DISCRETE ELEMENT MODELLING: TROUBLE-SHOOTING AND OPTIMISATION TOOL FOR CHUTE DESIGN

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ABSTRACT

Conveyor transfer stations play a key role in many industries that handle bulk materials. Transfer stations can be rather sensitive to changes in material properties and can lead to relentless problems regarding reliability, wear, bottlenecking and blockages. Wet and sticky ores are typically difficult to handle materials due to their obnoxious ability to form a cohesive arch, adhere to surfaces and poor flow ability. Mines that are situated in areas with seasonal high rainfalls or that have started to exploit newer and more difficult to mine and handle ores, often from below the water table, experience vast difficulty in reliably conveying and processing bulk material with such diverse flow ability over time. Mining and processing operations which add water into bulk solids for processing purposes also may experience handling issues further along the handling and processing line.

Cohesive and adhesive effects of wet, sticky ore on transfer stations which contain impact plates, ledges and curved or straight chutes can make it difficult to design a system to reliably guide material in the direction of the receiving belt. Therefore, the usage of the discrete element method (DEM) to model the flow of cohesive and cohesionless materials through industrial transfer stations is increasing. This paper gives a short overview of the implementation of DEM to trouble-shoot and optimise a transfer station and shed some light on the strength and weaknesses of DEM. Some of the vital calibration techniques used to 'tune' the DEM material model using numerous bench-scale tests to produce representative flow behaviour of wet, sticky ores is also discussed.

1. INTRODUCTION

Belt conveyors are commonly used in a multitude of industries to transport granular products from one location to another, which often have transfer points to redirect between conveyor belts. It would be ideal to have no transfer stations in a production line; however, with the limitations of conventional idler conveyor technology (i.e. limited length, horizontal curve design, layout) and plant design more often than not, transfer stations are required. Simple transfer designs are best, but far too frequently transfer chutes do not operate successfully due to the flow ability of a product, wear, flooding, plugging, spillage, poor control of the material flow and inadequate chute design.

Conveyor transfers are a critical link in many conveying systems and can be costly to operators when they do not operate to design specifications, as operators may reduce throughput to decrease maintenance and housekeeping as a method to minimise down time. Under-performing chutes can make it difficult to achieve annual production and productivity goals and accrue high costs to operators with regard to maintenance, downtime, demurrage, labour and water costs (if water is used to help promote flow or clean chutes). Chutes when originally installed may work perfectly, however, over time the performance of a chute may decline due to increasingly difficult to handle materials (e.g. mining below water tables). When chutes become problematic it is common for operators and maintenance crews to start modifying chutes using trial-and-error by adding micro-ledges or rock boxes, cutting surfaces, injecting water and flow promotion devices which can exacerbate problems. The injection of water into sticky products is a logical solution to make products easier to flow, although this practice can be expensive due to increased water consumption and can potentially make the product more difficult to handle downstream as the material can dry out to an extent and return back to maximum strength conditions. With careful analysis of the flow properties of the product and the use of validated design tools, re-work of a transfer point is possible to improve performance and maintenance requirements.

There are many analytical techniques available in the literature to assist engineers design and trouble-shoot chutes such as conveyor discharge trajectory models [1; 2] and particle flow models for rapid flow [3]. However, these models are typically limited to two-dimensional analysis which makes it difficult for engineers to completely visualise and understand how material will flow through a chute and present onto the receiving conveyor belt. Discrete element modelling is a great tool to visualise particle flow and gather data of the interaction between particles and machinery/surfaces as the trajectories and physics of each particle in the simulation domain are analysed and recorded. DEM simulations also allow numerous 'what if' scenarios to be run on standard desktop computers which can be a lot quicker and easier than designing, constructing and testing scale prototype models or modifying current design via trial-and-error. This paper explores the methodology used to investigate numerous options to improve the performance of a transfer chute on a bauxite mine using a commercial DEM package [4].

2. CURRENT PROBLEM

A bauxite facility in Australia is currently experiencing numerous on-going problems with several different belt conveying lines which affect the operation and reliability of the facility with regard to limited throughput. Numerous transfer stations which convey product from rail or truck dump stations to stock piles and then to ship loaders experience product build-up leading to plugging, costly downtime and housekeeping. As a result, many conveying lines either operate below design tonnage to minimise the chance of plugging, or use water injection to increase the flow ability of product. This current remedy has its short comings as it takes longer to load a ship and there are occasional problems with reclaiming product from the stock piles which hinders the ship loading process. Also, water addition into the product is costly, not only the cost to deliver water to the injection points and water usage but the money lost in the reduced mass of dry product exported.

There are many types of chutes used in industry and trade-offs made in the selection of chutes, i.e. chutes which have rapid flow and are self-cleaning often experience higher liner wear while chutes which contain material using ledges have lower wear rates but greater flow problems especially if the product is cohesive. Often on many sites, transfer stations are designed using a combination of rock boxes and curved or straight chutes, however, chutes which use combinations of arrangement or complex configurations can be difficult to determine stream velocities and particle trajectories. A miscalculation of the trajectory of a material stream can be costly as wear on unexpected surfaces could occur on sections of the chute or plugging could occur if the material suddenly decelerates.

Two grades of bauxite are processed which need to be conveyed through this section of the facility after beneficiation. These products include monohydrate (MGB) and tri-hydrate (TGB) grade bauxite. Bauxite is a unique material as it consists of hard spheroids (pisolites) of approximately 2 mm to 20 mm diameter. TGB exhibits more difficulty to handle than MGB as TGB contains a higher percentage of fine particles which retains more moisture and is therefore more cohesive. Due to the location of exploration, MGB consists of a high proportion of fine mud which coats the surface of particles causing particles to stick to each other and surfaces which causes unwanted build-up on conveyor belts, scrapers, dribble chutes and transfer chutes. The bulk strength of the bauxite is relatively low when measured as a bulk sample with fine and coarse particles and the product is relatively free-flowing. However, when the fine material segregates and the product consists of a high percentage of fines, the strength of the material increases.

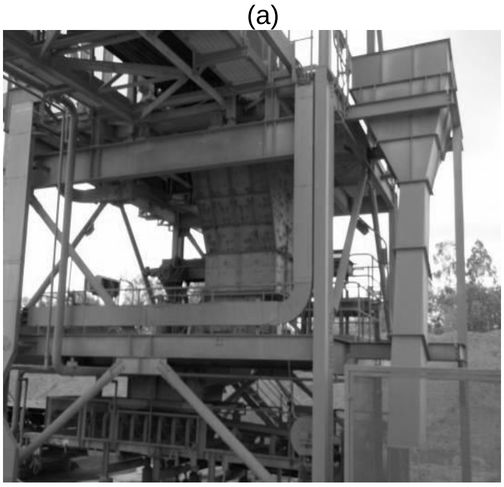
The processing equipment and belt conveying systems at the bauxite facility were designed and commissioned many years ago. However, over the years the characteristics (particle size) and flow properties of the bauxite have changed due to environmental factors (e.g. different exploration sites) and processing factors (e.g. addition of water) and this has made it more difficult to handle the bauxite, leading to flow problems. DEM modelling has significantly improved such that it allows reasonably accurate results to be obtained with validated simulation parameters which are ideal to comprehensively assess the design and functionality of bulk material handling systems. This case study provides an opportunity to evaluate the current bulk material flow problems and evaluate potential improvements before having to make essential changes to equipment. This study also allowed the methodology used to characterise and calibrate the bulk material in terms of particle size, shape and physics in the DEM model to be evaluated to assess the accuracy and value of DEM.

Figures 1 and 2 show the transfer chute which was selected for this case study to model the particle flow using DEM and compare results against quantitative and qualitative observations to determine if the calibrated DEM model (via. bench-scale calibration experiments) could represent the mechanics of particle flow on a large scale. The transfer station shown in Figure 1a is located between conveyor C1 and C2 (notation for this paper) which run perpendicular to each other and the drop height from the top of conveyor C1 to the top conveyor C2 is approximately 7.3 m. Transfer C1/C2 was designed to be a low maintenance transfer station where material discharges from conveyor C1 then impacts a vertical wall with a small ledge on the bottom (Figure 1b) which allows material to build up. Product is then redirected into the lower section of the chute which consists of several large horizontal ledges to create a rock box where the product is fed onto conveyor C2 through a V-plate to centralise the material. Details of the conveyors and design specifications are listed below:

<u>Conveyor C1</u>
Belt Speed: 3.52 m/s (measured), 3.4 m/s (design)
Discharge Angle: 3.04°
Head Pulley Diameter: 786 mm
Belt: 1800 mm x 24 mm
Design Tonnage: 3400 tph
Transition Length: 2987 mm
Troughing Angle: 35°

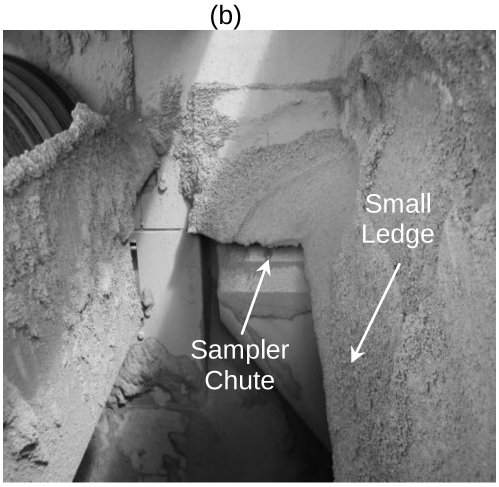
<u>Conveyor C2</u>
Belt Speed: 4.2 m/s
Inclination Angle: 0°
Belt: 1500 mm x 19 mm
Design Tonnage: 3400 tph
Transition Length: 4200 mm
Troughing Angle: 35°

(a)



(a) General layout

(b)



(b) Upper head chute

Figure 1. Conveyor transfer C1/C2

Transfer C1/C2 has been built with a sampling system as shown in Figure 1b where a sampling chute cuts through the product stream below the upper head chute at regular intervals for analysis. The sampling system consists of numerous drive assemblies, chutes and conveyor belts which are built around the transfer station (note: not entirely shown in Figure 2). A tramp metal magnet is also present above the head pulley on conveyor C1 which partially hangs into the upper head chute. Therefore there are numerous constraints which limit the amount of changes that can be made to the chute and supporting structure without making major modifications which cannot be completed within a major shut down.

