INSIGHTS FROM UTILISING DEM FOR RE-DESIGN OF A CONE CRUSHER FEED SYSTEM

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ABSTRACT

The discrete element method (DEM) is used extensively for modelling particle systems in a wide range of research and industrial areas. The simulations are typically performed to solve a problem, evaluate novel ideas or elicit knowledge regarding some system. However, there are very few examples in the literature where development and problem-solving strategies for particle-machine systems, in particular, are outlined. In this paper, we propose and evaluate a methodology for efficiently utilising the discrete element method in a problem-solving process. The example case application used to demonstrate this methodology is the feeding of a cone crusher at a mining site in North America. The DEM simulations are performed with the In-house DEM code Demify® developed at the Fraunhofer-Chalmers Centre. Rock particles are modelled using a non-convex polyhedral irregular shape representation with massively parallelised high-performance computation on graphical processing units (GPUs).

The results demonstrate how the DEM simulation can aid the engineering team and provide a more robust decision-making process. The final feeding solution resulted in a substantial improvement concerning production and liner wear rate in particular. The liner wear replacement period increased from around 3-4 weeks to 4 months, saving substantial cost, production downtime and energy solely from the liner wear improvement.

Keywords: DEM, cone crusher, feeding, simulation-based design, wear

1 Introduction

The Discrete Element Method, originally proposed by Cundall and Strack [1] is used for modelling particle systems in a wide range of industries such as pharmaceuticals, minerals processing, infrastructure, energy, additive manufacturing and many others. With the increasing technological maturity over the past decade, DEM is now used extensively in an industrial context. The technology adoption means that the industrial stakeholders expect that the DEM modelling and simulation efforts will be of instrumental value for developing new products and processes as well as aiding in solving problems. With the use of DEM, it is possible to gain otherwise impossible insights; however, there is a computational cost associated with large scale DEM simulations that can not be overlooked. This means that any engineering activity without a well-defined development strategy will likely result in trial and error simulation iterations and ad-hoc non-optimal solutions—both highly undesirable outcomes in the industrial context.

In this paper, we demonstrate the use of a system engineering approach for DEM, described in [2], based on an industrial case example. The authors have successfully applied the framework in several projects related to rock material flow and other bulk materials handling applications.

Particle solids that move in granular transportation systems such as conveyor belts, bins, chutes, feeders, and hoppers, tend to segregate by virtue of the difference in size, density, shape or other properties. The primary mechanism is stratification – interparticle motion causes finer particles to sift through coarser ones. In addition to the segregation effect, the bulk material tends to build up with a varying mass concentration in a given volume of interest. We commonly call this effect of varying mass concentration – miss-aligned feed. An example of misaligned and segregated feed can be seen in *Figure 1*. The issue of size segregation in minerals processing has been studied experimentally [3] [4] [5] and numerically with DEM [2] [6] [7] [8] [9].

1.1 Cone Crusher Operation and Feeding

The working principle of a cone crusher is based on an eccentrically moving mantle and a fixed concave. The machine is designed so that the pivot point of the mantle is positioned at the top bearing for top bearing supported (Hydrocone) type crushers and defined by the radius of the plain bearing for Symons type crushers. The mantle moves in a precession motion enabling the opening and closing of the compression surfaces. When rock material is fed into the chamber, the particles are compressed sequentially in a number of compression events depending on the chamber design, eccentric stroke and precession speed.

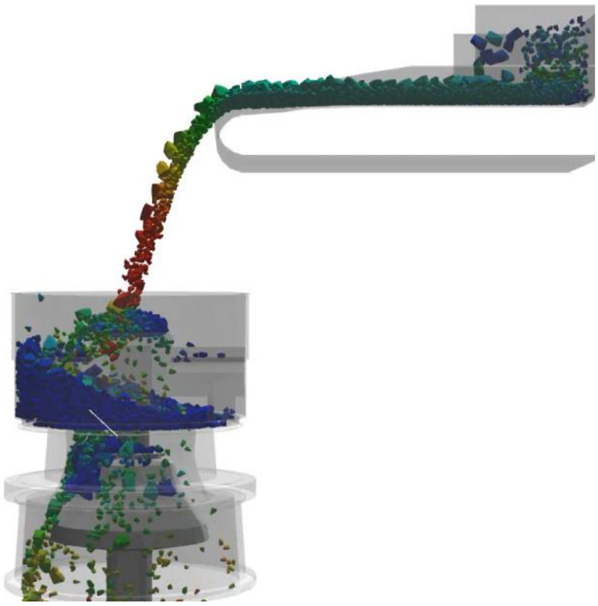

Figure 1. Example DEM simulation of a cone crusher feeding application showing significant miss-alignment and segregation

The critical point for this paper is that if an uneven mass distribution around the circumference (in a horizontal plane) and/or material with different sizes pass through the crusher, the compression and reduction response will be equally different. The effect of the miss-alignment and segregation is poor reduction performance, throughput capacity, uneven wear on liners and semi-long term fatigue failure of main shafts and other major components. A typical application example can be seen in Figure 2, where the crusher is choke fed. Hence the alignment is no issue however, the segregation is significant, leading to poor performance. The worst scenario is naturally the combination of segregation and miss-alignment.

Figure 2. Typical example of size segregation in a real application

In this paper, we demonstrate how the discrete element method can be used to improve a pebble crusher operation. The pebble crusher operates in a closed circuit with a SAG mill, and the processing plant had issues with premature wear of crusher liners and generally lower crusher performance than expected.

