamification system stage, where the developers should assess what are the most important knowledge that the player will acquire, Review, that uses the results to analyse the efficiency of the previous decisions, and Redesigning, where reviews are used to address the issues and success and to propose a new experience. (E. Villegas et al., 2019)

Eventually, the Design thinking framework (Figure 6) developed by the Norman Nielsen Group integrates the evaluation process into the methodology. The approach is a sequential work process, with three main parts and six secondary phases: Empathize, consisting in understanding the needs and hopes of the users, Define, consisting in establishing which problems should be solved in the gamified system, Ideate, where various ideas should be proposed, Prototype, consisting in assembling the first ideas, Test, where users try the gamified system and give feedbacks, and Implement, which consists in adding the acquired experience to the cycle before starting again (E. Villegas et al., 2019).
The GOAL Framework for gamification, designed primarily for Software Engineering, by Garcia et al. (F. Garcia et al., 2017), proposes a methodology for gamification of existing tools. It involves three main elements: Ontology, which is a set of concepts usable in software engineering; Methodology, which consists in a step-by-step approach that takes in consideration business goals and players feedbacks; Support tool, which gathers the definition of behaviors, rules and objectives.

Most frameworks developed lack valuable phases like Empathize and Test. The users are taken into consideration but their feedbacks or real motivations might be misunderstood. As a result, frameworks like Design thinking framework or Fun experience design could be considered as better approaches. Every framework remains unclear on the testing phases though (Villegas et al., 2019). The diversity and objectivity of testers is a crucial part of the efficiency of this phase. The human factor of testing is an issue in the global game industry, and recent studies suggest that automated testing could be highly beneficial by standardizing this phase (C. Politowski, F. Petrillo, Y. -G. Guéhéneuc, 2021).

The benefits of gamification on geometallurgy, especially on the flotation separation process, revealed that 80% of the experts testing a flotation-game would prefer a hybrid approach with human teaching assisted by new technologies. Only 12% thought that such games could replace the human instructor. It must also be noted the game is estimated more useful for university students than for novice operators (P.A.S. Bergamo, 2023). It is also suggested that such gamified approach could contribute to the reduction of the number of accidents in the mining industry by raising awareness in safe conditions (P.A.S. Bergamo et al., 2022).
II.2 Geology of the Malmberget deposit and properties of the minerals

The deposit that serves as a reference for this study is the Malmberget iron ore deposit in Northern Sweden. The area of Malmberget is located in Svecofennian supracrustal rocks (1.96-1.85 Ga), surrounded by Svecokarelian intrusive rocks (1.81-1.78 Ga) (S. Bergman, L. Kübler, O. Martinsson, 2001). The location is situated in a shear zone, between the Karesuando-Arjeplog deformation zone and the Nautanean deformation zone. The rocks are mostly gneiss, granites and metavolcanic rocks of the porphyry group. The Malmberget deposit is located near a large granite intrusion.

The total mass of mineable ore of the Malmberget area is higher than 900 Mt with an iron concentration between 51 and 61% and a grade of phosphorus lower than 0.8% (S. Bergman, L. Kübler, O. Martinsson, 2001; C. Lund, 2013). The Western and Northern parts of this deposit form an almost continuous horizon. The ore bodies of Malmberget include magnetite ore, hematite ore, and Fe-rich apatite ore. The eastern part presents isolated magnetite ore with a lower content of apatite. The main gangue minerals are biotite, pyroxene, amphibole and apatite with a grain size of 0.5 to 2 millimetres, while the host rocks are mainly felsic with albite and K-feldspar. A simplified geological map is shown in Figure 7.

Figure 7: Simplified geological map of Malmberget deposit (from C. Lund, 2013)

The Fabian ore body is a magnetite area, striking NE-SW and dipping from 75° SSE to sub-vertical, with an average content of 55.6% Fe and 0.35% P. The Hens ore body strikes SE and dips 55° SW with an average Fe grade of 53.5% and 0.8% of P. The Printzköld ore body strikes ENE and dips 70° SSE with a grade of 50.5% Fe and 0.75% P. These ore bodies are part of a large fold structure which plunge 40° to 50° towards the SSW. (S. Bergman, L. Kübler, O. Martinsson, 2001; C. Lund, 2013)

The overall mineralogical composition of the Malmberget area can be differentiated for semi-massive and massive ore. Semi-massive ore contains 55.1% of magnetite, 35.0% of albite, 7.6%
of actinolite, 0.4% of apatite and 1.8% of biotite. Massive ore that is amphibolite rich contains 66.4% of magnetite, 2.9% of albite, 23.0% of actinolite, 1.3% of apatite and 6.4% of biotite. Massive ore that is apatite rich contains 86.6% of magnetite, 0.1% of albite, 3.3% of actinolite, 7.1% of apatite and 2.8% of biotite. (V. Lishchuk et al., 2018)

The main minerals here are actinolite, feldspar (albite), apatite, biotite, epidote, hematite, magnetite and quartz. The studies analysing their associated magnetic susceptibilities (M.S.) show different results (Table 1) depending on the measurement methods and the properties of the minerals themselves.

**Table 1: Magnetic properties of important minerals.**

<table>
<thead>
<tr>
<th>mineral</th>
<th>actinolite</th>
<th>albite</th>
<th>apatite</th>
<th>Biotite</th>
<th>Epidote</th>
<th>Hematite</th>
<th>Magnetite</th>
<th>Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.S. (Amps)^([1])</td>
<td>0.3-0.9</td>
<td>&gt;1.7</td>
<td>1.4-1.7</td>
<td>0.2-1.2</td>
<td>0.3-1</td>
<td>0.025-0.5</td>
<td>&lt;0.01-0.05</td>
<td>&gt;1.7</td>
</tr>
<tr>
<td>M.S. (m^3/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mass susceptibility (m^3/kg)</td>
<td>-0.49 - 0.67 *10^4</td>
<td>52 - 98 *10^4</td>
<td>22.7-23.6 * 10^4</td>
<td>10-760 *10^4</td>
<td>20-110 *10^5</td>
<td>4.1 * 10^3</td>
<td></td>
<td></td>
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<tr>
<td>Diamagnetic susceptibility (SI)</td>
<td></td>
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<td></td>
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<tr>
<td>Initial susceptibility (SI)</td>
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<tr>
<td>Paramagnetic susceptibility (SI)</td>
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<td></td>
</tr>
</tbody>
</table>

Sources:

2. (P.S. Minyuk, T.V. Subbotnikova, A.A. Plyashkevich, 2010)
4. (A. Sigamony, 1944)
5. (Hunt et al., 1995)
6. (S.K. Tripathy et al., 2017)
8. (F. Heider, A. Zitselsberger, K. Fabian, 1995)
9. (D.J. Dunlop et al., 2006)

Biotite as well as other phyllosilicates present a significant anisotropy of magnetic susceptibility (F. Martin-Hernandez, A.M. Hirt, 2003).
II.3 Mineral processing of iron ore

Iron ores can be processed using different types of mineral processing flowsheets that involve different physical separation processes; such as magnetic separation, gravity separation, flotation. Magnetic separation is the common process to separate iron minerals from gangue insofar as they have a high magnetic susceptibility. Low intensity magnetic separation is used to separate magnetite. High intensity magnetic separation is then used to separate hematite. A pre-concentration of hematite can be done by gravity separation.

The crushing of the ore is the first step of size reduction and liberation and can be done using several machines including gyratory crushers, cone crushers and jaw crushers. Gyratory crushers are suitable for high production rates that can exceed 1500 tons/h and are mostly recommended for hard and abrasive materials (R. Pothina, V. Kecojevic, M.S. Klima, 2007). Cone crushers use compressive crushing and are the most common machines used for secondary and tertiary crushing. The most important parameters of cone crushers are the close side setting or CSS, that is the smallest gap between the crushing parts, and the open side setting which is the opposite (J. Quist, C.M. Evertsson, 2016).

The grinding is done by milling the ore using different kind of mills:
- Ball mills, where the grinding media are steel balls within the mill;
- Autogenous mills, where the grinding media are larger particles of the ore itself;
- Semi Autogenous mills, which is a combination of the two previous mills;
- Rod mills, where the grinding media are a batch of metallic rods within the mill;
- Pebble mills, where the grinding media are a large amount of pebbles.

The size of the mills must be adapted to the feed of ore. The ball mill dimensions can be calculated using the internal diameter of the mill $D$, the length $L$, the feed size $D_f$, the product size $d$, the Bond work index and the capacity $T$ (K. G. Tsakalakis, 2004). The formula is shown in equation 1.

$$D^{3.5} \left( \frac{L}{D} \right) = \left( \frac{1}{0.38^{10.38} + 0.9180} \right) * 0.106 D_f^{0.193} * d^{-0.962} T$$  \hspace{1cm} \text{Equation 1}

The size of metallic balls when using wet grinding is determined by the $P_{80}$ of the feed to the ball mill. A $P_{80}$ of 5 to 10 mm requires a ball size between 60 and 90 mm while a $P_{80}$ of 0.9 to 4 mm requires a ball size between 40 and 50 mm. (C. A. Rowland, 1982)

Several established flowsheets exist to process iron ore depending on its specifications. Gravity separation-based flowsheet appear less common. For example, the flowsheet proposed by M. Khokhulya, A. Fomin and S. Alekseeva (Figure 8) is based on gravity separation using spiral separation and table concentration and magnetic separation. This flowsheet has been developed for processing iron ore tailings.
In case of phosphorus minerals like apatite, reverse cationic flotation can be applied in basic pH with anionic collectors and depressant for gangue minerals (H. Sis, S. Chander, 2003). The flotation of biotite is possible using reverse cationic flotation and an addition of iso-alcohols to ether diamine (Filipov, Severov, Filipova, 2014).

Depending on the feed requirements, different sizes of flotation cells exist (Table 2). It appears that the most important costs of processing ore are crushing and grinding, then flotation and tailings removal (Table 3).

Table 2: Sizes of several existing cells, modified from B.K. Gorain et al., 2000.
<table>
<thead>
<tr>
<th>Item</th>
<th>Percent cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing</td>
<td>2.8</td>
</tr>
<tr>
<td>Grinding</td>
<td>47.0</td>
</tr>
<tr>
<td>Flotation</td>
<td>16.2</td>
</tr>
<tr>
<td>Thickening</td>
<td>3.5</td>
</tr>
<tr>
<td>Filtration</td>
<td>2.8</td>
</tr>
<tr>
<td>Tailings</td>
<td>5.1</td>
</tr>
<tr>
<td>Reagents</td>
<td>0.5</td>
</tr>
<tr>
<td>Pipeline</td>
<td>1.4</td>
</tr>
<tr>
<td>Water</td>
<td>8.0</td>
</tr>
<tr>
<td>Laboratory</td>
<td>1.5</td>
</tr>
<tr>
<td>Maintenance support</td>
<td>0.8</td>
</tr>
<tr>
<td>Management support</td>
<td>1.6</td>
</tr>
<tr>
<td>Administration</td>
<td>0.6</td>
</tr>
<tr>
<td>Other expenses</td>
<td>8.1</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

These costs are mostly caused by the significant energy consumption of the motors that are required to rotate the mills or agitate the pulp.