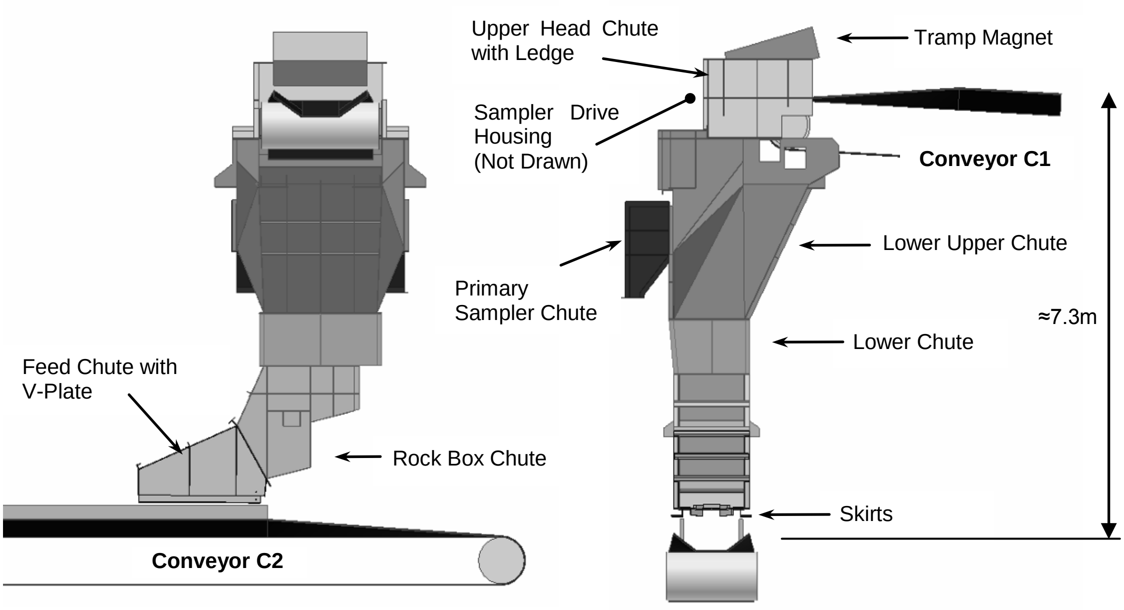
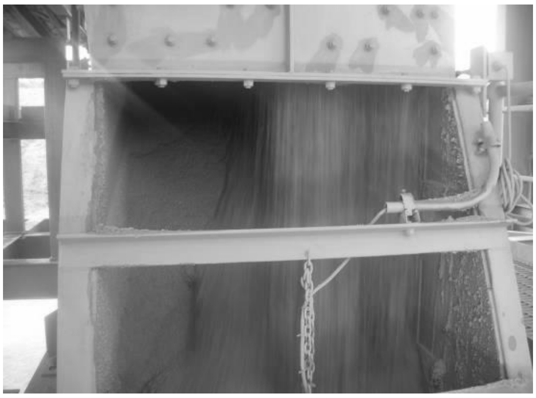


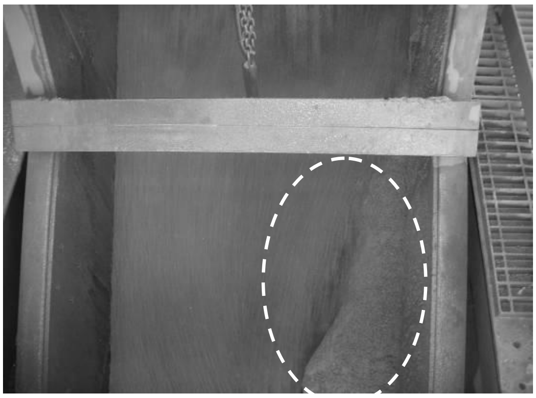
Figure 2. CAD model of current design of transfer C1/C2

With the current design arrangement and the large drop height (7.3 m) which consolidate the product in the rock box upon impact, transfer C1/C2 suffers from the following problems:

- The far wall of the upper head chute is too close to the head pulley of C1, which causes the material to flow non-symmetrically into the rock box that leads to build-up problems (Figure 3a),
- due to segregation and restriction of flow due to the V-plate, dead regions are eventually created which lead to plugging and non-central loading onto C2 (Figure 3b),
- when blockages occur (at regular intervals), the lower section of the chute is washed out to remove the blockage or prevent the chute from plugging. The material in between the horizontal ledges is usually heavily consolidated from the impacting product which requires a high pressure hose to remove the bauxite (Figure 3c),
- although V-plates or V-profiles are good for centralising material flow, they are not ideal for cohesive materials as they restrict product flow and force the product to flow through the V as shown in Figure 3d. The V-plate in the feed chute is situated about 700 mm above C2 which causes the material to almost drop vertically from the feed chute and splats onto the conveyor belt and skirting that leads to eventual wear of the skirts and belt cover,
- as shown in Figure 2, the effective inclination through the rock box and feed chute or the slope of the upper surface of the ore stream is rather low which reduces the material stream velocity and exacerbates the slow build-up of material. Bulk materials generally flow better against smooth surfaces instead of shearing against itself, therefore large inclinations are required to ensure cohesive materials will maintain momentum and rapid flow,
- the upper head chute does not confine the bauxite like a hood type chute does which causes the product to impact the sides of the lower upper chute (Figure 2) and lower chute causing either unlined surfaces to wear or unnecessary wear to bisalloy liners which are difficult to replace and monitor (due to location).



a) Non-symmetrical flow in the lower section of the chute



b) Development of dead zones

c) Constant house-keeping to remove compacted bed or unblock the chute

d) V-Plate in feed chute restricting flow

Figure 3. Issues with current design of transfer C1/C2

3. DESIGN AND SIMULATION PROCESS

There are numerous papers in the literature that examine DEM theory and the application of DEM as detailed in [5] and [6,] but there are only some papers [7; 8] which examine the application of DEM to chute design and validated methods to calibrate the material model. With an increasing number of commercial DEM packages on the market, DEM is proving to be an intuitive and powerful tool where complex 3D CAD models can be imported into DEM simulations and complex particle shapes can be modelled. Instead of just adjusting parameters in large scale DEM simulations via trial-and-error until the results look realistic or similar to observations on site, a rational bench-scale calibration and characterisation procedure has been implemented. Although adjusting parameters until results look reasonable saves the hassles of physical characterisation testing, large scale simulations with over 100,000 particles can take hours, if not days to compute depending on the simulation setup which can be very time consuming and there is no confidence in the results especially when trying to model ‘difficult’ bulk solids.