The authors worked with the mining site engineers and an external engineering company to provide a new feeding arrangement solution. A slight variant of the systems engineering approach, seen in Figure 5, was applied given the specific circumstances, existing solution ideas and time constraints.

2 Method

2.1 The Discrete Element Method

The discrete element method is the dominating methodology for the simulation of particles and particle-machine systems. First proposed by Cundall and Strack [1] for modelling of granular materials in two dimensions, it has since seen a technological development allowing for tens of millions of particles, including advanced multi-physics couplings to e.g. FEM and CFD models. The simulations in this work are performed in the DEM software Demify® developed as an in-house code at the Fraunhofer-Chalmers Centre for Industrial Mathematics (FCC). Through implementation on GPUs and very efficient algorithms, Demify® is currently the fastest DEM code on the market for non-convex polyhedral, spherical, multi-sphere and dilated-Minkowski convex polyhedral particle representations.

2.2 Irregular non-convex polyhedra

The shape and topology of crushed rock particles can be described as angular, irregular and non-convex. This means that modelling such shapes needs to facilitate these characteristics. There are two dominant particle shape modelling approaches employed for DEM, the multi-sphere method where several sub-spheres are clustered and the polyhedral approach. The multi-sphere method has an advantage in the inherent ease of achieving non-convex irregular shapes, however, with difficulty representing angularity. On the other hand, the polyhedral approach has the inverse advantage since a polyhedral shape can be made relatively angular however it is computationally challenging to model non-convex polyhedral particles.

The Broad phase contact detection is performed using a Bounding volume hierarchy (BVH) implemented on the GPU CUDA architecture. The Narrow phase contact detection is performed by filtering triangles using plane equations to calculate the volumetric overlap between objects in contact. The contact force interaction is based on the Hertz–Mindlin Deresiewicz no slip model. The reader is referred to [9] for further details on the numerical implementation.

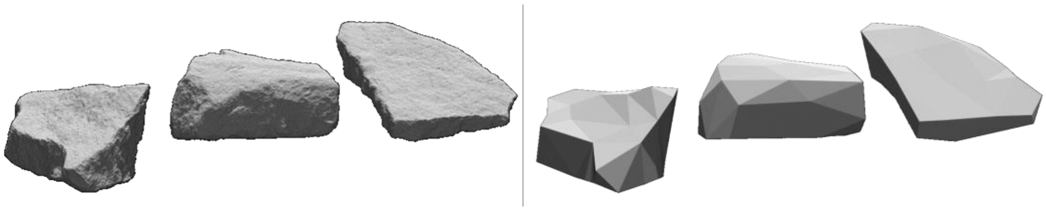

Figure 3. Example of 3D laser scanned rock particles with the triangle resolution decimated from 100’000 to 60 triangles.

The contact model parameters were calibrated using the calibration flow device developed by Quist and Evertsson [10]. The calibration of rock particles for the present case can be seen in Figure 4. Further details on the calibration optimisation routine are omitted for brevity.

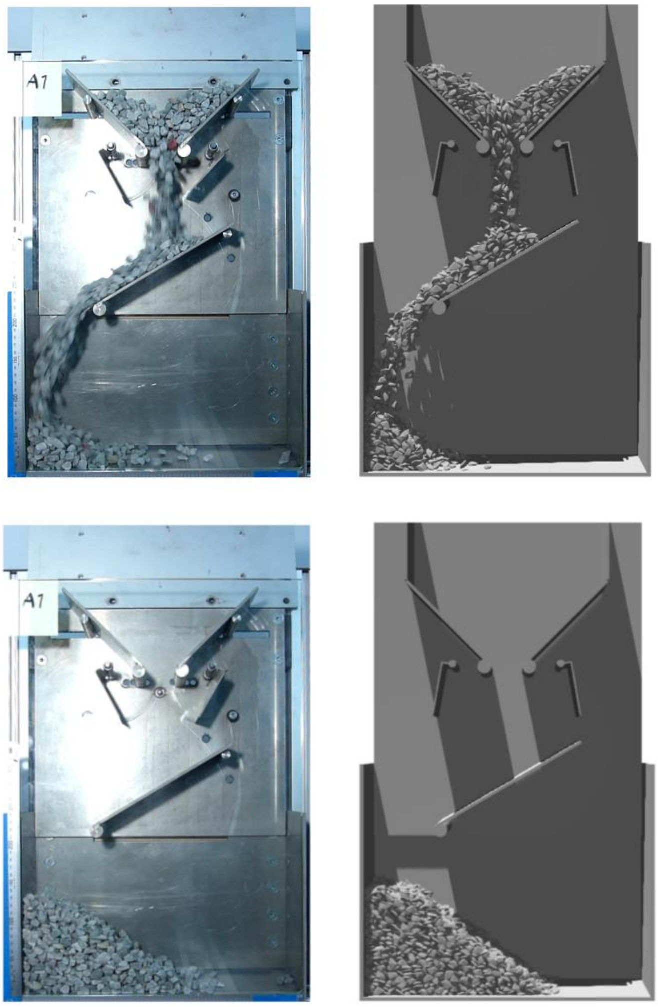

Figure 4. Interaction contact model parameter calibration. The slight difference in visual appearance is due to a small difference in bulk volume.