II.4 Geometallurgy and modeling methods

Geometallurgy is a cross-discipline approach that combines geology, mineral processing and economics to provide predictive models for mineral processing plants (P. Lamberg, 2018). Through this approach, ore blocks are characterized and through simulations can be categorized as economically profitable or not. Geometallurgy contributes to finding correlations between geological or mineralogical properties and processing parameters to create better models for the prediction of mineral production. Contrary to a pure geological approach, the geometallurgical approach revolves only partially around the mineralogical characterization with a stronger emphasis on mineral processing, i.e. by including process mineralogy in the block model. (C. Lund, 2013)
A geometallurgical model for the Malmberget deposit can be represented by several specific models: a geological model, a particle breakage model, a unit process model and a production model. Each model uses the parameters of the previous one to be generated. The full guideline (Figure 9) for creating a geometallurgical model includes logging, mineralogical study, tests, survey and specific models like breakage model and grinding model. (C. Lund, 2013)

A synthetic geometallurgical model can be generated using incomplete data by following a modified method. The term synthetic refers here to the artificiality and less precise nature of the model. Related and available data should be collected and used to create additional synthetic data, resulting in several scenarios. Different modeling approaches for the geological model are available depending on the amount of data and the required realism and smoothing. Geostatistic-based methods include estimations (e.g. indicator and block kriging), simulations (e.g. block error simulations), whereas non-geostatistic-based methods include regular statistics (e.g. inverse distance weighting) and machine learning (e.g. K-means, neural networks). The software HSC Sim can be used as a mineral process simulator and requires specific parameters like the initial particle size distribution, the minerals of the system and their respective grades. The geological model should be created as a three-dimensional voxel model where each block is a cube. (V. Lishchuk et al., 2018)

Figure 9: Guideline of a production model creation, from C. Lund, 2013.

The production model can be obtained by assigning economic values to the blocks of the geometallurgical model. By subtracting the costs to the revenues of a block, a model of profitable blocks can be obtained depending on when the revenue occurs. The selection of the mining method and the mine plan are then used to obtain the real profitability of a block. The
production model enables afterwards estimation of the optimal depth for transitioning from open pit to underground mining. (E. Bakhtavar, K. Shahriar, K. Oraee, 2009)
III - Methodology

III.1 Gamification Framework

III.1.1 Structure

The selected framework used here for developing the game rules and structure is a modified version of the Design thinking framework developed by Norman Nielsen Group. The modifications involve a different testing process while the game is in development. Indeed, the testers here should be called experts insofar as they give their opinions and critics when presented with an idea or a concept, instead of testing a prototype and giving feedbacks.

Another difference is the prototype phase. Indeed, it is not possible to create a prototype of every idea before the game is almost achieved. The prototypes are here replaced by game-concepts that are the translation of a game idea in a mechanic that could be integrated in the game.

III.1.2 Understand - Empathize and Define

The first phase consists in understanding what the user of the game wants. The users are supposed to be students and teachers of the mining, geology, engineering or management fields. The teachers require a tool suitable to a class that could be used to train small groups of students. It should be a realistic game, that requires involvement and concentration of the players. It must be repeatable and similar between groups to evaluate the different choices that students will make, and at the same time offer potential variation if the objective is to evaluate the capacity of the students to adapt to new situations. The game should be “winnable”, i.e brought to a close within a few days or hours of work to match with the academic schedules.

The game should enable the players to discover and experiment with concepts of geometallurgy and mining, while offering elements that could be analyzed with a serious and pragmatic approach. As a result, the mechanics within the game must be a precise and simple adaptation of a real case. The students need a challenging experience that requires the application of their studies and expertise. Several tools of statistics, modeling and management should be used. An important rule is that players should be allowed to also do actions that are not impossible but would never be done in real-life.

The second phase is the definition of the players’ objectives and their potential problems. As a result, a system of score should be added so that the users can easily know the efficiency of their decisions. The objective of the game is not to mine the entirety of the ore, but to reach a score that can be decided by the teacher or as a personal objective of the student.
III.1.3 Explore - Ideate and Game-concept

The third phase is the Ideate phase. Everything that occurs in a real-life mine and exploitation plant should be present in the game. This includes:

- Mining methods and mine plan;
- Transportation;
- Processing strategies;
- Geometallurgical tests;
- Cost data for CAPEX and OPEX;
- Rehabilitation.

The basis of the game itself is an idea: the area of Malmberget should be adapted by simplifying the lithologies, modifying the size, and the database of the game must match the technical constraints of the development team.

Every idea is discussed and then translated into a game concept. Because of the technical constraints, many concepts must be discarded during the fourth phase. Once a game concept is established and if it does not contradict the objectives of the game or the other concepts, it moves to the fifth phase.

III.1.4 Materialize - Experts-review and Implement

Expert-reviewing is done by two groups of experts. The first one is a scientific committee composed of teachers from Luleå University of Technology, the second one consists in the developers’ team. The scientific committee evaluates the efficiency of the game-concept as well as its realism. A concept that does not represent an essential aspect of a real-life case is sent back to the third phase. The developers’ team should assess whether the concept is feasible or whether it is impossible to add it to the game system. Once a concept is accepted by both groups, it reaches the sixth phase, i.e. the implementation.

Implementation of the game-concept involves writing down the concept in the rules of the game and use it as a base for other ideas.

III.1.5 Scheme of the method

The modified Design thinking framework, or decision tree, can be seen on Figure 10.

An example of this methodology applied to the case study is the open-pit slopes discussion. Open-pits are shaped as reverse cones because it enables stable slopes. The concept of stability is not present in the game insofar as the gravity is not a parameter. As a result, the situation is as follows:

- Initial concept: reverse-cone-shaped open pits;
- Technical constraints: Blocks in the game structure are perfect cubes oriented with Easting, Northing and Depth axis, concept of gravity doesn’t exist in the game,
- Gamification: the adaptation must be simple, logical and intuitive for the user, and at the same time be an important obstacle for the player to take in consideration and to overcome;
- Available initial data: coordinates, BWI, mass of every block;
- Discarded parameters: the mass of the blocks is not used in the adaptation.

Two gamified concepts were then proposed to adapt the shape of open-pits, referred here as the “surrounding blocks” approach and the “intrinsic block property” approach (Tab. 4). Both these approaches required the creation of a specific parameter for each block, the hardness, which is interpreted here as the resistance to collapse.

Table 4: Example of the methodology applied to the idea of shaping the open-pits.

<table>
<thead>
<tr>
<th>Gamified approach</th>
<th>Surrounding blocks</th>
<th>Intrinsic block property</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Key concept</strong></td>
<td>A block can be mined only if requirements defined by the surrounding blocks are met</td>
<td>A block can be mined only if requirements defined by the property of the block itself are met</td>
</tr>
</tbody>
</table>
Gamified approach

when selecting a block of interest at layer n for mining, the 25 blocks that form a 55 blocks square in the layer n-1 are analyzed. The corners of this square are not analyzed. If one or more of the 21 blocks has a hardness value of “Soft”, it must be previously mined for the block of interest to be mined. Otherwise, any block in the 9 blocks square in the layer n-1 must be mined no matter what their hardness value is.

Possible slopes obtained
Fluctuating slopes between two ranges : 30° to 45°.

Benefits
Simplicity regarding technical structure, few parameters involved, unique-shaped pits, close to real constraints.

Issues
Narrow range of potential slopes.

Final decision and consequences
Adopted, requires the creation of a hardness parameter.

Intrinsic block property

When selecting a block of interest at layer n for mining, the hardness property determines the blocks that must be mined beforehand:

- If the block is soft, the 25 blocks in the 55 square in the layer n-1 must be previously mined;
- If the block is medium, the 9 blocks in the 33 square in the layer n-1 must be previously mined;
- If the block is hard, the single block in the layer n-1 as well as the 9 blocks in the 33 square in the layer n-2 that are above the block of interest must be previously mined.

Fixed slopes : 30°, 45° and 60°.

More variations of the slopes and reverse-pyramid-shaped open-pits.

More complex, less realistic and too regular pit-shapes.

III.2 Block model

III.2.1 Procedure

III.2.1.1 Deposit model generation

The model is based on the available data of the Eastern part of the Malmberget deposit, consisting in Dennewitz, Alliansen, Vitafors and Koskullskulle (S. Bergman, L. Kübler, O. Martinsson, 2001; C. Lund, 2013).

The objective here was to obtain a realistic database instead of an almost perfect depiction of the real underground Malmberget area. The available software, materials and data as well as this objective lead to the choice of applying regular statistics. This approach requires large initial datasets that had to be created by extending the available data.

As a result, the methodology that was adopted here is described in Figure 11.
Step by-step explanation:
- Digitalization of available maps to obtain a map grid of the area;
- Addition of available data (grades, lithologies etc.) and multiplication by delimited random variation;
- Generation of an extended dataset by extending the grid vertically;
- Creation of a statistical model using adapted search methods for important parameters;
- Corrections, normalization and minor modifications;
- Validation of the model.

The statistical model is likely to require a larger database, and large corrections can be detected in the validation phase.

III.2.1.2 Element to mineral conversion

An important issue to solve is the conversion between a mineral composition and a chemical composition. Indeed, the transition from minerals to elements is fairly simple, but the opposite is a bigger challenge insofar as a same element can be present in more than one mineral. Element to mineral conversion was used to switch between the available data. The procedure consists in solving a series of equations between the chemical composition of the minerals and the global chemical composition of a sample (Equation 2) (M. Parian et al., 2015).
\[ A \times x = b; \begin{pmatrix} a_{11} & \ldots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \ldots & a_{nn} \end{pmatrix} \times \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix} \]

Equation 2

Where:

- \( A \) is the matrix of the chemical composition of every mineral of the system;
- \( x \) is the vector that includes the unknown mineralogical composition of the system;
- \( b \) is the vector of the global chemical composition.

The vector \( x \) can then be determined using the non-negative least squares method (M. Parian et al., 2015).

### III.2.2 Application

#### III.2.2.1 Mapping and digitalizing the area

The mineral composition is simplified to only eight main minerals, with elemental compositions as follows (Table 5):

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Si</th>
<th>Ti</th>
<th>Al</th>
<th>Cr</th>
<th>Fe</th>
<th>Mn</th>
<th>Mg</th>
<th>Ca</th>
<th>Na</th>
<th>K</th>
<th>Sr</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>hematite</td>
<td>0.112</td>
<td>0.2038</td>
<td>0</td>
<td>0</td>
<td>69.62</td>
<td>0</td>
<td>0.01206</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>magnetite</td>
<td>0.02</td>
<td>0.12</td>
<td>0.03</td>
<td>0.05</td>
<td>70.37</td>
<td>0.09</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>quartz</td>
<td>46.13</td>
<td>0.1079</td>
<td>0.1588</td>
<td>0.4105</td>
<td>0</td>
<td>0.03872</td>
<td>0</td>
<td>0.2573</td>
<td>0.09644</td>
<td>0.3653</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>biotite</td>
<td>17.22</td>
<td>2.727</td>
<td>6.949</td>
<td>0</td>
<td>0.3637</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>albite</td>
<td>31.71</td>
<td>0</td>
<td>10.4</td>
<td>0</td>
<td>0.03887</td>
<td>0</td>
<td>0.02412</td>
<td>0</td>
<td>8.212</td>
<td>0.2407</td>
<td>6.968</td>
<td>0</td>
</tr>
<tr>
<td>epidote</td>
<td>17.71</td>
<td>0.084</td>
<td>13.46</td>
<td>0</td>
<td>8.239</td>
<td>0</td>
<td>0.066</td>
<td>16.83</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>actinote</td>
<td>25.58</td>
<td>0.0126</td>
<td>0.7727</td>
<td>0</td>
<td>7.462</td>
<td>0.1239</td>
<td>10.82</td>
<td>9.119</td>
<td>0.8494</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>apatite</td>
<td>0.617</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3498</td>
<td>0.2168</td>
<td>0</td>
<td>36.79</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>22</td>
</tr>
</tbody>
</table>

The available map of the area of study were digitalized with an arbitrary 59*59 grid. Each cell contains a reference number and a lithology. The parts of the area where orebodies are present are more precise to ensure stable results during modeling, and outer parts are less detailed in order to reduce the amount of data to be processed while keeping reference points to control the realism of the final model. The scale of the area is not preserved between the initial map (Figure 12) and the final model (Figure 13).
Figure 12: Initial simplified map of the Malmberget area used to generate the grid, modified from C. Lund, 2013.