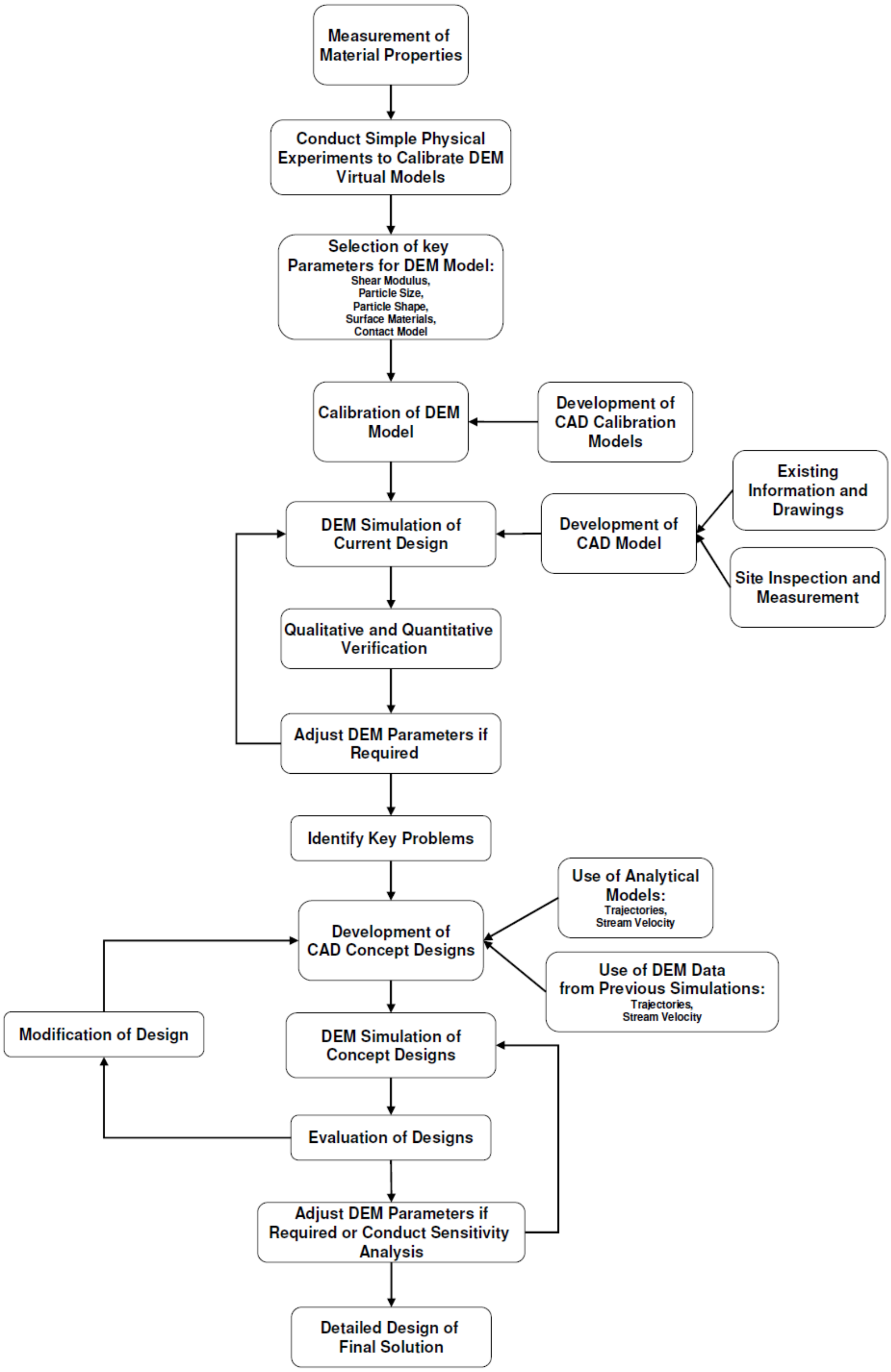


Figure 4. Basic flow chart of simulation and design process

Figure 4 shows the process adopted to set up the DEM models, select the material properties of bauxite for modelling, develop and evaluate the 3D CAD models for dynamic chute flow modelling and engineering a solution(s) to solve the flow problems. The first critical step of the process like for any design procedure involving bulk solids is flow property measurement and characterisation. Samples of TGB and MGB were taken from site for laboratory testing as exact properties are not known. To assist in the development of the DEM material model, a series of tests were conducted using dry bauxite to determine the bauxite parameters for free flowing conditions. More importantly it is crucial to understand the flow behaviour of the bauxite under 'worst case' conditions with maximum cohesive strength to develop a set of material properties using an appropriate DEM contact model that can model cohesive and/or tensile forces during contact.

Once the essential bulk material properties have been measured and the bench-scale calibration experiments completed, the development of the DEM model can commence. Before the key parameters for the material properties (i.e. shear modulus, particle shape and size distribution) were selected for calibration and large scale simulations, an analysis of the large scale model was conducted. The purpose of this pre-processing analysis is to estimate the computational time based on the number of particles required in the model domain, the time step and the geometric size of the model (i.e. evaluate the amount of memory required and the efficiency of the solver for contact detection) to determine if any parameters should be scaled and/or truncated. Figure 5 shows the measured particle size distribution of TGB, hence to model the bauxite identically would require in excess of five million particles which is not feasible for most design processes. The approach adopted for this research, as shown in Figure 5, was to scale-up the particle size distribution and truncate the minimum particle size, which governs the numerical time step required for stable simulations.

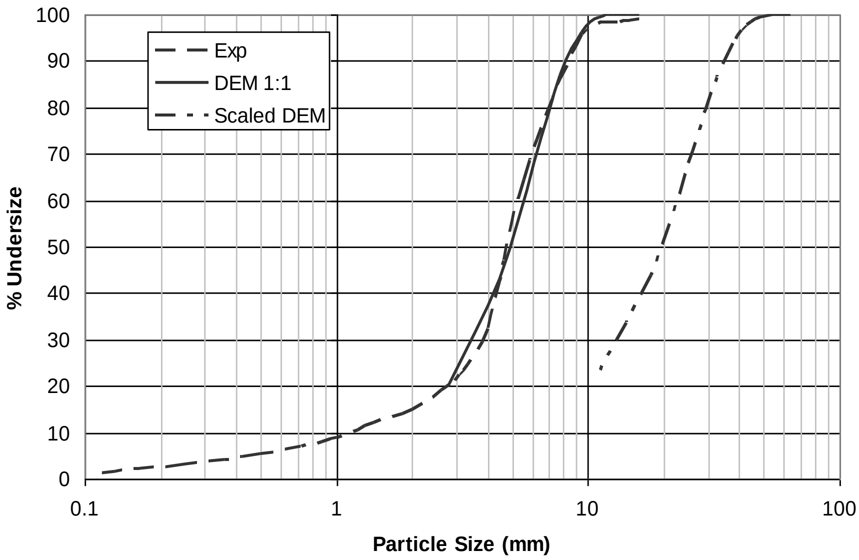


Figure 5. Particle size distribution of TGB

Particle shape representation in DEM modelling has typically been simplistic using a single sphere which is efficient to achieve good basic results. When modelling raw bulk products, the shape of the particles can be random in size and geometry and often be quite angular with rough surfaces that are impossible to numerically model using a single spherical particle. Although it would be ideal to model bulk materials using hundreds of random particle shapes with asperities, this task would be slow, impractical and computationally unfeasible and is not necessary. Particle shape representation is often misunderstood where simple non-spherical particles can be implemented into DEM models to achieve realistic bulk physics (i.e. rolling and interlocking behaviour) in conjunction with restraint in the contact models. Bauxite particles are distinctive as they are relatively spherical from exploration besides the larger particles (say >10 mm) which are irregular. Although the particles are mostly spherical, a non-spherical particle shape was mainly implemented in this study as shown in Figure 6 which consists of four clustered spheres. As the fine particles are not included in the DEM simulations, the non-spherical particle shape representation helps compensate for the fine particles which assists the bulk material to gain strength and stick together. Therefore this particle shape representation helps to model cohesive strength with appropriate calibration of the contact model parameters (i.e. friction, coefficient of restitution, cohesion, adhesion).

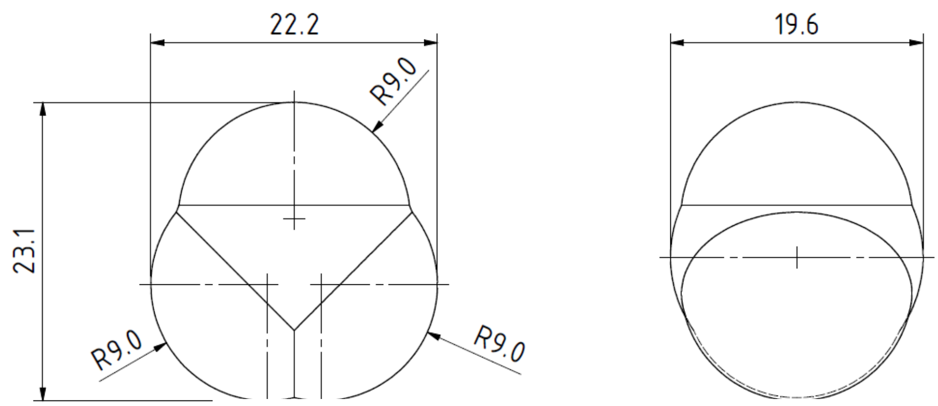


Figure 6. DEM particle representation of bauxite, mean scaled particle, dimensions in millimetres

4. DEM CALIBRATION

To have confidence that the modelled particle physics are realistic and representative, calibration of the particle size distribution, particle shape and the contact models is required to determine the bulk behaviour of a material. Design of comprehensive calibration routines and equipment is ideal to thoroughly examine different flow mechanisms, but to numerically replicate the same behaviour may be time consuming and difficult. The approach adopted in the literature [9-11] is to conduct DEM and physical experiments which resemble similar flow mechanisms to those in large scale DEM simulations such as rapid flow, compacted bed flow or compression tests.

A program of test work was conducted on the bauxite when the product was dry and wet. Internal shear tests were performed using a Jenike shear tester to determine the moisture content when maximum strength occurs. To determine suitable parameters for contact models of wet and cohesive bauxite, a data set of parameters for dry bauxite were measured or calibrated first. Developing a material properties data set for dry material made it easier and more methodical to adjust minimal parameters or introduce an additional contact model to incorporate cohesion and adhesion. The contact models used for this investigation include the viscoelastic Hertz-Mindlin model [12] and linear cohesion model [4;13]. Properties which were measured and directly implemented into the DEM models include static friction, coefficient of restitution, particle size distribution and solids density.

To check that the latter properties measured are suitable and to calibrate other contact parameters which are not easy or possible to measure such as rolling friction, cohesion and particle shape, numerous bench-scale experiments have been conducted to examine and 'tune' these parameters. Once a particle shape has been selected the rolling friction is calibrated by conducting several simple slump tests (Figure 7) and flat bottom hopper discharge tests (Figure 8) to match the simulated drained and poured angle of repose as well as discharge times for cohesionless bauxite against experimental data. To model the wet bauxite, additional contact models are introduced with extra parameters such as cohesion energy to model a cohesive product with greater drained and poured angles of repose. As previously discussed, the particle size distribution was scaled up by approximately a factor of four to reduce the large scale DEM computational periods and the effects of scale-up have been calibrated to achieve similar bulk behaviour of the bauxite. If the bench-scale CAD models were not modified with the scaled up particles there would not be a large number of particles in the simulations and it would be difficult to achieve realistic bulk behaviour. Therefore the geometry of the slump tester and the flat bottom hopper have been respectively scaled up in size and the mass of product/particles in the simulation has also been scaled as the drained, slumped and poured angle of repose are good properties to scale.