2.3 Systems Engineering Approach

In general terms, most (if not all) engineering activities are aligned towards identifying and bridging a gap between a current state and a preferred state for some system. The research field of engineering design and product development deals with creating an efficient eco-system of people, tools, and workflow strategies to bridge this gap. This is the case independent of if its the industrial field of e.g chemical, mechanical, electrical engineering, etc. In the mechanical engineering context, literature is abundant on development and problem-solving methodologies and strategies written over the past hundred years. In virtual development and simulation-based design (SBD), particularly using the DEM, there are few descriptions on how to effectively utilise the strength simulations has in aiding the engineering process. A conscious choice of engineering workflow process is of course always beneficial compared to the ad-hoc alternative. This is especially true when working with DEM modelling or other computationally expensive methods since each performed simulation may be linked to a high cost in time and resources.

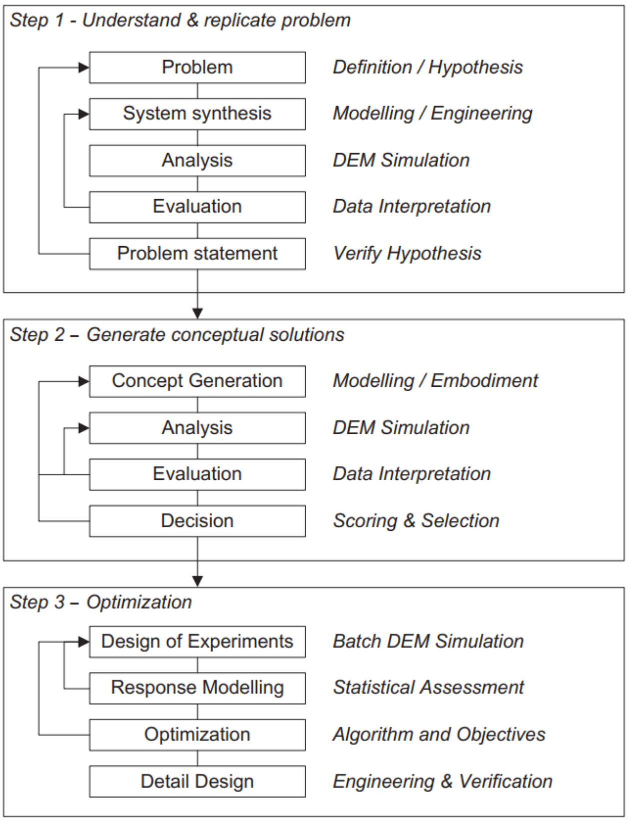

Figure 5. The proposed problem solving methodology for particle systems

A lack of structure may also lead to a decision-making process biased by the psychological traits of certain development stakeholders or their level of seniority and organisational status.

For this reason, we propose a development and problem-solving methodology that can be used by engineers and researchers who are working with DEM to solve real problems. A schematic diagram of the methodology is presented in Figure 5.

As mentioned in the introduction, the case application used as an example in this paper did not follow the exact steps in the methodology. However, the central principles of the method were applied in that step 1 was well executed, step 2 was performed in the sense that different versions of a pre-decided concept were parametrically evaluated. In step 3, the optimisation was performed more as an operational robustness analysis to review the solution performance at different high and low operational levels in terms of mass flow and feed size distribution.

2.4 Segregation and mass concentration analysis

An ideal crusher feeding would be a perfectly mixed population of particles that are evenly distributed in the hopper. There is hence one aspect of where the bulk material is positioned, and a second aspect what the size distribution is for a sub-sample at every location. We here define the first aspect as the local mass concentration and the second as the segregation. In the post-processing routine, the particle population state and properties are sorted according to bins in Figure 6. The suitable number of segments needs to be balanced to achieve reasonable statistical significance in each bin. Too few bins reduce the resolution at which the feeding can be analysed, too many bins risks sampling for a very long time to reach statistical convergence.

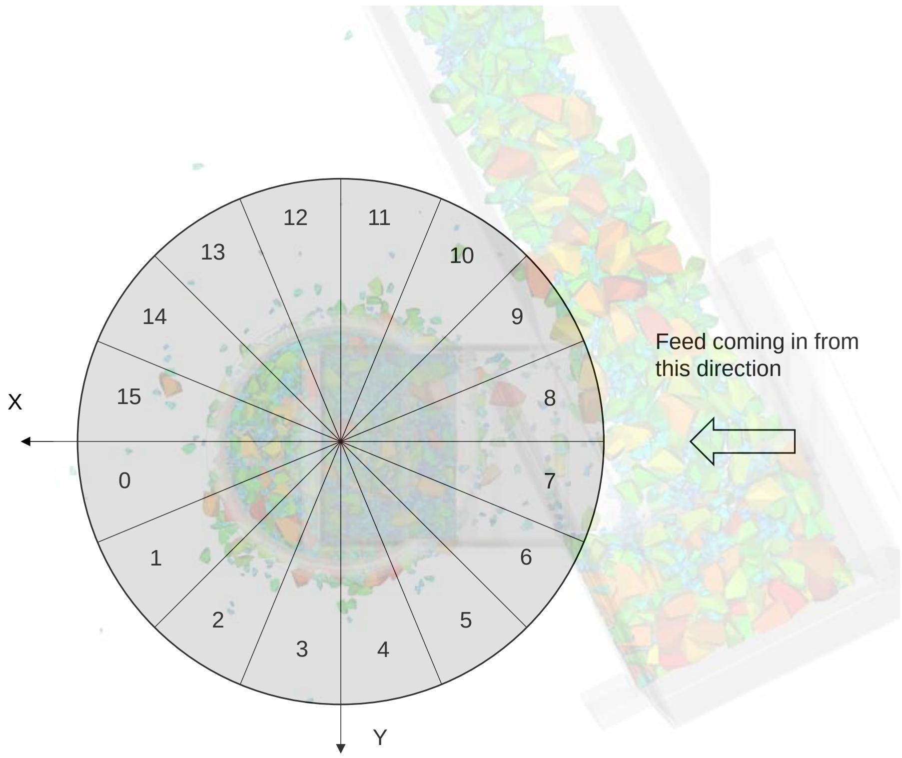

Figure 6. Schematic illustration of the calculation of response variables for segregation and alignment in circumferential segments.