Figure 13: Resulting grid used to generate artificial logs. Blue = Metavolcanics, Green = Skarn, Pink = Granite, White = Leptite, Red = empty cell.
Knowing the lithology of every cell as well as the average composition in terms of minerals or elemental grades for these lithologies, an elemental composition was recreated by assigning values to every cell. These values were determined by random selection of a value between fixed minimum and maximum. The extrema can be seen in Table 6.

The grade of albite is determined by completing the composition to reach 100%. The composition in terms of hematite and magnetite is obtained by applying a multiplicative coefficient to the iron oxide grade that varied depending on the orebody. This coefficient doesn’t rely on scientific sources and is used to artificially diversify the orebodies. It is calculated using a similar method of random number within fixed extrema.

### III.2.2.2 Creation of the artificial logs and interpolation

#### Table 6: Parameters used to generate mineralogical composition depending on the lithology.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Actinolite</td>
<td>0-25 %</td>
<td>0-1 %</td>
<td>5-65 %</td>
<td>0.3-2.7 %</td>
<td>0.2-1.9 %</td>
<td>0-7 %</td>
<td>0.5-6 %</td>
</tr>
<tr>
<td>Apatite</td>
<td>0-0.8 %</td>
<td>0-0.8 %</td>
<td>0.1-1.3 %</td>
<td>2-10 %</td>
<td>1.3-4 %</td>
<td>0.95-4.35 %</td>
<td>0.4-2.9 %</td>
</tr>
<tr>
<td>Biotite</td>
<td>1-26 %</td>
<td>2-5 %</td>
<td>0-5 %</td>
<td>0-2 %</td>
<td>0-2 %</td>
<td>0-2 %</td>
<td>0.1-1.9 %</td>
</tr>
<tr>
<td>Epidote</td>
<td>0 %</td>
<td>0 %</td>
<td>8-12.5 %</td>
<td>0.1-2.1 %</td>
<td>0.1-1.1 %</td>
<td>0.3-1.4 %</td>
<td>0.2-1.4 %</td>
</tr>
<tr>
<td>Iron oxyde</td>
<td>0-10 %</td>
<td>0.5-1 %</td>
<td>0-15 %</td>
<td>68-83 %</td>
<td>68-89 %</td>
<td>50-93 %</td>
<td>69-83 %</td>
</tr>
<tr>
<td>Quartz</td>
<td>10.5-20 %</td>
<td>25-32 %</td>
<td>0 %</td>
<td>0-0.2 %</td>
<td>0-0.2 %</td>
<td>0-0.2 %</td>
<td>0.2-1.7 %</td>
</tr>
</tbody>
</table>

After this step, every cell of the grid has a mineralogical composition. Every cell is then used as the starting point of an artificial log where the values are determined by the procedure explained before. The objective is to do the opposite of what is usually done in sampling and logging. Indeed, the objective of the log is usually to go through underground structures, possibly with a perpendicular angle. The approach required to be adapted insofar as here, the underground structure of the orebodies is not known. In order to constraint the simulation, the logs (Figure 14) are here aligned with the assumed orientation of the structures. This orientation was determined through the assumption that the orebodies were in continuation of the others of the Malmberget area.
The artificial logs were then used as a base for the model simulation, using regular statistics. The objective is to obtain a smooth and realistic model and not a precise depiction of the underground structures. A model based on inverse distance weighting without declustering is preferred over a geostatistic approach with block kriging insofar as the logs are purely artificial and cannot reveal trends for geostatistics (V. Lishchuk et al., 2018). The model that results is then transformed into a 40*40*10 block model. The block size is fixed at 40m in all three dimensions afterwards.

The parameters used to interpolate the values and generate the block model are detailed in Table 7. The minerals are simulated independently, which requires a correction afterwards insofar as the total composition doesn’t reach 100%. A simple calculation is applied to correct the results (Equation 3):

$$x_i = a_i \times \frac{100}{\sum a_i}$$  \hspace{1cm}  \text{Equation 3}$$

Table 7: Parameters used in the interpolation to generate the geological structure

<table>
<thead>
<tr>
<th></th>
<th>Actinolite</th>
<th>Albite</th>
<th>Apatite</th>
<th>Biotite</th>
<th>Epidote</th>
<th>Hematite</th>
<th>Magnetite</th>
<th>Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpolant</td>
<td>Linear</td>
<td>Spheroidal</td>
<td>Linear</td>
<td>Linear</td>
<td>Linear</td>
<td>Linear</td>
<td>Linear</td>
<td>Linear</td>
</tr>
<tr>
<td>Alpha</td>
<td>X</td>
<td>3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Total Sill</td>
<td>40.0</td>
<td>100.0</td>
<td>40.0</td>
<td>60.0</td>
<td>20.0</td>
<td>100.0</td>
<td>20.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Base range</td>
<td>500.0</td>
<td>120.0</td>
<td>50.0</td>
<td>500.0</td>
<td>50.0</td>
<td>50.0</td>
<td>20.0</td>
<td>500.0</td>
</tr>
<tr>
<td>Drift</td>
<td>Constant</td>
<td>None</td>
<td>Constant</td>
<td>Constant</td>
<td>Constant</td>
<td>Constant</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>Nugget</td>
<td>1.0</td>
<td>3</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.070</td>
<td>0.64</td>
<td>0.01</td>
<td>0.1</td>
<td>0.05</td>
<td>0.02</td>
<td>0.65</td>
<td>0.2</td>
</tr>
</tbody>
</table>
The explanation about these parameters is adapted from the Leapfrog Geo website (LeapFrog, 2023).

There are two possible methods of interpolation. The first one is spheroidal, which resembles a spherical variogram, which means that the interpolated value is the constant sill beyond the value of the range. The linear interpolant is more affected by nearby values that are close to the interpolated point, and is relevant for irregularly sampled data. The spheroidal model was used for albite only insofar as it is the dominant mineral of the area. A linear model would be too unrealistic.

The alpha is a parameter specific to spheroidal interpolant. It is used to determine the steep of the interpolant before reaching the total sill. A low alpha value gives values at intermediate distance less weighting compared to higher alpha values. The alpha value was set at three in order to obtain slightly smoother results at direct proximity of the measurement points.

The nugget is the variation value that represents very local anomalies. It was decided to use small nugget values in order to obtain smoother results. The value of albite is higher in order to mark a slightly bigger transition between metavolcanics and host rocks.

The total sill represents two parameters. The first one, for spheroidal interpolant, determines the upper limit at which there ceases to be any correlation between values. When using Linear interpolant, this parameter is combined with the Base range to set the slope of the interpolant. When the distance is higher than the Base range, the interpolation value is the total sill. The total sill of non-ore minerals is set at a potential maximum value.

The base range is the distance at which the interpolant value reaches 96% of the Total sill in cases where the Nugget value is 0. This distance should cover the distance between drillholes. As a result, it was decided to use a small Base Range value for minerals that are located in the ore area (apatite, epidote, hematite, magnetite) and a higher value for minerals that are more abundant in host rocks that are less sampled.

The drift is a value behaviour model of points far from the data. The Constant model leads to the interpolant going to the average value at far distances, while the None model leads to the interpolant decrease until zero. The drift is set as None when using spheroidal model in order to decrease the amount of albite within the ore itself, and the drift is set as Constant when using linear interpolant insofar as the linear drift could result in negative values.

The accuracy is calculated by taking a fraction of the smallest difference between available values. For example, if the minimal difference between two values is 0.01, then a decent usual accuracy value would be 0.001. Reduced accuracy value would result in longer simulating time. Here, given the particularities of the available values and the objectives of the modeling, it was decided to increase the accuracy value in order to obtain results that differ more significantly to the initial values.
The grain size of magnetite is also simulated in this model in order to calculate other parameters afterwards. The model (Figure 15) is spherical and aims at obtaining smooth decreasing values when the distance to the ore increases.

### III.3 Processing and tests

The player should be able to carry out tests in order to understand the area within the game and take logical decisions. Several tests or analyses are possible in reality. Here their number is limited to 4 types.

The tests available for the user include:

- Grindability test, that returns the BWI of the Block;
- Davis tube tests, that indicate the repartition of magnetic minerals;
- Laboratory processing tests;
- Pilot scale processing tests, that share the same results as the final processing database.

### III.3.1 Bond Work Index

Through a geometallurgical approach, the Bond Work Index (BWI) can be correlated to other parameters of the rocks. A study on Chadormalu iron ore mine demonstrated that the BWI is correlated to the grade of magnetite with a significant spread around the regression curve (Figure 16) (H. Inanloo Arabi Shad et al., 2018).
A link between the Bond Work Index and the grain size of the magnetite particles within the ore is observed for drill cores from Malmberget (Figure 17). It suggests that the grain size is slightly positively correlated to the Bond Work Index (A. Mwanga, 2014).

![Figure 16: Correlation between magnetite% and BWI (from H. Inanloo Arabi Shad et al., 2018)](image)

The Bond Work Index is assumed to be a combination of both trends. The correlation between BWI and magnetite grade appears more efficient and more reliable insofar as it is based on a wider sample.
The proposed equation to represent BWI is then (Equation 4):

\[
BWImag = 0.8 * ( -8.14 * \ln(x_{mag} + 19) + 40.619 ) + 0.2 * (0.0092d_{mag} + 9.2324) \quad Equation 4
\]

Where:

- \(x_{mag}\) is the grade of magnetite;
- \(d_{mag}\) is the grain size of the magnetite particles in the ore.

### III.3.2 Davis tube tests

A test by Davis Tube consists of separating higher and lower magnetic fractions of a magnetic ore. In the case of a hematite and magnetite ore, the Davis tube test enables a separation of magnetite from hematite and other minerals of low magnetic susceptibility (V. Murariu, J. Svoboda, 2003).

In the case of this study, Davis tube tests are only obtained by computer calculation. The results of tests highlighted the impact of particle size on the separation efficiency, having a negative impact. The optimum conditions depend on the initial sample and the magnetite recovery fluctuates also depending on the particle liberation, the magnetic field strength, the amount of flush water and the flow speed (V.N. Ortynski, 2018; M. Dworzanski, 2012).

The results of Davis Tube tests were computed by adapting the results of M. Dwozanowski (Figure 18 and Figure 19):

![Figure 18: Influence of the Fe mass of the sample on the Fe% of the magnetic fraction](image-url)
The impact of the particle size is neglected. The mass pull value is based on the proportion of Fe which is contained within magnetite.

**III.3.3 Flowsheets for laboratory tests and processing results**

**III.3.3.1 Structure and basis of the different flowsheets**

The Malmberget process, which served as an inspiration, doesn’t require flotation because of the low phosphorus content. In order to offer a strategic choice that could be either beneficial or detrimental, it was decided to include the possibility to use apatite flotation. The player must decide if the quality increase is worth the investment.

Eight different flowsheets were created by using the same processing elements: grinding can be done either by ball mill or by SAG mill and only magnetic separation is mandatory. Flotation and gravity separation can be added resulting in the 8 flowsheets:

- Ball Mill as grinding, magnetic separation only;
- SAG Mill as grinding, magnetic separation only;
- Ball Mill as grinding, magnetic separation and gravity separation;
- SAG Mill as grinding, magnetic separation and gravity separation;
- Ball Mill as grinding, magnetic separation and flotation;
- SAG Mill as grinding, magnetic separation and flotation;
- Ball Mill as grinding, magnetic separation, flotation and gravity separation;
- SAG Mill as grinding, magnetic separation, flotation and gravity separation.

An example of one of these flowsheets is available on Figure 21. It is worth mentioning that the flowsheets detailed here are simplified and not destined to be usable in a real processing plant. The software HSC Sim was used to draw, test and perform the process simulations.
IIIIII.3.3.2 Input parameters, processing time and output parameters

The input parameters of the simulation were:

- Feed mass in tons per hour, this parameter is calculated by dividing the total mass of the block by the number of processing days;
- Mineralogical composition;
- Bond Work Index (BWI);
- Run-of-mine particle size distribution, obtained by literature review (Figure 20).