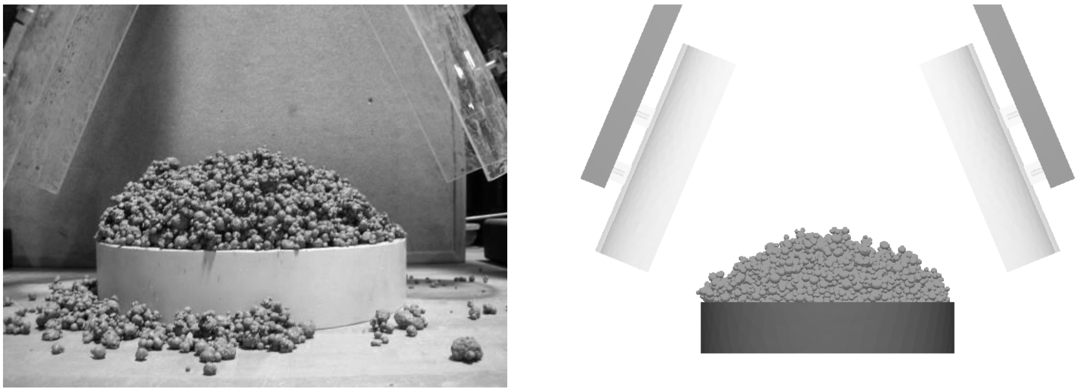


Figure 7. Examples of the calibration of the particle-to-particle interactions under rapid flow conditions using a novel swing-arm slump tester. Left: Experimental results; Right: DEM results

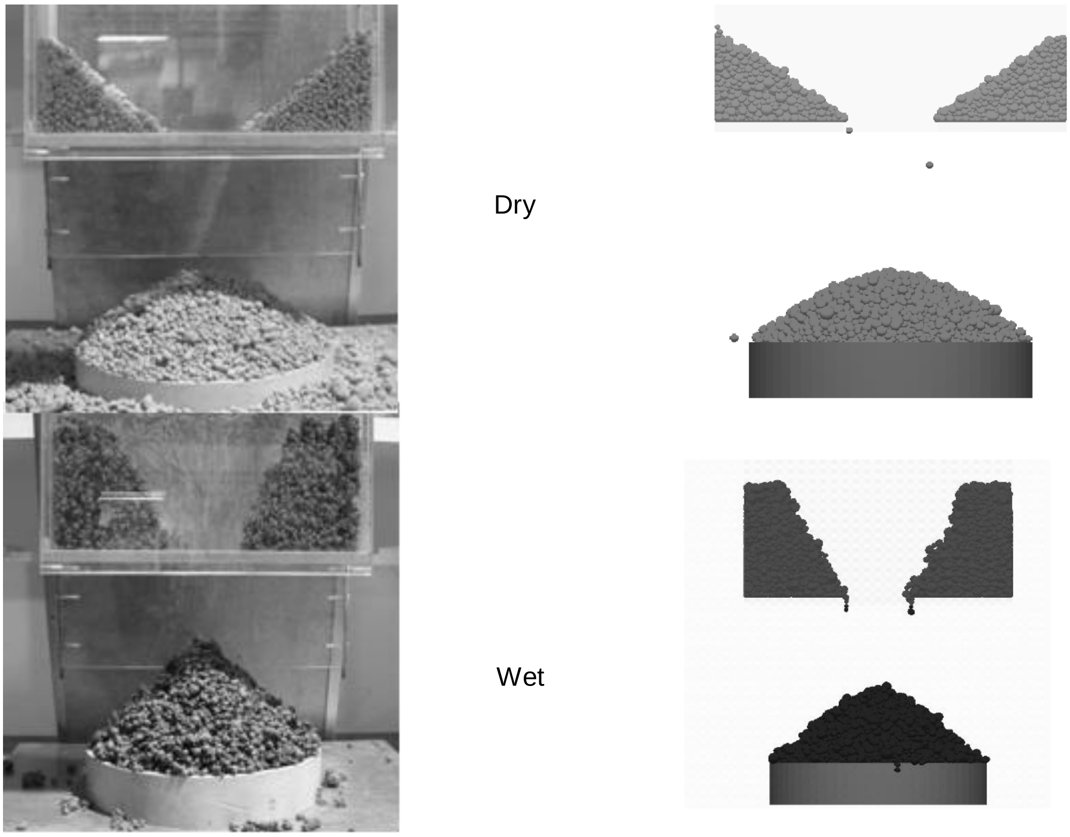
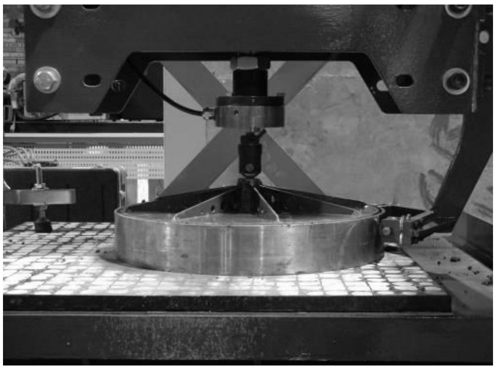


Figure 8. Examples of the calibration of the particle-to-particle interactions using a flat bottom hopper. Left: Experimental results; Right: DEM results; Top: Dry bauxite; Bottom: Wet bauxite

Friction between the bauxite and wall liners is a key property for the reliable design and modelling of chutes. To examine and measure the wall friction of particles less than 20 mm, a new Jenike type large scale wall friction tester (LSWFT) [14] was developed at the University of Wollongong which consists of a 300 mm (maximum) shear cell as shown in Figure 9. The wall friction tester can also measure the wall friction on large wall samples (e.g.600 x 500 mm) and can investigate the effects of joining methods between plates or tiles (e.g. welds, raised edges, caps, rubber). To verify the interactions between the bauxite and the chute wall liners are satisfactory in the DEM models, a series of validation tests was conducted using DEM, as shown in Figures 9 and 10 to compare the measured and simulated wall yield loci. Due to particle scaling (Figure 5) the geometry in the DEM models was also scaled respectively to keep the aspect ratio similar - normal pressures below 4 kPa were not possible from the self-weight of the material in the large shear cell. However, the correlation between the DEM results at different shear rates and the experimental data is good. To complete the numerical wall friction tests in a reasonable time frame the shear rate of the cell was increased from 0.0000423 m/s (2.54 mm/min) to 0.005 m/s and 0.05 m/s.

The current transfer chute C1/C2 is lined with bisalloy 400 wear plate and domite wear bars along the horizontal edges. Therefore the interaction between bauxite and bisalloy 400 has been used for the DEM simulations.



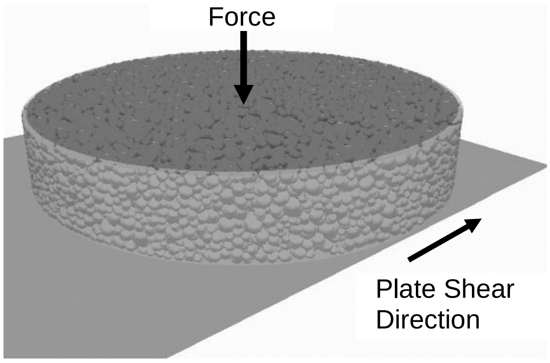


Figure 9. Large scale wall friction tester (left) and DEM validation of large scale wall friction test (right)

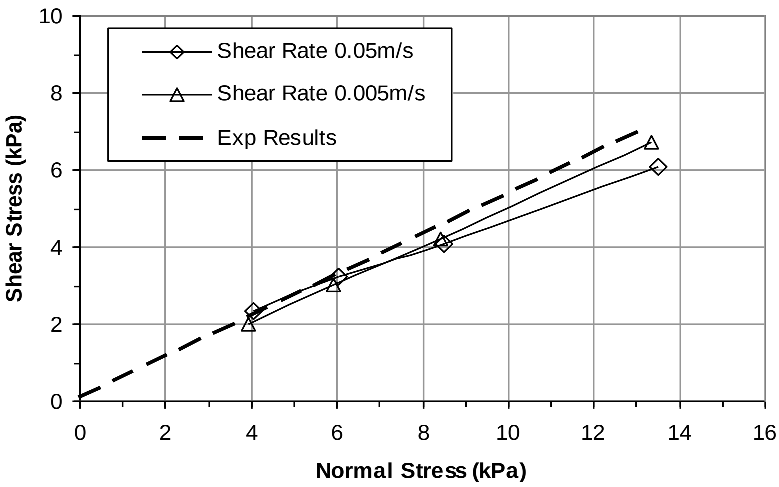


Figure 10. Experimental and DEM (Hertz-Mindlin with linear cohesion) wall yield loci of TGB at 16% wet basis moisture content and bisalloy 400

5. DEM MODEL OF CURRENT DESIGN

A 3D CAD model of transfer C1/C2 was developed using existing manufacturing drawings and site measurements and subsequently imported into the DEM software package, as shown in Figure 4. A detailed CAD model was developed and a simplified CAD model was derived from the detailed model consisting of the critical surfaces (via surface modelling) as shown in Figure 11. Once the material model of TGB (worst material to handle) was developed from the results of the calibration work, a large scale DEM model of transfer C1/C2 was developed and the following was specified:

- Material properties of surfaces and bauxite.
- Contact interaction properties.
- Cohesion.
- Surface kinematics i.e. belt speeds, head pulley angular velocity.
- Particle initiation procedure.
- Particle/material throughput and size distribution.
- Solver settings i.e. time step, contact detection grid size, write out period, simulation time.

Figures 11, 12 and 15 show the DEM simulation of transfer C1/C2 using the calibrated material model of TGB at maximum strength conditions. Figure 12 clearly shows the non-symmetrical flow of bauxite into the feed chute and correlates well to the observations in Figure 3a. As the fine bauxite is sticky, the material adheres easily to the belt and relies on the mist bars and scrapers to clean the belt as shown in Figure 13 and the DEM simulations. Due to the drop height from the feed chute to the belt on conveyor C2, the material tends not to form a distinctive surcharge profile as shown in Figures 12 and 14 which causes the material to flow onto the skirting.