The segregation index is defined as the average particle size divided by the total particle population mean size in each bin. The mass-concentration index (alignment) is defined as the mass fraction in each bin divided by the total mass in all bins. An example of the calculation for the case shown in *Figure 1* is presented in Figure 7.

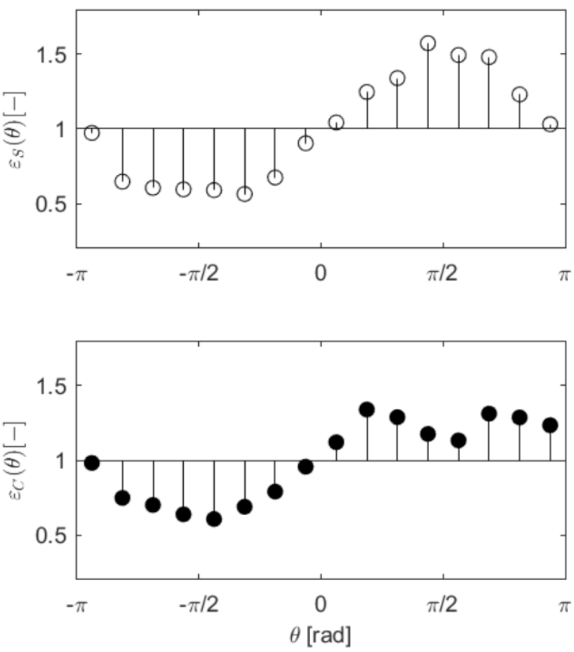

Figure 7. Example of segregation and mass-concentration results for a typical cone crusher application with uneven feed in Figure 1.

3 Simulation

The following section will describe the engineering design and simulation process performed in the project. As previously mentioned, some deviation from the process described in Figure 5 due to the specific nature and time constraints.

3.1 Understand and replicate the problem

The current arrangement consists of a feeding conveyor belt dropping off the material in a head chute. A diverter gate is used to facilitate the by-pass of the pebble crusher. Further on, the stream is directed through a chute to a previously installed dynamic feeding device. The previous feeding arrangement had serious malfunctions and was replaced by a fixed pipe. In the first stage of the process, the system geometry and operational conditions were gathered from site engineers. A separate CAD model was extracted and prepared for the simulation purposes from existing system CAD models. Historical data in terms of particle size distribution and mass throughput was analysed to find the system's worst-case boundaries. The analysis of the current arrangement was performed in a number of iterations together with the local engineering team to make sure that all measurements and detailed features were correct in the model. An example of this is a welded ledge on the diverter gate, not seen in engineering drawings, that significantly influenced the flow behaviour. The system and one of the simulations from stage 1 can be seen in Figure 8. In Figure 9, the material in the crusher is displayed coloured by mass, indicating the segregation effect. The results from stage 1 replicated the observation done by engineering on-site and verified miss-aligned and segregated feeding conditions. The problem description and the simulation model are qualitatively and quantitatively verified through this simulation stage based on several sources, including data, videos, photos, and personal observations.