The time required to process a block can be estimated using the BWI insofar as it influences the total energy required during crushing and grinding, which influences the capacity of the mills. The number $n$ of processing days is calculated by applying this formula (Equation 5):

$$n = \lfloor -0.02 \cdot BWI^2 + 1.1 \cdot BWI \rfloor$$

This formula is postulated in order to offer a time-management system within the game and doesn’t refer to previous studies.

The output parameters are:

- Recovery of main elements;
- Mineralogical composition of the output;
- Water consumption;
- Mass flow of the final concentrate;
- Mass flow of the feed to every crushing and grinding device;
- P80 of feed and output to every crushing and grinding device.

IIIIII.3.3.3 Crushing and grinding parameters

The crushing is the same procedure for every flowsheet, using closed circuits. The first screen has a mesh size of 100mm, the second screen has a mesh size of 14mm. The gyratory crusher has a closed-side-setting (CSS) of 90mm, with a medium crusher type and a coarse chamber type. The BWI is a parameter automatically adapted for every simulation. The cone crusher has a CSS of 9mm, a medium chamber type and an eccentric speed of 290rpm. The water is added in the grinding step and is adapted depending on the requirements of the next steps.

When using a ball mill, the parameters are adapted to the volume and the required PSD of the outcome. The ball mill has a diameter of 6m and a length of 10m. The opening size of the grate is set at 0.2mm.

The parameters for the SAG mill are a length of 9.14m and a diameter of 5.44m. The opening size of the grate is set at 0.2mm.
III.3.3.4 Gravity separation method and parameters

The gravity separation is done with spiral separators. The first one separates the ore in three flows whereas the middlings are directed to a second spiral separator, that only removes the tailings. The two concentrate flows are mixed and sent to the next step. The first spiral separator uses five specific gravity (SG) classes and the quality of the separation is assumed to be independent on the size of the particles. The concentrate contains: 0.5% of the particles from the feed with a SG of 2-2.8, 1.2% of the particles between 2.8 and 3.6, 2% of the particles with a SG of 3.6-4.4, 10% of those between 4.4 and 5.2, and 85% of the particles with a SG of 5.2-8. The middlings contains: 0.3% of the particles with a SG of 2-2.8, 12% of the particles between 2.8 and 3.6, 80% of the particles with a SG of 3.6-4.4, 78.5% of those between 4.4 and 5.2, and 14.5% of the particles with a SG of 5.2-8.
The second spiral uses 4 SG classes only, between 2.3 and 5.5. The repartition of the feed to the concentrate is: 0.3% of the particles between 2.3 and 3.1, 2% of the particles with a SG of 3.1-3.9, 5% of the particles with a SG of 3.9-4.7, and 91% of those between 4.7 and 5.5.

### III.3.3.5 Magnetic separation method and parameters

Normally, the magnetic separation uses a first step with low intensity and a second one at high intensity, with a low intensity magnetic field being approximately 0.3 T (K. Singh, 2017).

The magnetic separation is done using two wet magnetic separators. The first one serves as a rougher and the second one as a cleaner. The parameters of the magnetic separators are shown in Table 8. The rougher and the cleaner use a low magnetic strength insofar as magnetite is a ferromagnetic mineral that doesn’t require a strong magnetic field. The field strength is set at 0.3 T which is the value for wet low-intensity magnetic separators (K. Singh, 2017). The matrix fractional loading is automatically adjusted to the magnetite content of the input. The other parameters are left as default values.

**Table 8: Parameters used for the wet magnetic separation in the simulation.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values for both rougher and cleaner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field strength (Tesla)</td>
<td>0.3</td>
</tr>
<tr>
<td>Saturation magnetic field strength (Tesla)</td>
<td>0.3</td>
</tr>
<tr>
<td>Interstitial velocity (m/s)</td>
<td>0.1</td>
</tr>
<tr>
<td>Matrix fractional loading</td>
<td>Automatically adjusted value</td>
</tr>
<tr>
<td>Magnetic cut point for low susceptibility minerals</td>
<td>0.00263</td>
</tr>
<tr>
<td>Magnetic cut point for high susceptibility minerals</td>
<td>0.0001062</td>
</tr>
</tbody>
</table>

The mineral mass susceptibilities had to be calculated for three minerals. Indeed, the mass susceptibility was not found for actinolite and apatite, and the one available for epidote doesn’t seem usable in this simulation because the mass susceptibility would be higher than the one of hematite. In order to obtain realistic values, a correlation between the results of magnetic susceptibility and mass susceptibility was used (Figure 22). The correlation was used on measurements of actinolite, apatite and epidote to obtain the list of parameters detailed in Table 9.
Figure 22: Correlation between mass susceptibility by Hunt et al, 1995 and magnetic susceptibility by Rosenblum and Brownfield, 2000.

Table 9: Mass susceptibilities used in the simulation for each mineral.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Mass susceptibility ($m^3/kg$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albite</td>
<td>-4.9 x 10^{-9}</td>
</tr>
<tr>
<td>Actinolite</td>
<td>1.08 x 10^{-7}</td>
</tr>
<tr>
<td>Apatite</td>
<td>7.08 x 10^{-10}</td>
</tr>
<tr>
<td>Biotite</td>
<td>9.8 x 10^{-7}</td>
</tr>
<tr>
<td>Epidote</td>
<td>1.88 x 10^{-7}</td>
</tr>
<tr>
<td>Hematite</td>
<td>3.8 x 10^{-6}</td>
</tr>
<tr>
<td>Magnetite</td>
<td>1.12 x 10^{-3}</td>
</tr>
<tr>
<td>Quartz</td>
<td>-5.0 x 10^{-9}</td>
</tr>
</tbody>
</table>

III.3.3.6 Flotation separation method and parameters

The flotation step is based on the reverse flotation of apatite, which is the same method as for Kiruna iron ore. Flotation is done using a modified fatty acid, Atrac-1562, as a collector and sodium silicate with a SiO$_2$/Na$_2$O ratio of 3.3 as a dispersant (F. Su et al., 1998). The kinetic parameters of apatite are based on the available measures, and are assumed independent of the size of the particles (Table 10). The flotation kinetics of the other minerals are inferred without available source in order to obtain realistic results.
After running the simulations, it appeared that the use of flotation was rarely appropriate. Indeed, the grade of apatite in every block is already low and most of that mineral appears removed beforehand. In order to increase the relevancy of flotation, the requirements for phosphorus grade can be lowered during the testing of the game. Thus the player can make a decision between flowsheets with a higher Fe-recovery without using flotation, or flowsheets with lower Fe-recovery but without any risk of penalty due to the phosphorus content of the concentrate.

Table 10: Flotation kinetics used in the simulation.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Infinite recovery (%)</th>
<th>Maximum flotation rate constant (1/min) – rectangular distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actinolite</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>Albite</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>Apatite</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>Biotite</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>Epidote</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>Hematite</td>
<td>7</td>
<td>2.5</td>
</tr>
<tr>
<td>Magnetite</td>
<td>7</td>
<td>2.5</td>
</tr>
<tr>
<td>Quartz</td>
<td>9</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The dimension and other main parameters of the flotation cell are:

- Residence time of 3 min;
- Net volume of 100 m³;
- Pulp area of 28.3 m²;
- Froth surface area of 17 m²;
- Rotor diameter of 1300 mm, speed of 85 rpm;
- Gas hold-up of 10%;
- Air flow rate of 18 m³/min.

III.3.3.7 Simulation and tests parameters

The simulations were done for every block of the geological model on the 8 flowsheets using the scenario editor of the software. Every scenario changes the variables to adapt to every cell. Each simulation is done for three rounds, and the maximum number of iterations at each round is 25. The pilot tests use an initial feed calculated by dividing the total block mass by the required processing hours and each calculation is done for three rounds.

The laboratory tests use the same flowsheet structures with a few differences:
- The initial feed is fixed at 0.08 tons per hour;
- The dimensions of the machines are reduced;
- The SAG mill is replaced by a rod mill;
- 2 rounds of calculation instead of 3 for pilot.

The parameters for the rod mill used for the size reduction of the SAG mill are: 193.5mm of diameter, 245mm of length, volume loading of 23% (H. Lee, M.S. Klima, P. Saylor, 2011). The laboratory-scaled ball mill has a diameter of 40cm (E. Albertin, A. Sinatoria, 2001), and the length is fixed at 60cm or 150% of the diameter.

### III.4 Economics

The economic analysis revolves on two main aspects: the database-related costs and the global costs. The final database contains the initial parameters of each block and the results of processing for each of them. Global costs include labour costs, building costs etc., while the database-related costs are calculated using values of the final database.

It is very important to mention the fact that the costs detailed here may be modified for the final release of the game. The calculations and estimations are here mostly indicative of the procedure. Indeed, if the final game is not winnable or is way too difficult because the profitability is too low, then the costs are likely to be slightly adapted. The objective of this serious game is not to offer a perfect simulation of the reality, but to offer an experience that stimulates the player.

The power consumption $W$ of the processing is based on the Bond Work Index (J.M. Burke, 2015) (Equation 6). Crushing and grinding represent most of the power costs of processing (M. Jahani, 2020). The energy consumption of the other machines (e.g., magnetic separator, flotation cells, spirals) is supposed independent of the block and are integrated in the fixed daily energy costs of the processing plant.

$$ W = 10 \times W_i \left( \frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right) $$

*Equation 6*

The P80 and F80 are extracted from the simulation results as well as the BWI of the block, and the energy consumption is obtained by multiplying $W$ with the total mass of the block. The energy costs of the processing of a block is eventually obtained by multiplying the energy consumption to the electricity price.

The costs of reagents can be estimated using the simulated database too, with water being one of the reagents. The consumption is multiplied by the current market value. The costs of electricity used in magnetic separation is estimated using various sources. The iron ore price on the market is approximately 100$ per ton, and this price evolves during the events of the game, based on the evolutions of the iron ore price between 2012 and 2023 (Figure 23).
Regarding the other costs of the mine, the procedure consisted in analysing different similar mining projects and make averages of realistic costs. For example, the estimated average operating costs of the Kami project shows that mining and transport are the most important costs (Table 11) and details the mining costs (Table 12) (A. Grandillo et al., 2018).

**Table 11: Estimations of the LOM operating costs of the Kami project, modified from A. Grandillo et al., 2018.**

<table>
<thead>
<tr>
<th>Estimated Average LOM Operating Costs (US$/t Dry Concentrate)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining</td>
<td>11.25</td>
</tr>
<tr>
<td>Mineral Processing</td>
<td>5.72</td>
</tr>
<tr>
<td>General Site</td>
<td>0.50</td>
</tr>
<tr>
<td>General Administration</td>
<td>2.26</td>
</tr>
<tr>
<td>Environmental and Tailings management</td>
<td>0.37</td>
</tr>
<tr>
<td>Rail transportation and port services</td>
<td>10.62</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>30.72</strong></td>
</tr>
</tbody>
</table>
Table 12: Estimations of the mining costs of the Kami project, modified from A. Grandillo et al., 2018.

<table>
<thead>
<tr>
<th>Category</th>
<th>US $/t of concentrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment operating cost</td>
<td>3.66</td>
</tr>
<tr>
<td>Fuel and electricity</td>
<td>2.04</td>
</tr>
<tr>
<td>Blasting</td>
<td>1.72</td>
</tr>
<tr>
<td>Labour</td>
<td>3.09</td>
</tr>
<tr>
<td>Services</td>
<td>0.16</td>
</tr>
<tr>
<td>Equipment lease</td>
<td>0.58</td>
</tr>
<tr>
<td><strong>Total mine Operating costs</strong></td>
<td><strong>11.25</strong></td>
</tr>
</tbody>
</table>

The precise costs of reagents as well as their exact consumption was not found. As a result and still in the framework of simplifying the concepts of geometallurgy, estimations based on other mining projects are taken. The Norra Kärr feasibility study (P. Gates, C.F. Horlacher, G. Reed, 2013) establishes the reagent consumption for the flotation process and the water requirements (Table 13). The selected process of this study is different but the cost structure is considered to be similar.