Figure 11. Isometric view of DEM simulation of conveyor transfer C1/C2

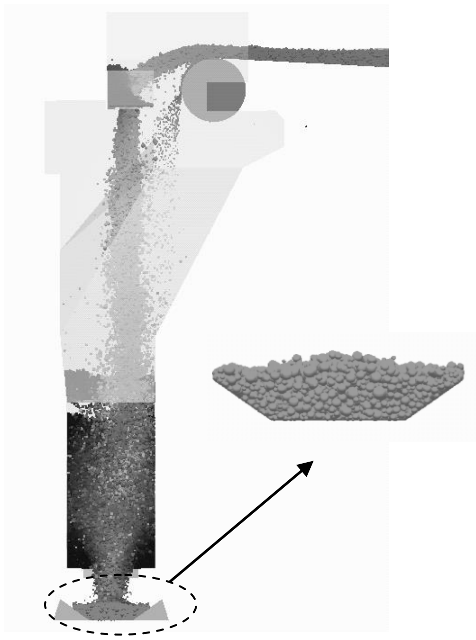


Figure 12. Front view of DEM simulation of conveyor transfer C1/C2

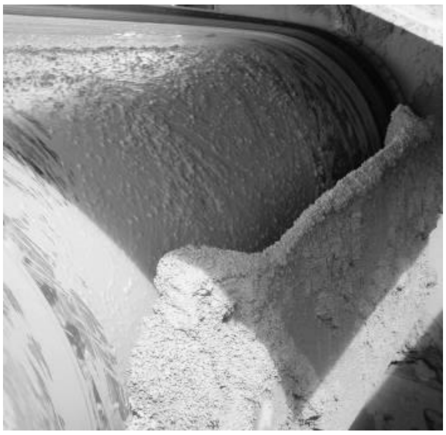


Figure 13. Wet bauxite sticking to belt on C1

Figure 14. Profile of wet bauxite on C2

One of the main causes of the flow problems in transfer C1/C2 is the insufficient angle of flow through the rock box and feed chute which causes the material to decelerate and form dead regions. Figure 15 shows the DEM predictions of the material flow through the lower section of the chute where there is a slow build-up of product caused by the V-plate which leads to eventual plugging. The cross-sectional area between the rock box and feed chute is low which causes the product to easily build-up and plug against the cross members which brace the chute as shown in Figure 15. When the product begins to decelerate and more material is retained in the rock box and feed chute, the angle of flow quickly begins to reduce which exacerbates the problem. To predict these flow problems using analytical methods and continuum mechanics is difficult and trying to visualise the flow behaviour is even more of a difficult task. Although DEM is usually only used to model steady state particle behaviour over short periods (say less than 30 seconds), caution and practical knowledge is required to determine any long term problems that can't be easily simulated or incorporated into the DEM model easily and feasibly (e.g. moisture migration, build-up of fine material, wear). The DEM simulations do show a gradual increase in the free surface over the short simulation period which is clear enough to suggest that the depth of the free surface will increase and block the chute.

Figure 15. Slow build-up of wet bauxite in lower chute section

The upper head chute is designed to be a low maintenance chute as product impacts on itself from product build-up on a small horizontal ledge. Figure 16 shows the DEM model of the plastic deformation and flow patterns of the product on the horizontal ledge which is very similar to reality as shown in Figure 16. It is difficult to distinguish in the DEM model in Figure 16 the presence of the secondary particle stream above the primary inflowing stream but particles do flow sideways over the inflowing stream into the lower chute section as shown in the photo from site of the actual material behaviour in Figure 16. Although the upper head chute works well to redirect the bauxite, the positioning of the far wall and horizontal ledges is not ideal as the bauxite is not fed into the centre of the lower chute section, as shown in Figure 12. Due the belt velocity of C1 and the sampling system it is not possible to reposition the far wall and horizontal ledge requiring an alternative technique to redirect product flow.

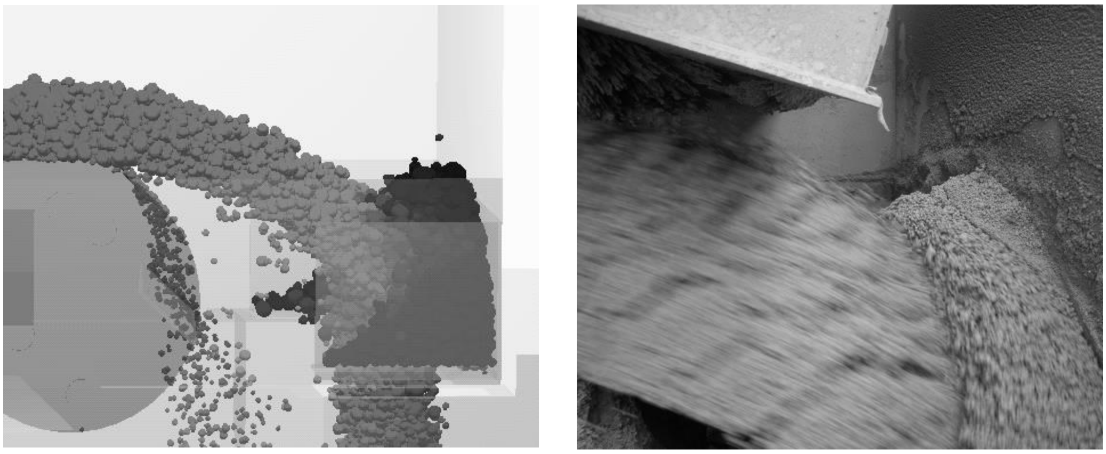


Figure 16. DEM (left) and physical (right) comparison of the flow of wet bauxite through upper head chute

To further validate the accuracy of the DEM simulations, Figures 17 and 18 show a comparison of the material build-up in the upper head chute once product flow has ceased. The correlation between the DEM model and the physical build-up is reasonably good even with the scale-up of the particle size distribution in the DEM simulations.

Figure 17. DEM prediction of the material profile of wet bauxite with no material flow in the upper head chute

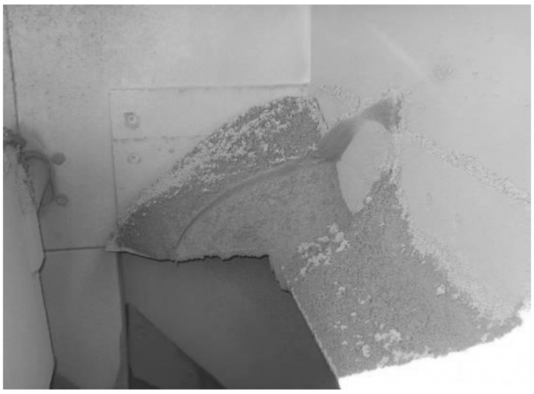


Figure 18. Material profile of wet bauxite with no material flow in the upper head chute

Figure 19 shows the material build-up of wet bauxite in the rock box and feed chute as the flow of bauxite has almost ceased. The DEM prediction of the material deposits compares well to the physical deposits shown in Figures 21 and 22 if the horizontal ledges in the rock box fitted with wear bars and the side wall are used as reference points. Figure 20 shows the material build-up in the DEM model based on a cohesionless bauxite material model where the angles of repose and the quantity of material deposited are much lower than the results in

Figure 19. Therefore DEM has the capabilities to model both cohesionless and cohesive product well if validated material properties are used. If the moisture content of the bauxite was reduced to a cohesionless and free flowing state, the current transfer station C1/C2 would most likely operate well.

Figure 19. Side view of DEM prediction of the material profile of wet bauxite with no material flow in lower chute section

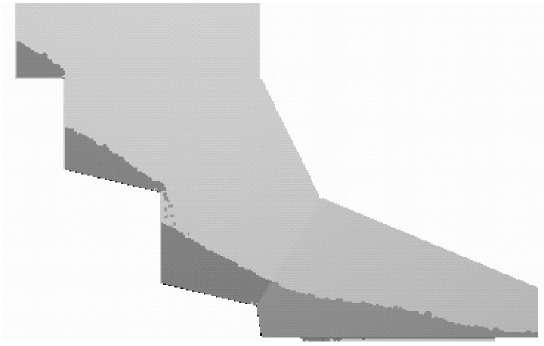


Figure 20. Side view of DEM prediction of the material profile of dry bauxite with no material flow in lower chute section

Figure 21. Front view of the material profile of wet bauxite with no material flow in the rock box

Figure 22. Front view of the material profile of wet bauxite with no material flow in the feed chute

6. DEM MODELS OF CONCEPT DESIGNS

Once the key problems were identified, several concept designs were developed using 3D CAD, analytical models (e.g. trajectories [15], chute flow [3], impact plates [16;17]) and data from DEM simulations. It is unknown what design objectives and constraints were originally set when designing the current upper head chute. For more reliable flow the centre of the material stream should be close to the centre of conveyor C2, however, the far wall and horizontal ledge in the head chute are incorrectly positioned resulting in the non-symmetrical flow into the lower chute section. To reposition the ledge in the head chute to the most appropriate position would require a major redesign of the upper chute and sampler assembly and with the extent of re-work required the whole transfer station should be removed and rebuilt. The aim of this study was to investigate using DEM the best modifications to achieve maximum improvement with the current structure where modifications would be feasible and can be implemented within a five day shut down.

Numerous concept designs were developed and evaluated ranging from insert designs to full replacement of the lower section of the transfer. This paper focuses on two of the concepts developed in the following sections. The main design criteria which were assessed to decide on the best concept to deliver the desired objectives were functionality, maintainability, accessibility, installation and estimated cost.