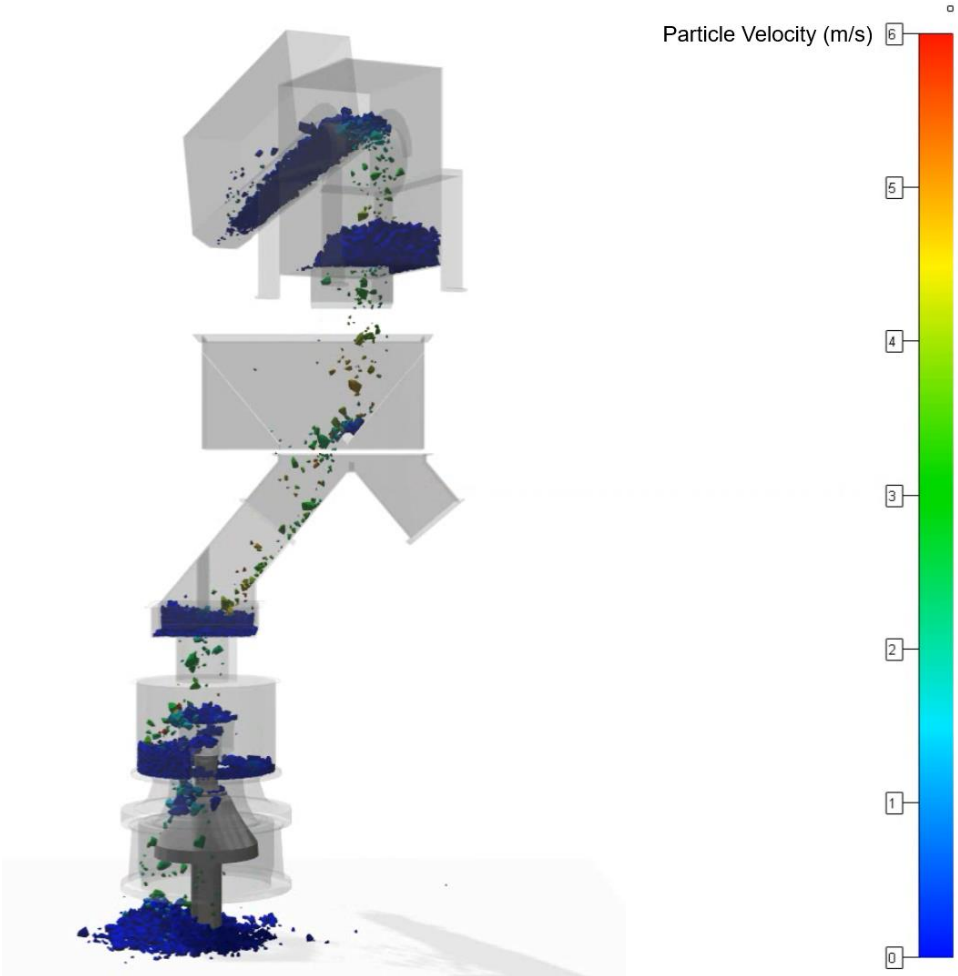

Figure 8. Simulation results from the analysis of the current configuration of the feeding system. Particles are coloured by velocity.

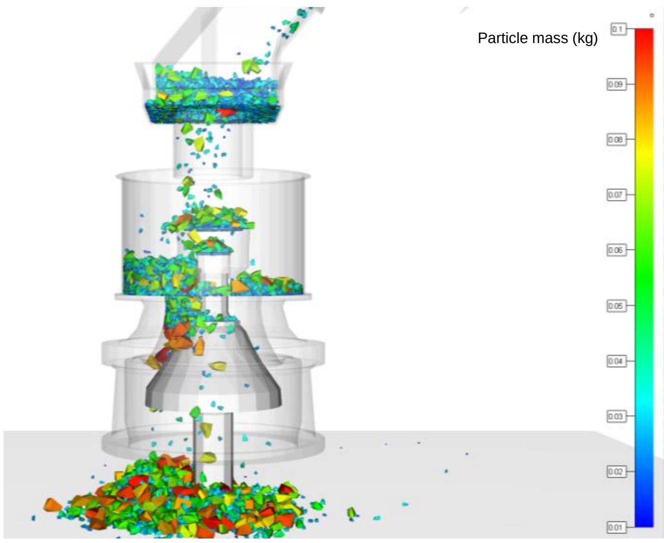

Figure 9. Simulation results showing the flow pattern in the cone crusher indicating a significant segregation and miss-alignment problem. Particles coloured by mass.

3.2 Evaluate conceptual solutions

A conceptual solution was already proposed when the case project was initiated. Hence, this was the main focus of conceptual analysis instead of the normally recommended concept generation and evaluation procedure. The first design concept was evaluated, which revealed a high risk of blockage, as shown in Figure 10.

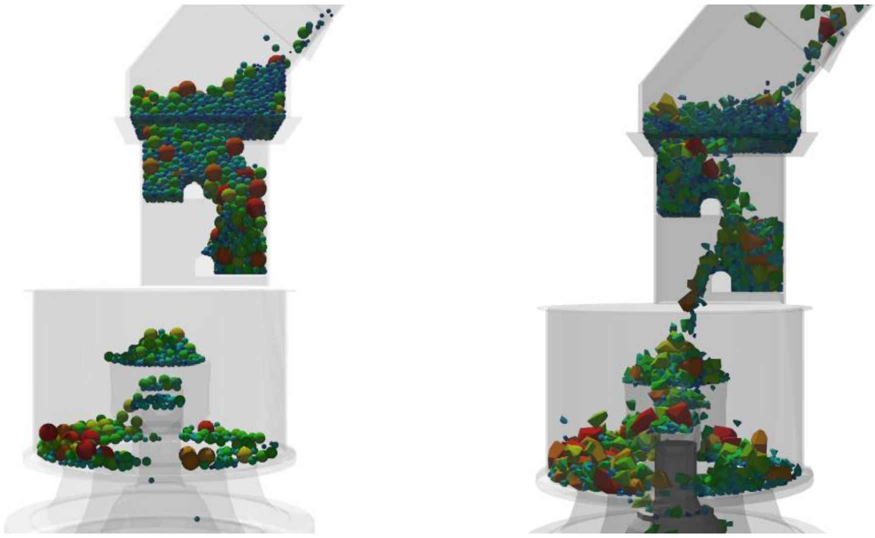

Figure 10. Original rock shelf design concept indicating high risk of blockage. Modelled with spherical particles (left) and polyhedral particles (right).

A parametric study was performed to evaluate a more optimal configuration of the shelf design. An improved version of the concept can be seen in Figure 11. The shelves were dimensioned and positioned to avoid bridging effects and guide the material for as even distribution in the crusher chamber as possible.