<table>
<thead>
<tr>
<th>Reagent</th>
<th>Units</th>
<th>Use/hour</th>
<th>Annual Usage</th>
<th>Unit Cost</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flocculants</td>
<td>tn</td>
<td>0.0077</td>
<td>65</td>
<td>3,500</td>
<td>226,380</td>
</tr>
<tr>
<td>Sulfuric Acid</td>
<td>tn</td>
<td>14.3</td>
<td>120,120,125</td>
<td>15,015,000</td>
<td></td>
</tr>
<tr>
<td>Sodium Carbonate</td>
<td>tn</td>
<td>6.7</td>
<td>56,280</td>
<td>14,070,000</td>
<td></td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>tn</td>
<td>0.05</td>
<td>421</td>
<td>40</td>
<td>16,834</td>
</tr>
<tr>
<td>Hydrochloric Acid</td>
<td>tn</td>
<td>4.0</td>
<td>33,266</td>
<td>190</td>
<td>6,320,523</td>
</tr>
<tr>
<td>Limestone</td>
<td>tn</td>
<td>4.0</td>
<td>33,600</td>
<td>150</td>
<td>5,040,000</td>
</tr>
<tr>
<td>Lime</td>
<td>tn</td>
<td>0.50</td>
<td>4,200</td>
<td>300</td>
<td>1,260,000</td>
</tr>
<tr>
<td>Water</td>
<td>m3</td>
<td>473</td>
<td>3,969,252</td>
<td>0.25</td>
<td>992,313</td>
</tr>
<tr>
<td><strong>Miscellaneous supplies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,972,000</td>
</tr>
<tr>
<td><strong>TOTAL (US$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>58,089,822</td>
</tr>
<tr>
<td><strong>Reagents: (Cost/1.5 Mt tonnes milled/year)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$38.73</td>
</tr>
</tbody>
</table>

The penalty elements have an important impact on the revenues of each block. The penalty elements for iron ore are Al, P, Si and S (Thermo Fisher Scientific Inc, 2011). The Fe grade is also a requirement to meet. The penalty levels are usually a 1% differential from the fixed standard that the buyer requires, but it is only a 0.01% difference for phosphorus (S&P Global – Platts, 2020). The processing results showing better results than expected, lower penalty requirements were taken to slightly reduce the amount of sellable blocks, in order to force the players to make decisions. The selected thresholds are shown in Table 14.
<table>
<thead>
<tr>
<th>Element</th>
<th>No penalty</th>
<th>Low penalty [%value]</th>
<th>Not sellable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>&gt;68%</td>
<td>65%&lt;X&lt;68% [20%]</td>
<td>&lt;65%</td>
</tr>
<tr>
<td>Al</td>
<td>&lt;1%</td>
<td>1%&lt;X&lt;2% [30%]</td>
<td>&gt;2%</td>
</tr>
<tr>
<td>Si</td>
<td>&lt;1%</td>
<td>1%&lt;X&lt;2% [30%]</td>
<td>&gt;2%</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.01%</td>
<td>0.01%&lt;X&lt;0.02% [30%]</td>
<td>&gt;0.02%</td>
</tr>
</tbody>
</table>

Table 14: Penalty elements and their impact on the price of the concentrate

The penalty for phosphorus can be imposed at a lower grade during the late development of the game in order to offer more processing approaches to the player. Indeed, preliminary tests reveal that the final grade of phosphorus is often below 0.01% even without using flotation. By imposing this low-grade requirement, the player will have to chose wisely the appropriate flowsheet.
IV - Results and discussion

IV.1 Game rules and structure

The game rules are still likely to change during testing of the game. It is possible that some mechanics and aspects listed here will be revised during the final development of the game.

IV.1.1 Game phases

The goal of this game is to successfully manage the mine and to have a positive total income. The game itself is split in four main phases:

1. The first phase is the exploration phase, where the player must discover and evaluate the iron ore deposits. The player has access to geological and geophysical maps of the area. Depending on the budget, the player can also select areas to drill holes and make analyses. No revenue can be done during this phase.

2. The second phase is the construction phase, which includes creating the assets required to the actual mining. The player must select the treatment process (the « flowsheet »), construct the processing plant, buy the equipment and place the entrance of the tailings dam. No revenue can be done during this phase but the player must take a loan from the bank for the investment (CAPEX).

3. The third phase is the mining phase. In this phase, the player starts to mine the blocks and earn revenue for the project. The player must select a mining method for every orebody he aims to mine, direct the mined blocks, take care of the price evolutions, stock and sell at appropriate times, upgrade or adapt the mine when it seems useful. The player also should take care of the quality of the concentrates that are produced and keep an eye on the penalty elements.

4. The fourth phase is the rehabilitation phase. The player has to properly close the mine by selecting the rehabilitation procedure.

IV.1.2 Interface

The interface (Figure 24) displays a view of the area as well as several buttons. The centre of the screen displays the mine projects. Around it, three types of objects: indicators (Time, Ecu, processing load, current price, current mine project, and legend) that cannot be clicked, folder buttons (in blue here: Documents, Samplings, Check Stockpiles) that open other options when clicked (e.g. here when clicking on Check stockpiles), menu buttons (Upgrades, Let’s mine, Next phase, add a mine project, go to next mine project, modify roads) that open menus with options or enable specific actions.
IV.1.3 Phase 1: Exploration

The objective of this phase is to obtain enough data to be able to quantify the resource and define the reserves of the area with a limited budget. The player has an initial budget granted by its company to carry out the exploration.

IV.1.3.1 Available documents

During this phase, the player can learn about the geology of the area using several maps (Figure 25 and 26): a geological map that indicates the nature of the rocks at the surface and the different geological objects (faults, metamorphism, etc.); geophysical maps including a gravimetric map that indicates the variations of the local gravity, and a magnetic susceptibility map that indicates the variations of the local magnetic field. The player can find explanations about these maps in “Documents”. The maps overlay each other with same locations being at the same coordinates so that the player can easily switch views. The area of the mine project contains different orebodies. The player should use the maps to determine the amount of orebodies. The area it covers is 480 000 m², and previous prospections showed that the base of the orebody is 200 m below the surface. The zone then consists of $40 \times 40 \times 10 = 16000$ blocks (40 blocks to the East, 40 blocks to the North, and 10 blocks in depth). Each block is a cube of rock with a side-length of 40 m.
The different orebodies have different characteristics in terms of mass, depth, size, shape etc. The orebody should be between 500 and 3000 blocks. They are composed of iron minerals, basically magnetite and hematite. The whole deposit is inspired by a part of a real iron mine in Northern Sweden.

A memo explaining the effects of the measures, some basic rules like the slopes stability system, and also the charts about the market price evolution as well as the total income, Net
Present Value are also accessible at any time. These documents remain accessible through the whole game through a clickable menu called “Documents”. These documents are also available for free.

IV.1.3.2 Drill program

After checking the maps, the player can click on a button called “start drilling campaign. The player must select blocks where a vertical drilling will be performed. The player can then know three parameters of the blocks within that column: the grain size by size class (fine-grained, medium-grained, coarse-grained) and the hardness by class (soft, hard), and the lithology of the blocks. The player doesn’t know the threshold that define the classes. The hardness is a parameter of each block. The collar or ID of each drilling is based on the coordinates of the original surface block that was selected. The number of the ID increases from 0001 to 1600 from left to right and top to bottom: the fifth block of the seventh line has the ID 0245.

IV.1.3.3 Sampling for analysis

During this phase, the player can use samples of the previously done drillings to make analyses and gain more knowledge on the area. The analyses have a cost that adds to the initial investment. To analyse, the player must click on “Sampling” and then “new analysis”. The game pauses and the player can click on a block that was drilled at the surface of the deposit. A dialogue box opens asking “Confirm analysing this drill hole? Cost: XXX Mine-Coin”. If the player cancels, the game unpauses and goes back to normal. If the player confirms, a table is opened indicating the measures and their values for each block in a vertical column. This table is saved and accessible in “Samplings” and then “Results”, and can be retrieved with its ID.

The parameters to take in consideration for the blocks are:

- Composition in terms of elements (iron, copper, silica, potassium, phosphorus...)
- Magnetite content (obtained by Satmagan analysis. Indicates the amount of iron that is present as magnetite)
- Grain size of the particles in micrometers
- Strength of the rock (important for stability, but also for processing: the harder the rocks, the more energy and money it requires to be crushed and processed.)
- Mineralogy.

Example (Table 15) of what is shown when an analyse is performed at the column of coordinates X = 15, Y = 33 (numbers were randomly generated, X is easting and Y is northing) or ID 1295:
### IV.1.3.4 Geometallurgical testing

Tests (Table 16) are similar to analyses but they are more expensive and the player can do less of them. Tests are more focused on the processing and its results. The player can access the tests for drillings that they already analysed. They must select only a single block of this column, and obtain a table with the results, that remain accessible in “Samplings” then “Results”. Regarding laboratory scale and pilot-scale tests, they are available for both flowsheets (see in the specified rubric). Laboratory tests are less expensive than pilot-scale tests, but the pilot-test better approximates the reality of the actual mining.

#### Table 15: Example of the results obtained when performing an analyse

<table>
<thead>
<tr>
<th>coordinates:</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
<td>33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>depth (layer)</th>
<th>Fe grade (%)</th>
<th>Si grade (%)</th>
<th>P grade (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>46.5</td>
<td>46.5</td>
<td>2.9</td>
</tr>
<tr>
<td>1</td>
<td>41.2</td>
<td>51.8</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>19.1</td>
<td>73.9</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>46.4</td>
<td>46.6</td>
<td>2.9</td>
</tr>
<tr>
<td>4</td>
<td>66.9</td>
<td>26.1</td>
<td>3.0</td>
</tr>
<tr>
<td>5</td>
<td>56.1</td>
<td>36.9</td>
<td>3.0</td>
</tr>
<tr>
<td>6</td>
<td>80.1</td>
<td>12.9</td>
<td>2.8</td>
</tr>
<tr>
<td>7</td>
<td>66.2</td>
<td>26.8</td>
<td>3.0</td>
</tr>
<tr>
<td>8</td>
<td>61.0</td>
<td>32.0</td>
<td>3.1</td>
</tr>
<tr>
<td>9</td>
<td>66.0</td>
<td>27.0</td>
<td>2.9</td>
</tr>
</tbody>
</table>

#### Table 16: Available tests and analyses in the game

<table>
<thead>
<tr>
<th>Tests</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical analysis</td>
<td>Elemental assays, Satmagan</td>
</tr>
<tr>
<td>Automated Mineralogy</td>
<td>Mineralogy, Grain Size</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>Specific gravity</td>
</tr>
<tr>
<td>Grindability test</td>
<td>Bond work index</td>
</tr>
<tr>
<td>Davis tube test</td>
<td>Fe, Si, P grade, Fe recovery, Mass pull</td>
</tr>
<tr>
<td>Laboratory-scale test</td>
<td>assays and mineralogy of concentrate and tails, elemental and mineral recovery, Mass pull</td>
</tr>
<tr>
<td>Pilot-scale test</td>
<td>assays and mineralogy of concentrate and tails, elemental and mineral recovery, Mass pull</td>
</tr>
</tbody>
</table>


The player can move to the next phase once two conditions are met: 33% of the budget for exploration is spent, and every different kind of analysis and test were performed at least once. The game automatically calculates the minimal money required to perform at least the required analyses and tests and stops the player if he doesn’t perform what he must. A checklist is present and indicates what the player should do.