6.1. DEM Model of Concept A

To improve the flow of bauxite out of the lower section of the transfer station, the lower chute, rock box and feed chute as shown in Figure 2 has been modified as shown in Figures 23 and 24 with a replacement partially micro-ledged spoon. Referred to as Concept A in this paper, the lower section of the chute is designed to be partially self-cleaning and operate under rapid flow conditions. The micro-ledges are lined with wear bars along the horizontal edges to form numerous small cavities where bauxite can build up to minimise wear of the chute from the vertical in-flowing stream where impact velocities range between 8 to 12 m/s. The slope of the lower chute has been optimised to achieve maximum slope with the current geometry to obtain as much momentum as possible into the upper section of the lower chute to minimise material build-up.

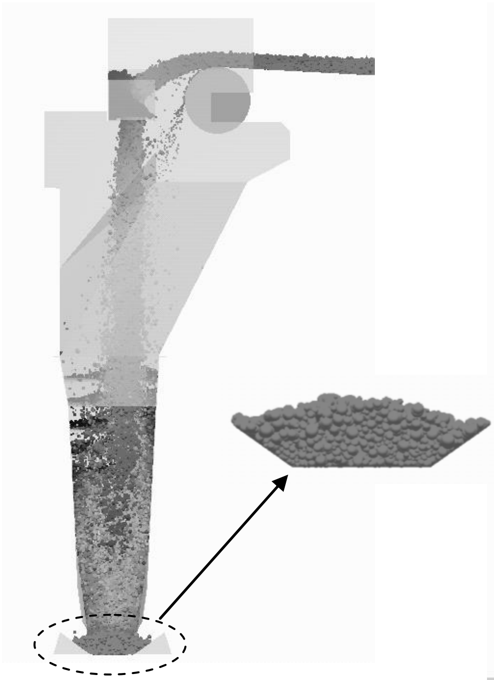


Figure 23. Front view of DEM simulation of Concept A with NO upper impact plate

Figure 24. Side view of DEM simulation of Concept A with NO upper impact plate

A curved spoon lined with wear resistant material is used to control the velocity of the stream and presentation of the material onto conveyor C2 by closely matching the horizontal velocity of the material and the conveyor belt at the point of impact. Controlling the way the material presents onto the receiving belt helps to minimise boiling or pooling, belt and skirt wear and belt mistracking. The concept currently used in the upper head chute of a small horizontal ledge shown in Figures 17 and 18 works well to divert the material into the lower chute but is poorly positioned. As shown in Figure 24, the bauxite is not confined well as the material is allowed to spread during impact in the upper head chute. To help confine the material stream and control the point of impact in the lower chute, an adjustable upper impact plate which has several micro-ledges as shown in Figures 25 and 26 has been investigated. The upper impact plate can be easily removed and has the capability to adjust the angle of the impact plate to adjust the direction of material flow into the lower chute and adjust the way the bauxite presents onto conveyor C2. Figure 26 shows the build-up of bauxite between the micro-ledges and on top of the inflowing stream which effectively creates a curved surface to redirect the material flow. The angle of impact of the inflowing stream with the impact plate is sufficient to minimise the material in the buffer zone above the primary material stream and cause plugging.

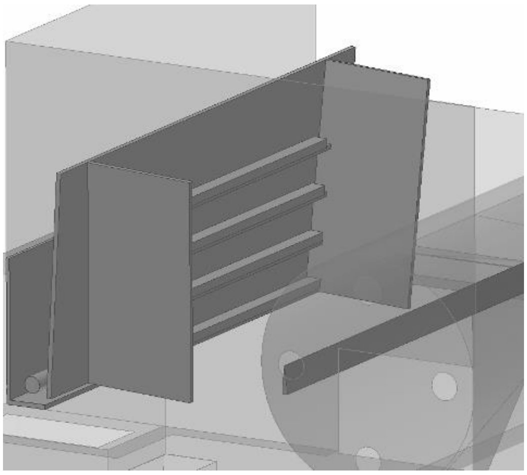


Figure 25 . CAD Model of adjustable upper impact plate

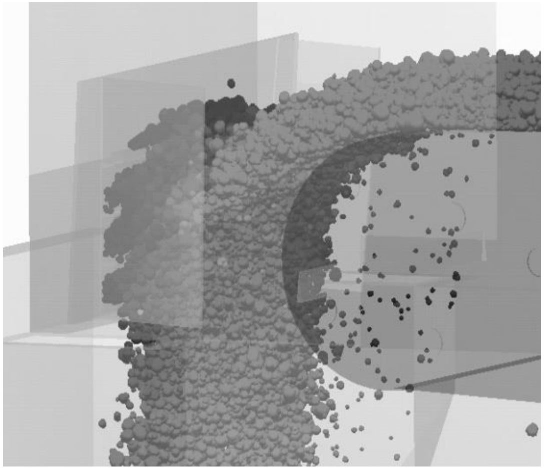


Figure 26. View of DEM simulation of material flow on adjustable upper impact plate

Figures 27 and 28 show the DEM simulation of Concept A with the adjustable upper impact plate with a slope of three degrees from the vertical. Although the flow behaviour is not significantly different with or without the upper impact plate, there are several benefits with the impact plate. Figure 28 shows that the upper impact marginally confines the bauxite stream which will reduce the wear of the sides of the upper lower chute and better present the material onto the partially micro-ledged spoon. The adjustability of the upper impact plate provides some method to control the flow of material through the spoon as the V-plate has been removed and adds more flexibility into the design in case the DEM predictions are not 100 per cent correct during installation. The adjustable impact plate has been designed so that the sampling chute can still effectively cut through the bauxite stream to take representative samples for analysis.

There is a distinctive difference in the way the bauxite presents onto conveyor C2 between the current design (Figure 12) and Concept A (Figures 23 and 27). As the bauxite is fed onto C2 via a spoon in Concept A, the material on the conveyor belt forms a greater surcharge angle compared to the current design where the surcharge angle is minimal as the bauxite is dropped onto C2 via a V-plate. To examine how the particles in the DEM simulations are fed onto conveyor C2, Figure 29 shows the setup of 2 bins used to count the number of particles on each side of C2. Figures 30 and 31 show the distribution of the particles on conveyor C2 without and with the upper impact plate, respectively during start up, steady-state flow and shut down. Generally there is a good even distribution of material on each side of the conveyor with or without the upper impact plate. During start up (between 0-6 seconds) and shut down (approximately after 12 seconds) more particles are loaded onto the left side of conveyor C2 especially with no upper impact plate. Once steady-state flow occurs and the spoon contains more bauxite, the distribution of material becomes more even which reduces the likelihood of mistracking.