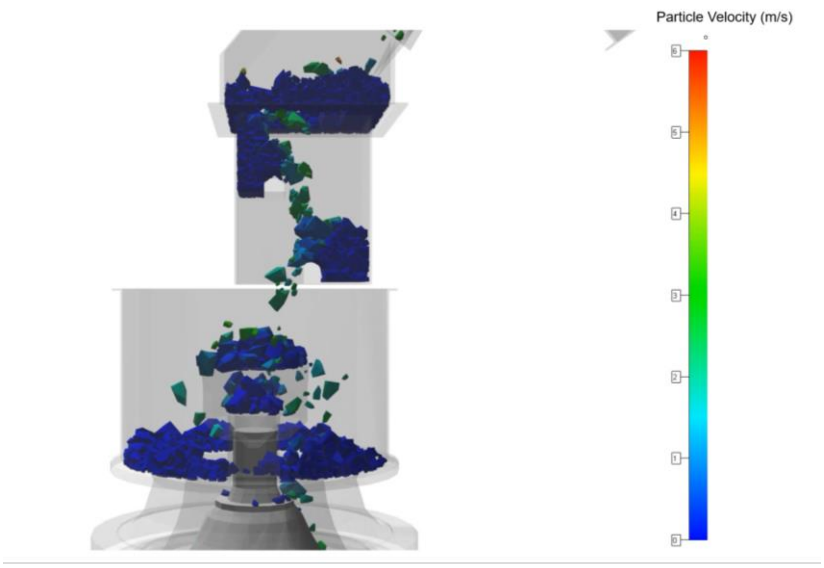

Figure 11. Improved rock shelf design concept by parametric evaluation of the rock shelf position and lengths to improve feeding performance and avoid risk for blockage..

3.3 Optimisation and robustness analysis

While the results from stage 2 indicated that the conceptual solution would perform well, it was concluded that the solution should be evaluated on a set of operational conditions corresponding to future processing plans and current worst-case scenarios. Therefore, four additional cases were simulated with parameters according to Table 1.

Table 1. Operational conditions for robustness analysis of rock shelf concept.

Case	**Feed PSD (mm)**	**Feed rate (tph)**	**Shelf config.**
1	+10 / -125	120	Complete
2	+10 / -50	120	Complete
3	+10 / -125	120	No middle shelf
4	+10 / -125	120	No shelves

The results from the robustness analysis in terms of alignment can be seen in Figure 12. Case 1 and 2 demonstrate relatively well-aligned feeds. The missing material seen in the plots corresponds to the location of the crusher spider arms.

When feeding coarse material in case 1, an interesting flow behaviour that first looked like a stochastic effect was demonstrated. However, the significant segregation effect seen for case 1 in Figure 13 can be tracked all the way up to the head chute in terms of how large particles preferentially flows. When entering the crusher region, the large particles are more likely to fall on one particular side of the spider arm.

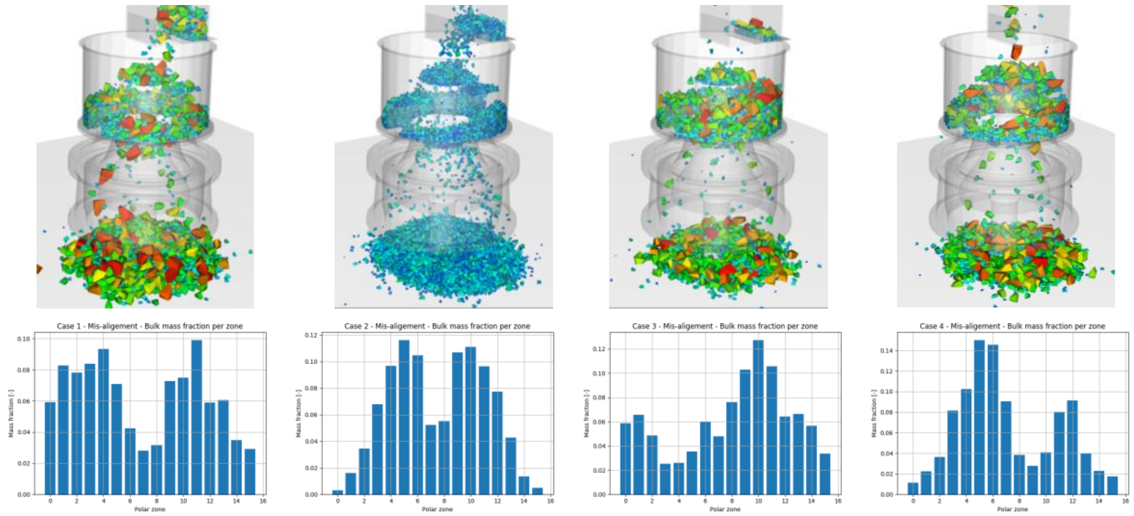

Figure 12. Miss-alignment results for adjusted rock shelf design with four different operational conditions evaluated.

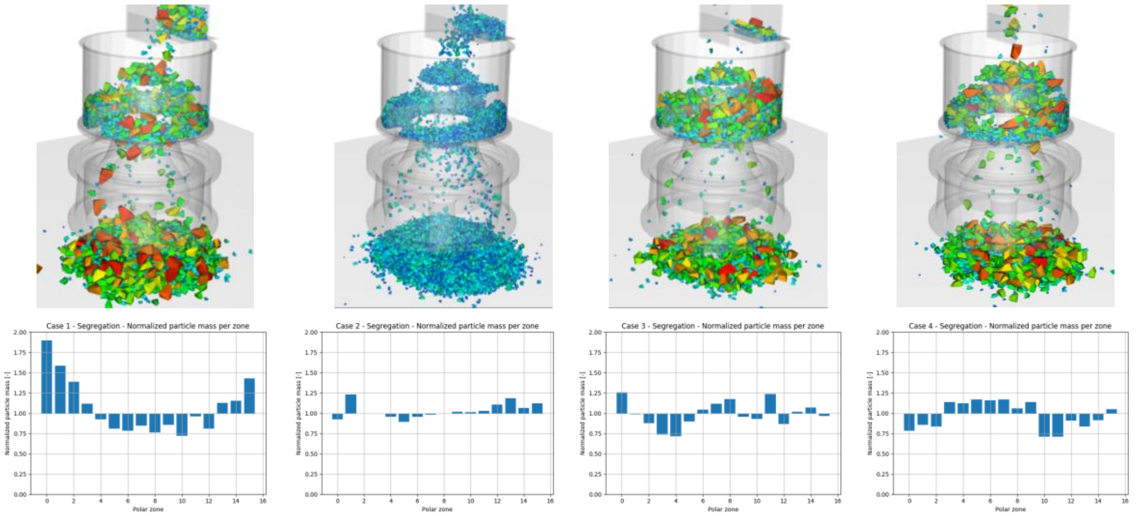

Figure 13. Segregation results for adjusted rock shelf design with four different operational conditions evaluated.