Whenever the player estimates it necessary, even during next phases, he can drill more as long as he has sufficient budget. The menu called “Drilling” is accessible at all time.

The player can access the next phase by clicking on a box called “Next phase”.

IV.1.4 Phase 2: Construction

The second phase is the construction phase. During this phase, the player must decide the mining equipment (various trucks are available) and facilities needed to start operations. The player uses a bank loan to buy the different items.

IV.1.4.1 Processing plant

When the flowsheet is selected, the player must select a place on the map to build the processing plant. The player must select a place that they are sure not to mine. When entering that part, the player sees the map and the surface required in transparency. The surface moves with the pointer of the player and its orientation can be switched by clicking a key on the keyboard. The transparent surface appears in red if it cannot be placed where the player points, in green otherwise. The player then chooses the entrance of the processing plant by clicking on one of the blocks that is in contact with the inside area (in green in the next picture).

IV.1.4.2 Flowsheet selection

The player must decide the flowsheet that will be used. The player does so by selecting parts of the process, the flowsheet units. The first part is the selection of the grinding. The two possible choices are a ball mill and a semi-autogenous mill. The second part consists in selecting the methods used for separation. The magnetic separation is a required part. The player can invest to add a flotation unit or a gravity unit. As a result, there are 8 different flowsheets: Magnetic only, Magnetic + flotation, Magnetic + gravity, Magnetic + gravity + flotation, multiplied by the two possibilities for crushing and grinding. The costs in terms of money and energy are specific to each flowsheet unit.

IV.1.4.3 Placing tailings and mine entrances

To place the tailing dam entrance, the player must first select a block at the edge or the area that is not within the processing plant area, and cannot be directly touching it. The entrance of the mine must then be selected by clicking on a block that is not within the processing plant area and cannot be directly touching this area and the tailing dam entrance.
IV.1.4.4 Select the mining method

After selecting the starting points of the mine, a dialogue box appears asking “How are you going to do it?” with two clickable options: “Open-pit mining” and “Underground mining”. If selecting Open-Pit, the player can start to mine immediately. If selecting Underground, a warning box appears saying “Warning: Once you go underground, you cannot go back to Open-pit for this sub-mine. Are you sure that you want to go underground?” with “Confirm” and “Cancel” buttons. If the player confirms, a dialogue box appears and asks the player to select a block where the production shaft of the underground mine will be. Once the production shaft is placed, the player must click a nearby block less than 8 blocks away for the ventilation shaft. After placing the shafts, the player can start the exploitation at the created mine. It is important to mention that the column corresponding to the shafts cannot be mined.

IV.1.4.5 Connecting the mine to the processing plant with roads

Once the first block is decided for the mine project, the player must connect this block to the entrance of the processing plant by constructing a road. A message appears asking the player to connect the mine by picking blocks, similarly to the procedure followed when picking blocks for mining (see later). To be a road, a block must be on the very first layer of ground. The road will then be used to determine the costs of transports, and constructing a road costs money proportionally to the amount of blocks picked for making the road. Only one road should be connected per mine project.

IV.1.4.6 Additional equipment & tailings

The player must then select the additional equipment that is required. A menu opens up asking “Which trucks are you going to use?” with different options. When clicking on one of the choices, another menu opens with details about the trucks, a “Confirm” button and a “Cancel” button.

The player also must buy the other infrastructures that are required for the staff members and for water and electricity, the excavators and specific devices that depend on the mining method.

The player has to select the entrance of the tailings dam by clicking a block at the edge of the area that is not within the processing plant. Then, the player must select a similar point at least 7 blocks away from the entrance to the tailings dam for storing the outcrop and the soil. This distinction is important for the phase 4, the rehabilitation.

The player can then access the phase 3.

IV.1.5 Phase 3: Mining

This phase is the only one where positive cash flow can be generated. During this phase, the player can pause the game at any point to take time to acknowledge the situation, check the price evolutions, give orders etc.
IV.1.5.1 Starting to mine

Mineable blocks

The design of the mine must respect safety rules. Some constraints make it impossible to mine the blocks without caution. When trying to mine blocks, a mineable block will appear green while the others will appear red. The player can change the layer he is looking at by scrolling.

Common rules for both Open pit and underground mine

To be mineable, a block must respect conditions:

- Being in contact with a previously mined block (or block picked for mining) of the same mine project, except for the first block being mined in a new project;
- Not being a block used for a road or conveyor belt;
- Respect the safety distance between two different mine project (see later);
- Respect the specific conditions of open-pit or underground mines.

If the player clicks on a block which is a road, the message that appears is a modified version of the base message, indicating that “This block is a road. You have to modify your roads first!”.

In case of Open Pit

The blocks have different parameters and statistics including their strength: Soft, Hard. Whenever the player wants, he can access a document in the menu “Documents” called “current stability”, which indicates which blocks are Soft (green) or Hard (Red). This parameter is important for pit and cave design:

- A Soft block cannot have a slope steeper than approximately 30°;
- A Hard block cannot have a slope steeper than approximately 45°.

These slopes can be approximated by imposing conditions to mine a block.

The conditions are simple: when the player wants to mine a block at the layer n, the 9 blocks situated in the upper layer (layer n-1) must be already mined, and any soft block in the 12 blocks in the layer n-1 surrounding these 9 blocks must be mined (Figure 27).

In case of underground mine

Regarding underground mine, inspired by cut and fill method (Figure 28), a similar condition is required. To be mineable, a block at layer n must touch a non-empty block directly above and directly below itself (Figure 29). The non-empty blocks are untouched or back-filled blocks (see later). Within the game, it is possible to mine under a backfilled block. The other limitation regarding the expansion of the mine is the quality of the air renewal. As a result, every time the underground mine reaches n * 100 blocks mined, an upgrade of the ventilation system is mandatory. See the Upgrades paragraph for further details.
Figure 27: Illustration of the game-concept of open-pit shape.

Figure 28: Illustration picture of the method used here for underground mining, source: Steemit.
IV.1.5.2 How to mine

**Directing and mining a block**

Every block that is mined can be either directed directly to the tailings dam as waste, to a raw-block stockpile or to the processing plant. Blocks that are sent to tailings as waste only cost the mining costs. Regarding the blocks sent to the processing plant, they are then either directly sold at the market prices, or stored in a processed-produce stockpile to be sold when the price increases. For further details, see the specific paragraph.

To mine a block, the player must then click on the “Let’s mine!” button. He can then select one or more blocks that will be mined in the same order he picked them. The blocks that can be mined appear in green when pointing them, the blocks that cannot be mined appear red. The blocks turn grey when they are picked by the player. Once the player has picked the blocks, he clicks on a button “Direct”, which opens a dialogue box with 4 choices: “To tailings”, “To raw block stockpile”, “Process then sell”, or “Process then store”. If any of the stockpile is full, a warning message indicates that “The [raw block/processed produce] stockpile is full. Every block that you send will replace an old stored block that will be sold.”. The player can then confirm or cancel. The blocks are mined when the game is not paused.

After a block is processed, the tails from the processing plant are automatically sent to the tailings dam.

**Safety distance between different mine-projects**

In order to avoid issues and ensure safety, it is important to avoid proximity between an open-pit and a cave of the underground mining. A cave from (e.g.) underground mine-project 2 cannot be less than 2 blocks away from the open-pit of mine-project 1.

Regarding the safety distance between two mine projects using the same method, that safety distance is reduced to 1 block.

**Converting an open-pit to an underground mine**

When operating an open-pit mine project, the player can convert it at will to an underground one if he estimates it necessary to mine more ore. A button called “Convert to underground
mine” is available, and when clicked, the player can follow the procedure when starting an underground mine (see “Select the first block and the mining method”).

There is no depth limit that forces the player to change the method from Open-pit to Underground. At any moment the player can convert an Open-pit sub-mine to an underground one. The opposite is not possible.

**IV.1.5.3 Organize the mine**

*Switching projects*

The player must deal with as many mine-projects as he decided to create. The player can pause the game at any time. The pause applies to every mine projects and the player can switch between them while they are paused by clicking on a button called “Next project”. It is possible to shut down a mine project whenever the player wants to spare on salaries.

*Backfilling blocks when using underground mining*

In order to be able to mine more than half of the layers of ore when using underground mining, the player is able to fill back the tunnels once he estimates that he mined all the accessible ore in the area. He can use the “let’s mine button” and use a right click to fill an empty block with concrete. This operation turns the empty block into a Backfilled block with no value, and reduces the amount of material in the tailings dam by 0.5. The player can fill any empty block but should start from the end of each tunnel to not lock an empty tunnel.

*Raw block stockpile behaviour*

The objective of this stockpile is to keep a stable feed to the processing plant. The initial capacity of the Raw-block stockpile is 10 blocks. The blocks that are mined and sent there are virtually separated in tiny piles of one block each. Whenever the player wants, he can access the parameters of the stockpile by clicking “Check Stockpiles” then “Check Raw block stockpile”. The content of the stockpile can be sent to processing whenever the player wants by clicking “empty Stockpile”, and then send selecting the blocks to process. Then, the player has the choice between “process then sell” and “process then store”.

When the size of the stockpile reaches 80 % of its capacity, a warning message is displayed indicating that “The raw block stockpile is at 80% full.” When the size of the stockpile reaches 90 % of its capacity, a warning message is displayed indicating that “The raw block stockpile is at 90% full. You will soon not be able to send more blocks.”. When the stockpile reaches 100%, it is locked and the player cannot send more material there. The only possible things are to reduce its size or upgrade it.

*Processed-produce stockpile behaviour*

The objective of the Processed-produce stockpile is to be able to sell the produce when the price is higher. The initial capacity of the Processed-produce stockpile is 35 units. The units that are processed and sent there are mixed, so the composition of the stockpile is the average of the units sent there. Whenever the player wants, he or she can access the parameters of the stockpile by clicking “Check Stockpiles” then “Check Processed-produce stockpile”. The
content of the stockpile can be sold whenever the player wants by Clicking “empty Stockpile”. A dialogue box opens asking “How much do we sell?” and the player inputs the amount of units to sell.

When the size of the stockpile reaches 80 % of its capacity, a warning message is displayed indicating that “The raw block stockpile is at 80% full.” When the size of the stockpile reaches 90 % of its capacity, a warning message is displayed indicating that “The raw block stockpile is at 90% full. You will soon not be able to send more blocks.”. When the stockpile reaches 100%, it is locked and the player cannot send more material there. The only possible things the player can then do are to sell or upgrade it.

Managing time and feed for processing

The blocks sent to the processing plant are put in a queue of 5 units. When the queue is full, the mining activities are halted until a spot is liberated in the queue. It is important for the player to think about the time required to process the blocks he or she sent there before sending more. The harder blocks are also longer to process. Indeed, they require more time for crushing and grinding.

Modifying the road system

If the roads must be modified to enable further mining, the player can click on a button called “Modify road organization”, which pauses the game and enable the player to deconstruct parts of the roads by pressing Right-click, and placing new roads by pressing Left-click. When the player is done, and if the road is not properly done, a warning message appears and mentions “Issues in the road. Check your work for any issue.”. Otherwise, if the roads connected to mine projects were modified, the game asks the player to select a new road block to serve as connection or to return to the previous step.

Deconstructing a road is free but constructing a new road costs the regular price. The player can experiment while modifying insofar as the costs are applied when the new road system is finalised and the player clicks “Done”.

IV.1.5.4 Costs and price evolutions

Profits and income sources

There are three ways for the player to generate positive cash-flow. The first one is the company allowance at the beginning of the game that is supposed to pay for the drill program. The second one is the bank investments or loan that the player can obtain at the beginning of the construction phase. The last one is by selling the concentrate obtained during the mining phase.

Price of the concentrate

The parameters that define the price of the concentrate are:

- The iron content, which determines the base value;
- The silica content, which reduces the value of the produce;
- The phosphorus content, which reduces the value of the produce;
- The price evolutions of the market.