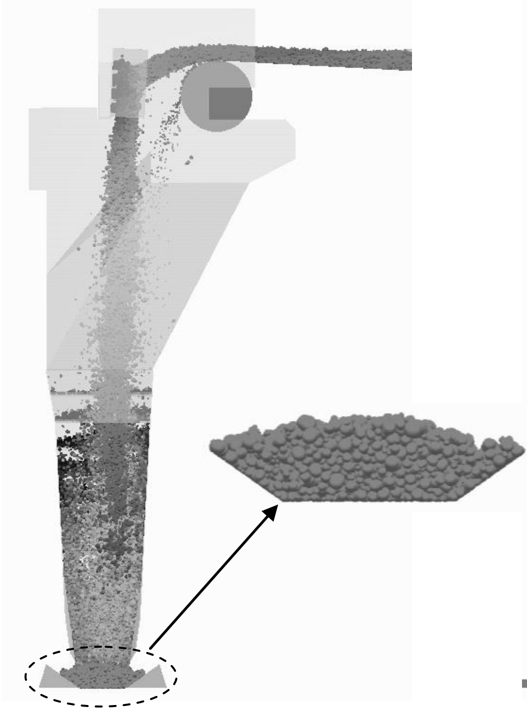


Figure 27. Front view of DEM simulation of Concept A with upper impact plate

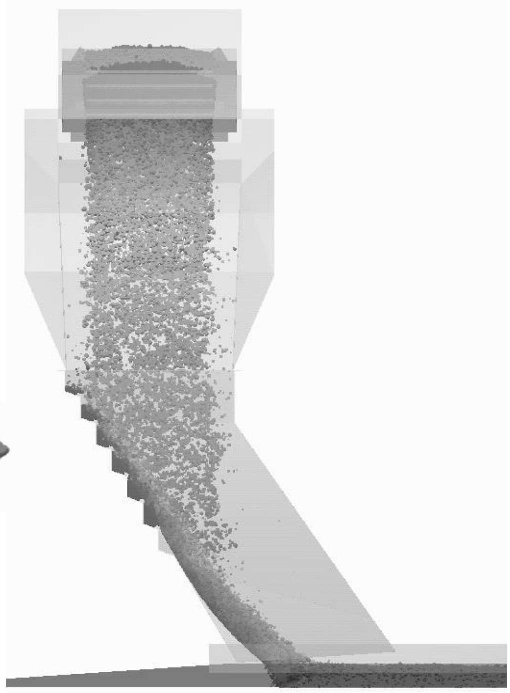


Figure 28. Side view of DEM simulation of Concept A with upper impact plate

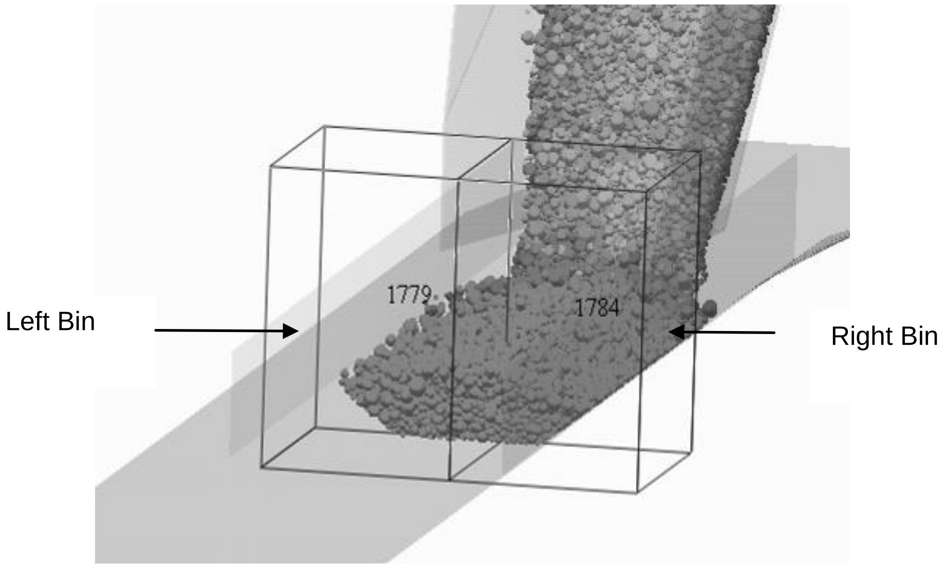


Figure 29. Setup of bins in DEM simulation on conveyor C2

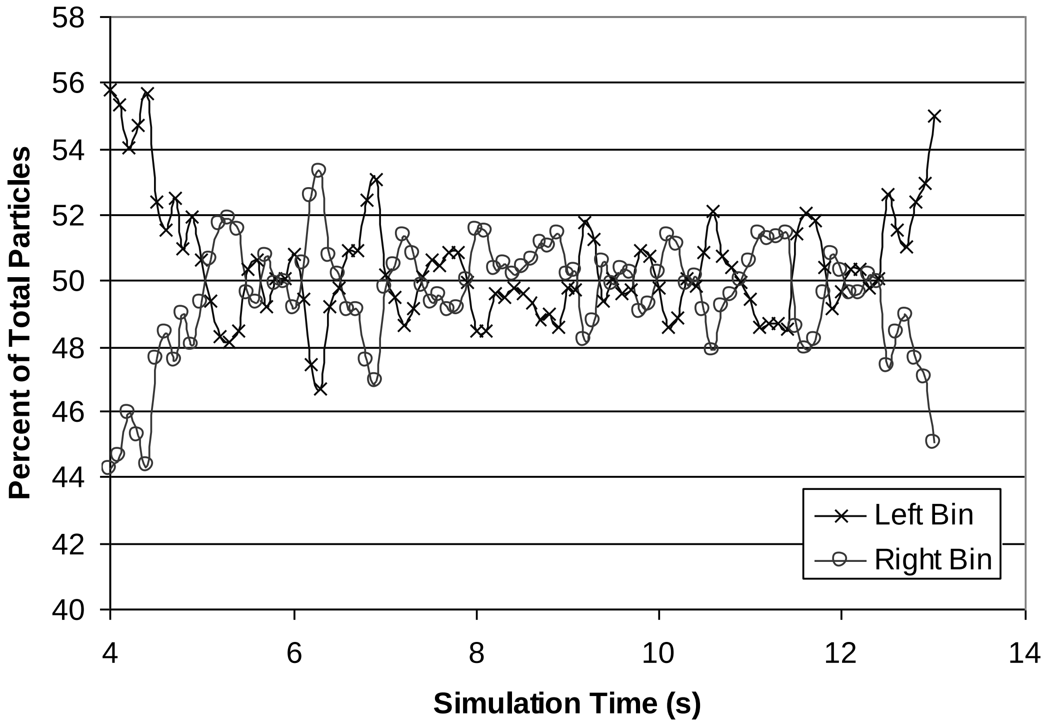


Figure 30. Number of particles in the left and right bin on conveyor C2 of Concept A with NO upper impact plate

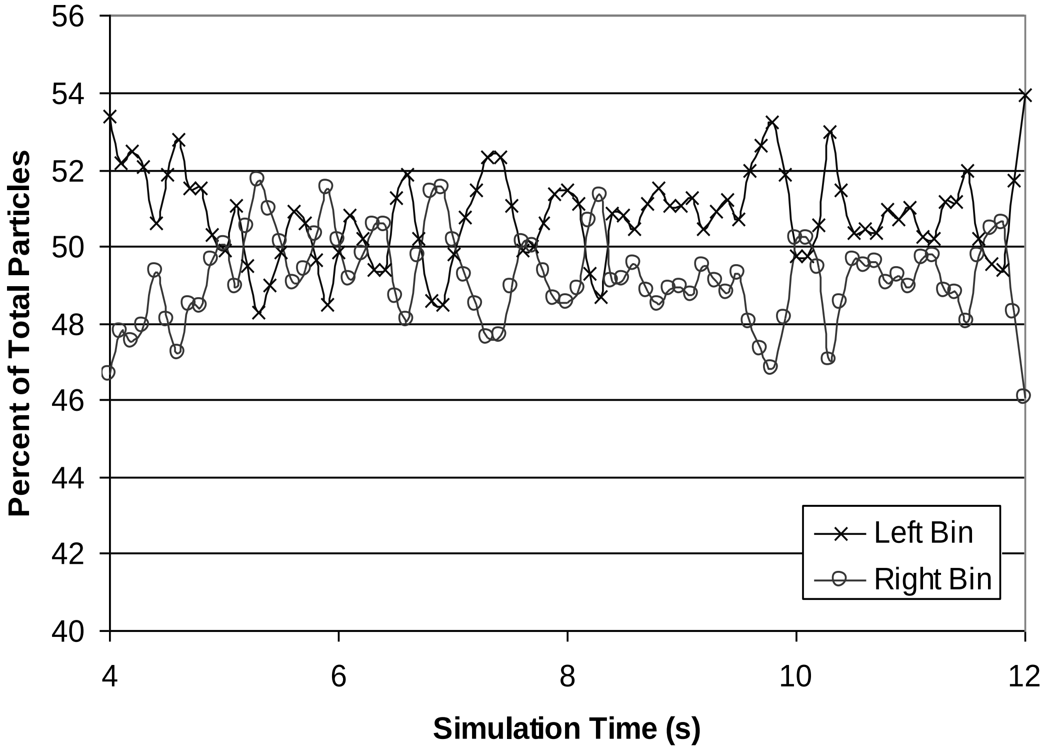


Figure 31. Number of particles in the left and right bin on conveyor C2 of Concept A with upper impact plate

6.2. DEM Model of Concept B

A concept was developed which required minimal chute sections to be removed or modified. Concept B shown in Figures 32 and 33 involve removing the feed chute with the V-plate and replacing the feed chute with a converging chute which bolts onto the rock box. Also the large ledges in the rock box are filled in with a micro-ledged and flat plate insert in the upper and lower ledge, respectively. Similar to Concept A, an adjustable upper impact plate has been added into the DEM simulation in Figures 32 and 33. Figures 32 and 33 show that the functionality of transfer C1/C2 can be dramatically improved by removing the V-plate and the large ledges in the rock box and installing a new feed chute and inserts in the rock box. Although V-plates are great for centralising material flow onto conveyor belts, they can be restrictive and remove a lot of momentum out of the material stream especially for cohesive materials, which leads to flow problems. The flat plate insert in the lower ledge of the rock box helps to accelerate the material stream as the failure envelop of bauxite against a smooth surface is typically much lower than the failure envelop of internal shear of bauxite. The DEM model predicts that the loading of the bauxite onto conveyor C2 will be fairly even as shown in Figure 32, however, fine adjustments can be made by adjusting the upper impact plate as discussed in Concept A previously.

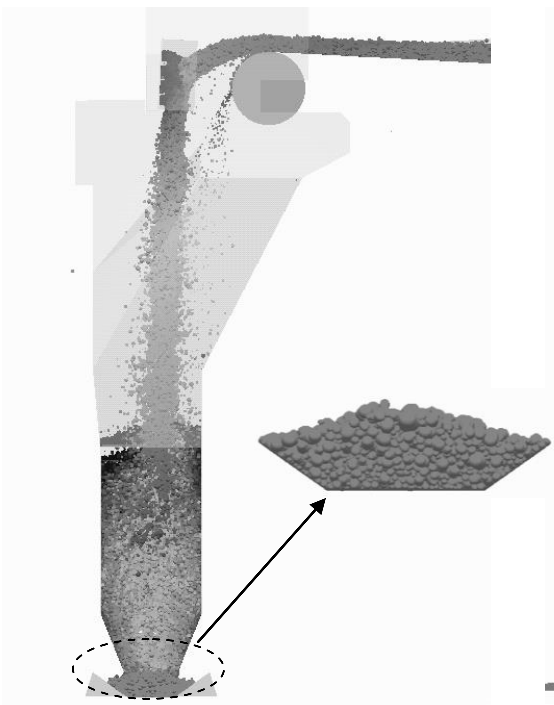


Figure 32. Front view of DEM simulation of Concept B with upper impact plate

Figure 33. Side view of DEM simulation of Concept B with upper impact plate

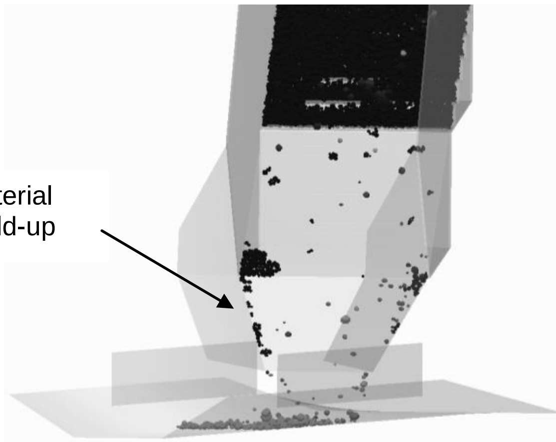


Figure 34. Material build-up in lower section of transfer chute of Concept B

The advantages of Concept B are that the modifications can be removed and the chute restored back to the current design if the functionality of the chute became worse. Concept B also allows small changes to be made to investigate what does and does not work well from these modifications. However, the DEM simulations provide confidence that Concept B would improve the functionality of the transfer station but there would be some minor difficulties installing and maintaining the inserts in the rock box due to access restrictions. As the new feed chute has been designed based on the geometrical restraints of the current rock box, the geometry of the new feed chute is not ideal due to larger than desired valley angles (Figure 34) and convergence angle (Figure 32) of the side walls. The larger valley angles cause a small amount of material build-up as shown in Figure 34 and the large convergence angles on the side walls will create areas of higher wear as the bauxite changes direction quickly as material is fed onto conveyor C2. With a calibrated DEM model the build-up of dead material in the micro-ledges after rapid flow has ceased can be effectively simulated. Using spherical particles and not calibrating the DEM model would be more difficult to model this scenario and may require unrealistic coefficients of rolling friction to obtain stable material heaps.