4 Results & Analysis

The total time for the DEM analyses, redesign, manufacturing, installation and commissioning of the new feed chute was about 8 months. After commissioning the new chute was immediately evaluated over a 4-month period. Examples of production data and crusher operating data are shown in the figures below.

The crusher control system (ASRi) had a set point for the "average peak pressure" at 3.8MPa. It can be observed from the graph that at feed rates above approximately 50 tph the pressure is limiting the set point is reached and the control system opens up the closed side setting (CSS). The particle size distribution is commonly directly related to the CSS, which means that the reduction and thus the fines generation decreases. At the same time, the top size of the product will increase. The limit for the peak pressure is a relatively low value and will later be increased to at least 5 MPa, resulting in a finer product size distribution.

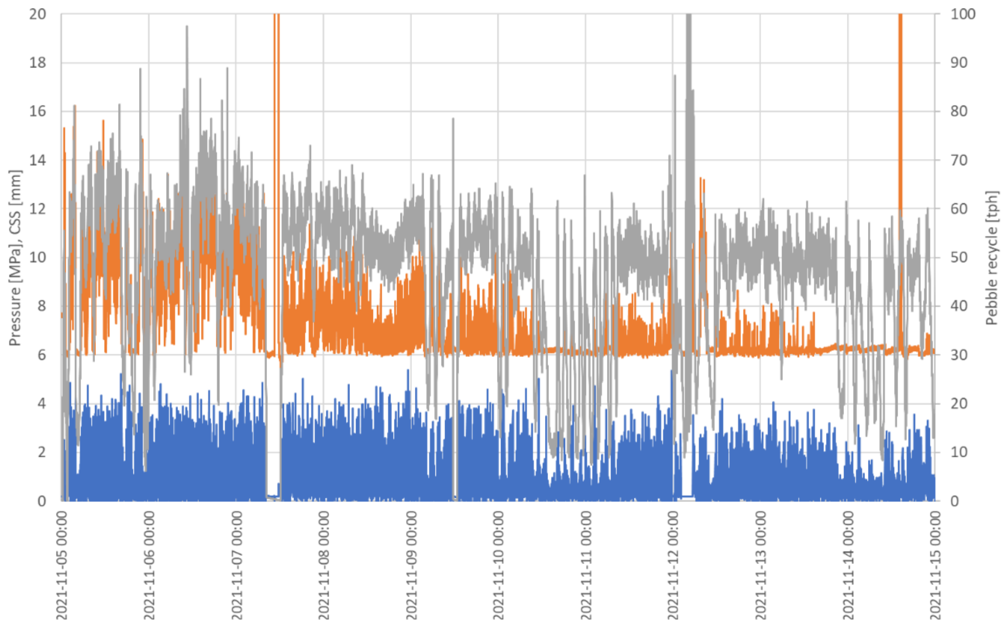

Figure 14. Example of logged time series data for crusher hydraulic pressure (blue), Closed Side Setting, CSS (orange), and pebble feed rate (grey).

With the new chute design the feed material has a better distribution around the inlet of the crushing chamber. This is difficult to observe or monitor without a dedicated monitoring system with high resolution. Instead indirect measure or interpretation of existing signals and data has to be utilised. In the figure below a comparison is made between the exiting and the new chute design of power draw vs hydraulic pressure. It can be observed that with the new design the crusher power draw is higher at lower hydraulic pressure which is beneficial for the crusher and is a consequence of better operating conditions. The improved operation conditions can be explained by better distribution of material around the crushing chamber in the horizontal plane resulting in a more even magnitude of the resulting crushing force.