Penalty elements are regarded as penalty elements only if they exceed a certain value. If they exceed the requirements, the value of the produce is reduced by a percentage that is proportional to the concentration of penalty element.

**Operating costs**

The operating costs include:

- Mining of the blocks
- Transport of the mined blocks
- Processing costs
- Storage costs
- Salaries

The cost of mining a block depends mostly on its properties. The harder it is, the more expensive it is to mine. The cost of transport depends on the X+Y distance between the initial coordinates of the block and the coordinates of the road connected to the mine project, plus the road distance to the outcrop and soil dam entrance or the processing plant entrance. For example, if the block at coordinates XYZ = (20, 23, -2) is mined and the beginning of the road is at (3, 25, 0), then the transport distance is $D = |20-3| + |23-25| = 17 + 2 = 19$. Then, if there are 20 units of road to reach the entrance of the processing plant, the total distance is 39. The transport costs are then calculated based on the fuel consumption trucks that are used and the distance.

The processing costs include the crushing, the grinding, the sorting costs, the separation (physical, flotation), plus the electricity costs of ventilation systems, trucks etc. The costs for water make-up are also important.

Storage costs are calculated monthly depending on the amount of material stored in the stockpiles. The salaries are monthly costs that depend on the amount of mine projects.

**Upgrades**

Whenever the player wants, he can upgrade parts of the equipment to try to reduce the costs or improve the positive cash flows.

Possible upgrades are:

- Improved water recycling system, that reduces the costs of water but slightly increases the costs of energy;
- Flowsheet modifications: the player can buy a flowsheet unit he didn’t invested in during phase 2, and can at will modify the flowsheet. For example, a player who invested in a magnetic + gravity process can buy the flotation unit, activate it and deactivate the gravity unit to obtain a magnetic + flotation process.
- Extension of both stockpiles by 20% of their initial capacities, available three times;
- Improvements regarding the ventilation system of underground mines. It’s the only upgrade that is mandatory to mine further when mining underground;
- Better roads reducing the oil consumption of the trucks.

Research and development cost money for each upgrade. The upgrades are designed to be progressive: some are less expensive and are available in the beginning, others are available later.

**Economics**

The price per iron content of the produce changes during the game because of market price fluctuations. The player should have access to the price evolutions and should be told about them using the “Documents” section. In order to enable players to play again with the same conditions to improve their results, the evolutions are procedurally generated using a seed.

The player should start with a loan that makes exploration and building possible. The objective of the player will then be to gain as much as possible and at least refund the loan. The player should then have access to key estimators like net present value or internal rate of return.

When the player estimates that it is not possible anymore to earn money with the projects, he can move to phase 4.

**IV.1.6 Phase 4: Rehabilitation**

The objective of this phase is to properly shut down the mine. This phase will cost money but some value can be recovered by selling parts of the equipment.

The underground mines can be closed and backfilled. The amount of tailings that can be used for backfilling is 50% of the total volume of the underground mine. After this potential backfilling, the rehabilitation requires to buy an amount of clay and soil determined by the total size of the tailings dam and the blocks that were stored in the soil and outcrop dam. An example of the formula for such a calculation could be (equation 7):

\[
clay\ required = \frac{1}{2} \times (\text{blocks in tailings} - 2,5 \times \text{blocks in soil dam})\quad \text{Equation 7}
\]

After the rehabilitation, the game ends and the player can see the results of the mine.

This rulebook summarizes efficiently the main aspects of a mine, but with the constraint of relative simplicity forces to discard interesting aspects. For example, the various underground mining methods are reduced to the cut-and-fill method only.
IV.2 Block model

The mineralogical compositions were simulated independently, their results were compared one by one. It must be noted that the values here are the raw values, without normalization.

IV.2.1 Results of actinolite simulation

The 3D model of actinolite (Figure 30) appears successful around the main orebodies, and the values tend to vary more at the edges of the area. When analysing the grade frequency distribution (Figure 31), it appears that 3 groups of values emerge: 25% of the cells have a low actinolite content (below 2%), around 5% have a high content (above 26%), the rest is between 2 and 26%. It can be noted that the results are slightly smoothed insofar as transition trends are observed with gradually decreasing frequencies between 2% and 8% and between 24% and 28% of actinolite content. The steps are still highly noticeable and the parameters of interpolation could be changed.

Figure 30: Result of the model of actinolite concentration before normalization.

Figure 31: Histogram of the content of actinolite before normalization.

IV.2.2 Results of albite simulation

The 3D model of albite (Figure 32) shows lower values at the location of the orebodies, and it also appears that the results decrease rapidly when no sample values is nearby. In order to correct this issue, two solutions are possible: simulating the direct proximity of the orebodies as an independent region or modifying the parameters of albite model.
Regarding the histogram (Figure 33), it appears the values are higher than expected, with a large proportion of the values being between 40% and 60% of albite.

![Figure 32: Result of the model of albite concentration before normalization.](image)

![Histogram of Value](image)

**IV.2.3 Results of apatite simulation**

The 3D model of apatite (Figure 34) appears to be fitting the location of the orebodies, especially the one at the North-West which is supposed to be an apatite-ore type. There are several areas where the value increases with smooth transitions.

Regarding the histogram (Figure 35), it appears that around 84% of cells are below 1% of apatite. The rest is spread between 1 and 10%, which is a decent representation.
IV.2.4 Results of biotite simulation

The modeling of biotite (Figure 36) appears similar to the one of Actinolite. Indeed, the concentration of biotite is lower on the location of orebodies as well as on other areas, but when analysing the histogram (Figure 37), two categories of values appear, without much smoothness. The parameters of biotite could require to be changed.
IV.2.5 Results of epidote simulation

The 3D model of epidote (Figure 38) appears different than the others, with large areas connected together and have smooth transitions. The analysis of the histogram (Figure 39) reveals two groups of values that didn’t interfere with each other. This is likely to be caused by the initial values that are low for every lithologies except skarn, and the low value of the total sill.
IV.2.6 Results of hematite and magnetite simulations

The models of hematite (Figure 40) and magnetite (42) are almost identical, with high values at the location of the orebodies, and low and fluctuating values on the other parts. It is noticeable that the Southwestern orebody is richer in hematite, while the Southeastern orebody is richer in magnetite. Such results are positive insofar as they will offer more diversity regarding the ores they are mining. The histograms of Hematite (Figure 41) and Magnetite (Figure 43) are also almost identical in terms of shape and distribution, with a slightly less steep decrease in frequencies of lower values for magnetite.
Figure 40: Result of the model of hematite concentration before normalization.

Figure 41: Histogram of the content of hematite before normalization.

Figure 42: Result of the model of magnetite concentration before normalization.
IV.2.7 Results of quartz simulation

The 3D model of quartz (Figure 44) is the most constant and regular one with only the orebodies showing a low grade of quartz. The histogram (Figure 45) reveals that the values used initially were not really affected by the interpolation.

![Figure 44: Result of the model of quartz concentration before normalization.](image1)

![Figure 45: Histogram of the content of quartz before normalization.](image2)
IV.2.8 Results of grain size simulation

Eventually, the modeling of the grain size, useful in the BWI estimation, reveals two major groups of values (Figure 46). A low value group between 0 and 5mm which represents 85% of the points, and a higher value group above 5mm which corresponds to the orebodies.

![Histogram of Value](image1)

*Figure 46: Histogram of the value of grain size in mm.*

IV.2.9 Results after normalization

After using normalization and reshaping the model within a 40*40*10 block model, the cells can be ordered in increasing order of magnetite content in order to determine the amount of blocks that could be regarded as ore. It appears (Figure 47) that among the 16000 blocks that form the block model, only 1700 contain more than 10% of magnetite, and could as a result be regarded as ore.

![repartition of magnetite% for every database point](image2)

*Figure 47: Magnetite% of every block of the database, in increasing order.*

As a result, this block model could be improved to offer more realism to the player, but the objective of obtaining a simplified and realistic geological model to use in the database is reached.
IV.3 Processing database

The efficiency of the different flowsheets can be estimated by analysing their respective recovery of iron (Table 17).

Table 17: Mean, median and standard deviations of the Fe recoveries of the different flowsheets.

<table>
<thead>
<tr>
<th>Flowsheet</th>
<th>Statistic parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball mill, magnetic separation only</td>
<td>Mean</td>
<td>95.5%</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>95.5%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>0.170</td>
</tr>
<tr>
<td>Ball mill, gravity separation and magnetic separation</td>
<td>Mean</td>
<td>71.1%</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>71.1%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>12.065</td>
</tr>
<tr>
<td>Ball mill, magnetic separation, and flotation</td>
<td>Mean</td>
<td>88.6%</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>88.6%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>0.38</td>
</tr>
<tr>
<td>Ball mill, gravity separation, magnetic separation and flotation</td>
<td>Mean</td>
<td>66.2%</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>66.1%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>11.25</td>
</tr>
<tr>
<td>SAG mill, magnetic separation only</td>
<td>Mean</td>
<td>95.5%</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>95.5%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>0.17</td>
</tr>
<tr>
<td>SAG mill, gravity separation, and magnetic separation</td>
<td>Mean</td>
<td>71.1%</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>71.1%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>12.07</td>
</tr>
<tr>
<td>SAG mill, magnetic separation and flotation</td>
<td>Mean</td>
<td>88.6%</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>88.6%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>0.38</td>
</tr>
<tr>
<td>SAG mill, gravity separation, magnetic separation and flotation</td>
<td>Mean</td>
<td>66.2%</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>66.2%</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>11.28</td>
</tr>
</tbody>
</table>
The choice of the grinding method does not particularly affect the results in terms of recovery. Indeed, the only difference in the process is the P80 of the ore after grinding. Both types of mills used a grate or 0.2mm, but the P80 of the SAG mill is slightly smaller. It results in barely noticeable differences in terms of data deviation.

The various recoveries that are observed can be explained by several factors. For flowsheets using gravity separation, the mean recovery is lower but the standard deviation is larger. Indeed, flotation is designed here to remove apatite from the final product, and magnetic separation sends mostly quartz and albite to tailings. Flowsheets not based on gravity separation are less influenced by the initial amount of iron in the feed (Figure 48) while flowsheets that use gravity separation are more influenced by the initial grade of iron, especially for low-grade blocks (Figure 49). A reasonable explanation of this phenomenon is the selectivity of the separation process. Flotation is focused on apatite whereas magnetic separation uses a wide range of mass susceptibilities while the different mineral densities are quite close to each other.

![Figure 48: Iron recovery as function of Fe wt% of feed](image)

*Figure 48: Iron recovery as function of the grade of iron in the feed for SAG per block – magnetic separation only flowsheet.*
Flotation separation decreases the global iron recovery by 5% to 7%. The positive impact of flotation should then be properly studied in order to increase the benefits. The composition of apatite could also be modified as well as other parameters like its mass susceptibility. Indeed, the mass susceptibility of Fe-rich apatite is likely to be higher. Nevertheless, the addition of a flotation step doesn’t prove efficient.

The analysis of the separation efficiency reveals a correlation with the grade of albite in the feed (Figure 50). This correlation can easily be explained by the gravity and the magnetic separation insofar as for both methods, albite is a mineral that is sent to tailings with good efficiency.
It is also noticeable that while laboratory tests and pilot tests use some different parameters, there is an almost perfect correlation between the two methods, even though it appears clearer for element recoveries than for mineral recoveries (Figure 51, Figure 52). This is an important benefit for gamification purposes insofar as users will be able to find trends and extend their knowledge of the process.

Figure 51: Comparison between regular processing results and laboratory test results for Fe recovery, Ball mill, magnetic, gravity separation and flotation.