7. ABRASIVE WEAR OF BELT

Conveyor belts are expensive items and subject to abrasive wear from the loading of bulk material onto the cover of the belt. Abrasive wear can be calculated as a product of the normal impact pressure ($\rho_{bl}V_{ey}^2$) and the relative slip velocity between the product and conveyor belt as follows [18]:

$$W_a = \mu_b \rho_{bl} V_{ey}^2 \left(V_b - V_{ex}\right) \quad \textit{(kPa m/s)} \qquad (1)$$

where μ_b = friction coefficient between the bulk material and belt cover
V_{ey} = exit vertical component of velocity from the chute (m/s)
V_{ex} = exit horizontal component of velocity from the chute (m/s)
V_b = belt velocity (m/s)
ρ_{bl} = bulk density (t/m^3)

Using the velocities evaluated from the DEM simulations as the bauxite exits the feed chute or prior to impact on the belt (i.e. current design), the rate of abrasive wear on conveyor C2 has been approximately calculated in Table 1. Currently the wear on conveyor C2 is not a significant issue on site, therefore if the expected wear rates on belt C2 from the modified feed chutes in Concept A and B are on par or better than the current design, there should not be any problems with greater belt wear with the modifications. Table 1 indicates that both Concept A and B should generate lower rates of belt wear, especially Concept A which should help to increase the service life of the belt compared to the current situation. However, it is envisaged that the lower chute sections in Concept A and B will experience more wear than the current design and wear resistant liners will be required.

	V_{ey} (m/s)	V_{ex} (m/s)	W_a (kPa m/s)
Current Design	3.29	1.18	21.57
Concept A*	2.81	3.13	5.59
Concept B*	2.84	2.49	9.1

*Adjustable upper impact plate used in DEM simulation

Table 1. Summary of calculated rate of abrasive wear on conveyor C2

A simple investigation of how the particles or material feeds onto conveyor C2 has also been conducted in Figures 35 and 36 to examine the particle slip and vertical component of velocity along the belt from the initial feed point, respectively. The current design with the V-plate has a longer acceleration zone as shown in Figures 35 and 36 as material is fed onto the belt over a greater horizontal opening shown in Figure 15 with a low horizontal component of velocity. The feed chutes in Concept A and B both load the receiving conveyor belt over a smaller area but with a greater horizontal component of velocity which generates less slip and a shorter acceleration zone which is ideal to minimise wear. Using DEM modelling Concepts A and B indicate that there several alternatives to improve the functionality and flow ability of material through transfer C1/C2 and also the way the material is presented onto conveyor C2 to reduce belt and skirt wear.

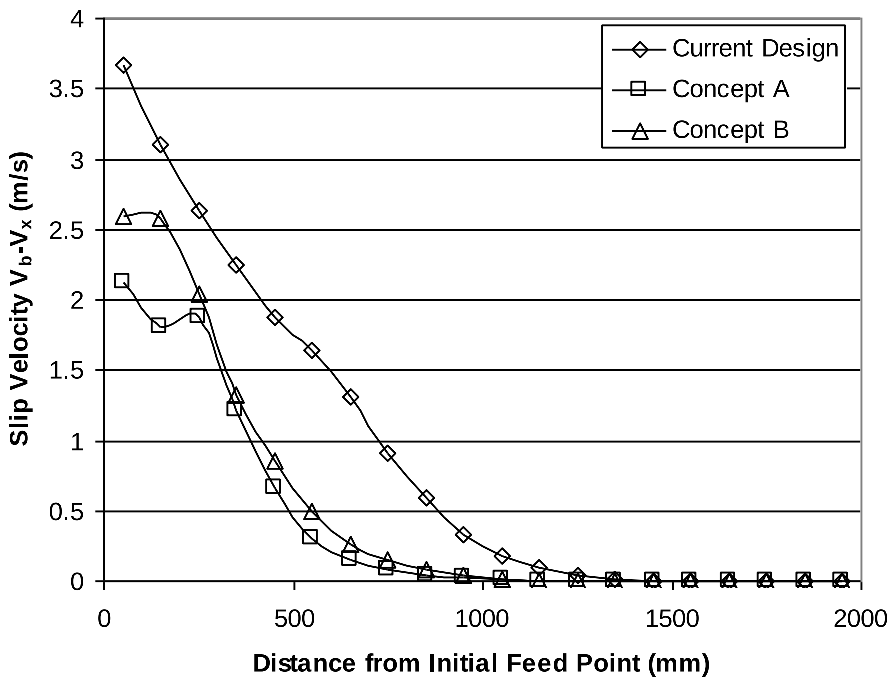


Figure 35. DEM prediction of the average slip between the particles and conveyor C2 from the initial feed point

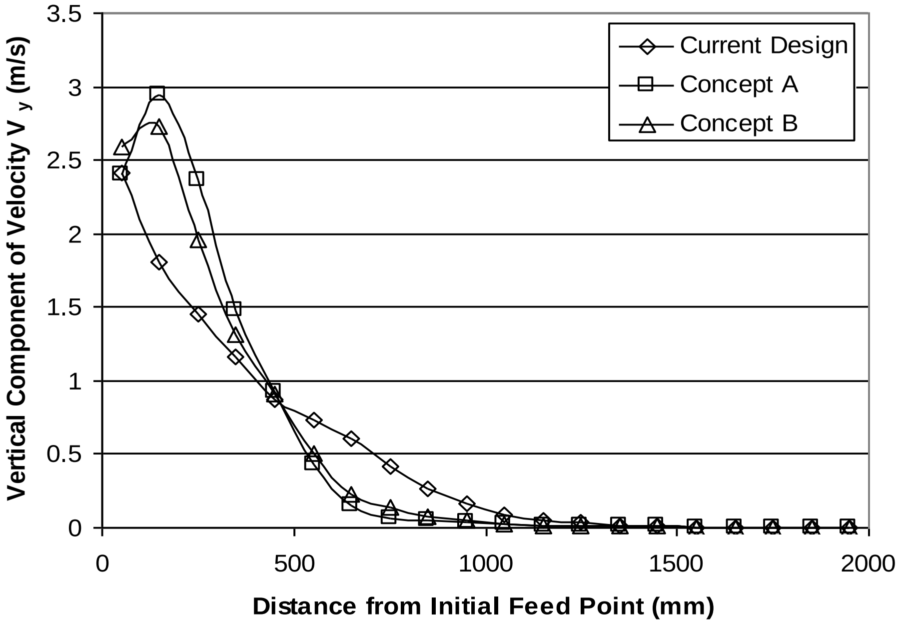


Figure 36. DEM prediction of the average vertical component of velocity of the particles on conveyor C2 from initial feed point

DISCUSSION AND CONCLUSION

This paper has shown how DEM can be an excellent design tool to model and visualise complex material flow where 2D continuum theories can be difficult to apply. The process and equipment which was used to characterise the bulk material, calibrate the DEM model and apply DEM methodology to trouble-shoot and design conveyor transfers were outlined to add further knowledge of the application of DEM to the literature. There was a good qualitative correlation between the DEM simulations and observations of an existing chute design which quantifies the accuracy and value of the characterisation and calibration methods.

Physical scale modelling can be a great way to examine a design but can be a difficult and expensive task when dealing with sticky and wet products. DEM in this work has been a feasible tool to prototype and investigate concept designs on a desktop workstation. The DEM simulations also proved to be an effective means to convey design ideas to other engineers and provide confidence that concept designs would work. When there are several different design solutions, DEM is a great numerical tool to assess selected design criteria and to select the optimum solution which satisfies the project objectives. Large amounts of useful data can also be collected from DEM simulations on a micro and macro scale. Without DEM, micro and macro data collection can be extremely complex or impossible, and it is time consuming to physically assess designs using scale modelling.

In the DEM simulations, bisalloy 400 was used as the wall material for the chutes, however, the redesigned chute sections in Concepts A and B would most likely be lined with a more robust material like a chromium carbide type plate (e.g. Arco plate) which has very similar frictional characteristics to bisalloy 400.

General observations of the large scale DEM predictions calibrated from simple bench-scale experiments were used to validate the current chute design and subsequent concept designs. Future research would be ideal to post-analyse the selected implemented concept design to further evaluate the accuracy of the design process and the validity of the DEM calibration *and scaling process.*

With the aid of the research presented in this investigation and the adoption of a systematic calibration process, DEM modelling provides a powerful optimisation tool to improve bulk material flow and prevent plugging, spillage, belt mistracking, belt wear and also minimise wear of structural parts. Abrasive and impact wear is a difficult task to accurately predict but

DEM can provide a basic insight to forecast the regions of wear and the intensity of wear, however, further research and verifications are still needed.

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