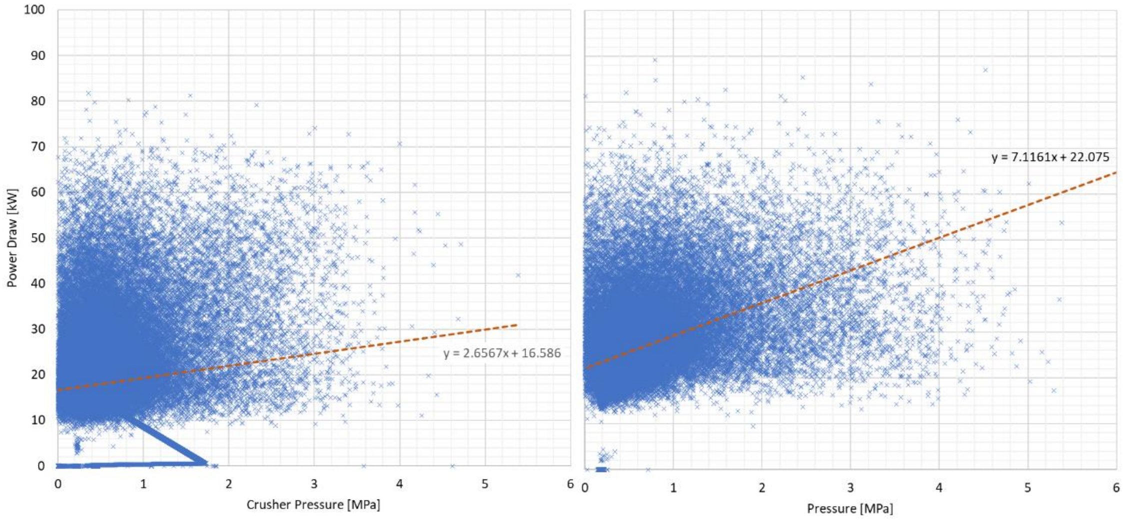

Figure 15. Crusher power draw vs hydraulic pressure, before redesign of chute (left), after redesign (right).

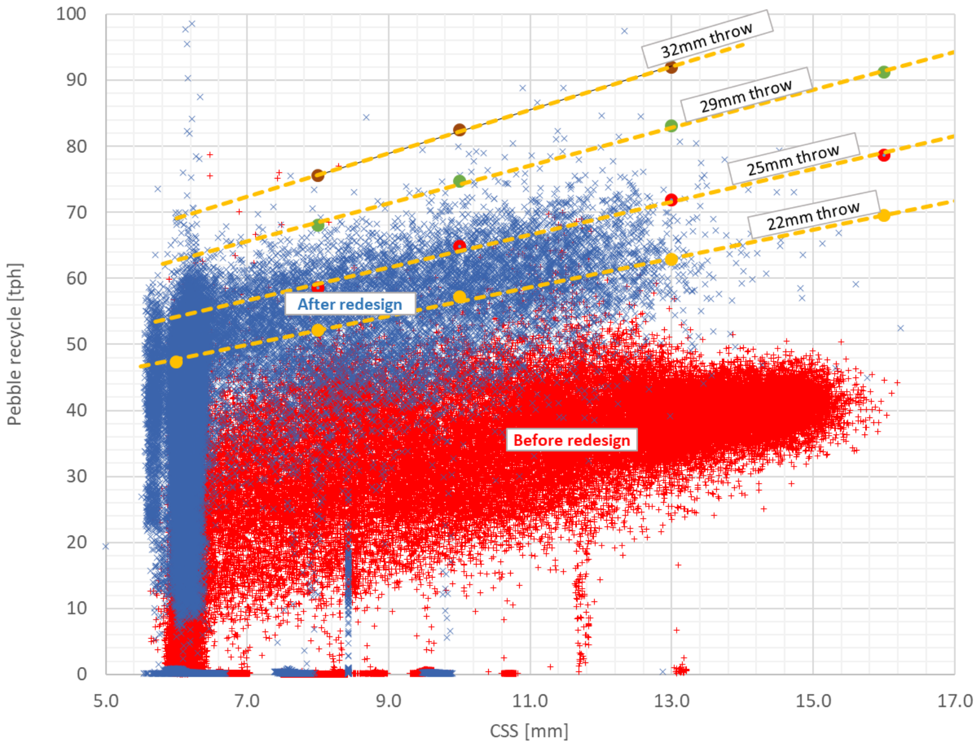

Figure 16. Pebble recycle performance for operation at different closed side setting. With the original feed chute (red markers) the crusher is operating at larger CSS than with the new design (blue). Crusher capacities for different eccentric throw are indicated with the dashed lines (yellow).

It was observed that the crusher had a strong tendency to open up CSS when the “average peak pressure” exceeded the set point in the control system (3.8MPa). The peak pressure is in principle corresponding to the highest amplitudes of the hydraulic pressure in the crusher and if there set point is exceeded at some point in the crushing chamber the system will react and try to lower the pressure by increasing the CSS. In Figure 16, a comparison is made between the old design and the improved design of the chute for pebble feed rate versus CSS.

It is very clearly seen that with the new chute design, the crusher can operate at smaller CSS for higher feed rates. In the figure, the nominal crusher capacities for different eccentric throw levels of the crusher is also indicated. The installed eccentric throw of the crusher is 22mm, and the results strongly indicate that the crusher is operating in the design range with the new chute design.

With the original feed chute design, the wear life of the crushing chambers (concave and mantle) was typically ranging between three and four weeks depending of the pebbles production from the mill. It is still in the early evaluation phase, but so far the lifetime for the first set of manganese crusher liners has exceeded four months.

5 Conclusions

The following conclusions can be drawn from the work presented in this paper:

- The feed distribution of the original feed chute was shown to be highly disadvantageous. This was observed in the daily operation, and it was explained by the reference DEM simulations in stage 1.
- The proposed chute design was shown to work significantly better after a few iterations of the design with DEM simulations in stage 2.
- After commissioning of the new chute design the crusher immediately showed improved performance and was able to operate at smaller CSS and higher throughputs.
- Crusher liner lifetime depends on how the feed material is presented to the crusher. Uneven feed with misalignment and segregation is detrimental and can lead to uneven war that in turn has an impact on the crusher operation as the CSS can vary around the chamber leading to high pressure variation. A more uniform feed distribution lead to a more controlled and even wear rate. The manganese steel may also experience better conditions for the work hardening of the manganese steel to take place.

The new feed chute design will be further evaluated during 2022 and the focus will be set on further improvements of the crusher operation through chamber selection and/or design, evaluation of increasing the eccentric through, and by introducing eccentric speed as an additional control parameter.

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