Figure 52: Comparison between regular processing results and laboratory test results for apatite recovery, Ball mill, magnetic, gravity separation and flotation.
IV.4 Geometallurgy model

IV.4.1 Profitability estimations

A complete geometallurgy model cannot be shown at the moment insofar as the game is still in programming. Indeed, as explained previously, many values are likely to be changed during the testing of the game. The objective of the player being to reach a certain amount of money, the experience would be ruined if the costs of processing are always higher than the revenue obtained by selling the ore. An explanation of the calculation of the benefits obtained for each block can be done though. The costs should include:

- Blasting costs;
- Transport costs (equal to the distance multiplied by the oil consumption);
- Processing costs (equal to the consumption of reagents, water and electricity multiplied by their respective prices, and added all together);
- Salaries (equal to the daily salary of the employees multiplied by the number of days required to mine the block).

The selling price of the ore is calculated by multiplying the amount of concentrate to the current selling price on the market and to the quality coefficient. If the penalty elements cause a 20%, 30% or 50% penalty, this coefficient will be respectively 0.8, 0.7 or 0.5, reducing the income of the ore. If the penalty exceeds 50%, the ore is not sellable and the coefficient is then set at 0.

By applying only processing costs and penalty elements, it appears that the flowsheets that do not use gravity separation are not profitable insofar as no block fulfils the penalty requirements. Indeed, the magnetic separation and flotation flowsheet recovers more than 87% of actinolite, biotite and epidote resulting in a silica grade above 2%. These results are caused by the flotation kinetics that were similar for most minerals and by the higher mass susceptibility of actinolite, biotite and epidote compared to quartz and albite. Different parameters for the second magnetic separators could improve the efficiency, but a more realistic approach would be to integrate particle liberation properties. Such an approach would surely require laboratory testing.

The question is then to evaluate the efficiency of flotation. When calculating the potential benefits of mining only the profitable blocks with a constant ore price of 100 $ per ton of ore, and neglecting transport, mining time and salaries, the total income of using gravity, magnetic separation and flotation is approximately 6940 M$, while it is approximately 7500 M$ for a flowsheet without flotation. The number of blocks that cannot be sold because of a high content of phosphorus is reduced, and as a result, the flowsheets using flotation should be used as a specific method for apatite-rich areas and not as a general flowsheet in order to maximize profits.

The difference between the profitability of ball mill and SAG mill is tighter. Indeed, using the same approach, the total potential income of using SAG mill with gravity and magnetic separation is approximately 7400 M$, which is a bit less than the same flowsheet with ball
mill. As a result, the best flowsheet is the one using ball mill, gravity separation and magnetic separation.

The addition of the costs of salaries, transportation etc. can be used to obtain a model of the optimal depth at which the player should transition between open-pit and underground mining. With a total daily salary of 56 k$, a base distance of 10 blocks between the mine and the processing plant and an ore price of 100 $ per ton of ore, a basic model can be established. Indeed, every block beneath the first layer requires at least the upper blocks to be previously mined. A block at layer n (if n>1) requires a certain amount of upper blocks to be mined, defined by this formula (Equation 8).

\[ \text{amount of blocks} = \sum_{i=1}^{n-1}(2i + 1)^2 \quad \text{Equation 8} \]

Mining a block at layer 5, for example, requires the 164 blocks above to be previously mined. Assuming a total mining cost of approximately 400 k$ (with seven days of mining time, 50 k$ of daily salaries and 50 k$ of maintenance, blasting, transportation etc.), the total cost of mining for a block at layer n can be estimated (Table 18).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Total costs (k$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>4000</td>
</tr>
<tr>
<td>3</td>
<td>14000</td>
</tr>
<tr>
<td>4</td>
<td>33600</td>
</tr>
</tbody>
</table>

Table 18: Required mining costs depending on the layer of the block

The player should then think about using underground mining after layer 3 in order to increase the final benefits. But this transition requires backfilling which increases the costs. Open-pits should be used mostly for large orebodies to delay the transition to underground mining. Underground mining can be used for every ore bodies but the benefits are reduced.

IV.4.2 Propositions of various strategies for the players

Several potential strategies can be proposed by the players:

- Reduced waste strategy with open-pits, which consists in focusing on mining the ore and not the host rocks. It results in small pits, with a maximum depth of three blocks. This strategy is linked to a short life-of-mine which is efficient insofar as rehabilitation costs are drastically reduced as well as losses due to blocks being directly sent to waste. This strategy would imply to not invest in the different upgrades available.

- Optimized transitions between open-pits and underground mining, which consists in mining as much as possible using open-pit until underground mining becomes more
valuable. This strategy expands the life-of-mine but increases the costs insofar as underground mining, due to mandatory equipment, is more expensive.

- The very-long-term strategy, which consists in investing as much as possible during exploration in order to get a clear model of the area, and buying every upgrade at the very start of the game. By using hybrid trucks, and using optimized transitions between open-pits and underground mining, the players can try to maximize the long-term profitability. This strategy is related to higher risks and should be done by more experienced players.

There are hundreds of potential variations of these strategies depending on the choices of the player regarding their investments, the moment they invest, their sampling methods, their preferred mining method, their mine-organization, the moment they decide to sell the ore, the flowsheets they use etc.

The purpose of this game is then reached insofar as it offers a realistic depiction of the constraints of mining and geometallurgy, while also giving a large diversity of methods and approaches. The multiple potential choices result in a wide spectrum of strategies that can be modified during the events of the game, stimulating the sense of adaptation of the players.
V - Conclusions and recommendations

The adapted Design thinking framework was used to elaborate the game concepts of the geometallurgy game and enabled a good representation of a gamified environment. The rules are complex as a whole but the division of the game in phases results in a better understanding of the mining systems. The simplifications are adequate and offer a wide range of possibilities. The rules are made to ensure that the players never feel restricted: they are allowed to do mistakes and can even take bad decisions. The final results ensure that a feedback is given to the player in order to procure experience and a better understanding of each decisions.

The database was obtained by following a slightly adapted procedure, based on the real methods. Logs are included at important places of the area and used as a base for a geology model using non-geostatistical interpolation. Eight different flowsheets were created to simulate the mineral process model, which complements the database.

The structure of the game can also easily be adapted to other cases with different orebodies and different mineral of interest. Indeed, the method described here is focused on simplicity and efficiency. The rules and economic aspects are likely to remain similar.

In order to offer an experience closer to reality, the part that should be improved is the geological modeling. Indeed, a geostatistic approach would be beneficial. In order to do this, two solutions exist: either the use of a perfectly known deposit with an existent block model, or the creation of a full-synthetic model, for example with thermodynamics. The second approach being much more complex, the use of an already defined model seems more suitable to a geostatistical approach.

If a similar method to the one explained here is used, a few recommendations should be done: the data used to generate the geological model should be de-clustered and the interpolant should be extended. It would also be particularly useful to modify the initial data generation insofar as the limits of randomization quickly appeared. Ideally the game should use a fully artificial deposit area that is already known underground. The development of a software for quickly generating some basic models with a few parameters like the ore, the geological context and the size of the area, would be a wonderful tool for the future of this serious game.

Another solution would be to integrate the flowsheet creation in the simulation by adding the several models to the game itself. This would reduce the size of the mandatory database and offer a unique experience to each player. The geological modeling could also be integrated, but this would require years of development or cooperation with existing software like Leapfrog, IoGas, or ModSim. The potential result would be an ideal teaching tool, but it would be less a game than a modeling software.

The game developed here could also be expended by adding other parameters to take in consideration. The maintenance, the logistics, the exportation, and even negotiations could offer a more diverse experience. Other aspects like social and environmental impacts would lead to more responsible approaches and could prove beneficial on the long term to fulfil future needs with sustainable solutions. The player could also decide the salaries of the
different employees, that could be a reason for protests and discussion. Accidents could occur, forcing the player to halt the activities or to take in consideration a longer mining time.
VI – Relevance of this thesis for sustainable raw material supply

The geometallurgical game developed in this thesis is a part of an EIT funded project called Emeraldinho. It is a project that seeks to grant students the assets they require to learn and acquire an entrepreneurial mindset. By organizing different activities like business school, field trips or seminars, the project develops a collaborative environment among its participants. The different backgrounds, origins and interests of the students results in a cross-disciplinary approach to tackle the challenges of geosciences and engineering. Through these challenges, the students can stimulate their creativity and their entrepreneurial mindset, two relevant qualities for both academic and industry careers.

The topic of gamification is relevant for Emeraldinho, as it contributes to develop a virtual teaching method for geometallurgy. The methods of gamification imply both a deep and precise knowledge of the mining and geometallurgy fields, and a sense of creativity. Indeed, translating real-life constraints into computable constraints requires various ideas, attempts and concessions to be successful. It is also worth mentioning that the cooperation with EcoSim adds technical constraints in terms of feasibility, efficiency and optimization.

The definition of sustainability involves three main elements: social, economic and environmental perspectives. This thesis is linked to all these aspects. Indeed, this gamified approach of geometallurgy is developed to encourage the future generations of mining engineers to understand the mining industry and contribute to the economical world of tomorrow. Mining will remain a capital domain of our societies and is linked to the economic growth of several countries. With the development in France of Lithium extraction, a specialty in mineral processing is a valuable asset. The requirements within the serious game to take decision based on scientific facts could also be important to reduce economical risks in the future.

The social aspect of this game is also a major one. Indeed, this game could contribute to the development of other serious games that could benefit the societies. The possibility to use modern tools and new technologies is likely to maintain interest in education. The accent put on responsibility within the game is also a key to highlight the precautions that are taken within the mining industry, that could result in a more nuanced perception of mining by the public. The social concerns are currently a major issue for the mining industry due to communities’ high expectations in terms of positive outcome and to a lack of public trust (S. Bloch, 2019).

Eventually, the environmental aspect is less developed, but could be expanded in this game with more development time. The accent put in the game towards rehabilitation in the end of a session is not a major aspect, yet it aims at installing the idea that rehabilitation is mandatory after mining an area. Future perspectives of this game could integrate more hazardous choices, for example the possibility to use cyanides for gold recovery, which would raise social and environmental concerns.
The impacts and positive outcome of this geometallurgy game are likely to have a small but noticeable impact on the long term. Indeed, the game uses concepts that are taught in class but could be easily forgotten. For example, among the other students of the cohort, the perceptions of social and environmental aspects varied significantly. This simulation makes these notions more concrete and could prove to be efficient in conditioning the future engineers to the benefits of using a geometallurgical approach as well as having an entrepreneurial mindset.

This project also significantly helped me to develop my notions of geometallurgy. Creating the game rules while respecting the reality and the technical constraints was an interesting challenge and as several teachers told me, the best way to learn is to teach. The required simplifications lead to a better understanding of the fundamental aspects of geometallurgy.

Eventually, this project is likely to be a valuable asset for my future perspectives. Indeed, several projects in Europe could benefit from the experience in geometallurgy, management and processing that was offered within the Emeraldinho project. The creation of a mining software for students could also be an asset if I eventually decide to become a teacher myself. Developing this project increased my awareness of the needs and expectations of the students as well as the various tools that can be used to get their interest.
Funders and special thanks

I would like to thank EIT Raw Materials for funding this project and for their important contribution to the Emerald programme and the Emeraldinho project. With their contribution, I was able to develop a wide range of skills and expand my international network.

I would also like to thank Associate Professor Mehdi Parian for his advices when creating the HSC flowsheets and Balazs Orova from EcoSim for his professionalism and availability when developing the game rules.

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References


SGU (Sveriges Geologiska Undersöckning), [https://www.sgu.se/ - Website of the Sveriges Geologiska Undersöckning](https://www.sgu.se/) [last consulted 14/08/2023]

Sigamony, A. (1944). The magnetic properties of tourmaline and epidote.


Steemit, [https://steemit.com/science/@mannylumanao/5z1ca1-the-three-common-underground-mining-methods-science-and-education - Website that mentions and explains the main underground mining methods](https://steemit.com/science/@mannylumanao/5z1ca1-the-three-common-underground-mining-methods-science-and-education) [last consulted 14/08/2023]


