Increasing grab lifetime through wear management

by

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Preface

This report documents my master thesis, performed in graduating at the Delft University of Technology, Section Transport Engineering and Logistics, Department of Maritime and Transport Technology, Faculty of Mechanical, Maritime, and Materials Engineering. The goal of my research was to investigate new methods to assess and reduce wear on a bulk grab. The research was conducted in collaboration with Nemag.

I would like to take this opportunity to thank the people who have helped me during my research.

First of all I would like to warmly thank Wilbert de Kluijvert, my supervisor at Nemag, for his excellent guidance. He was always willing to make time to discuss my progress, findings and ideas. His help and guidance is more than appreciated. I would like to thank Michel Corbeau for giving me the opportunity to conduct this research at Nemag. I want to thank him for his wise words, that helped to keep me focused. I would also like to thank everyone else at Nemag for their warmth, kindness and hospitality, making my time there a very pleasant one. I couldn't have asked for a better experience.

My thanks and appreciation also goes out to Javad Mohajeri, my daily supervisor at TU Delft. He was always prepared to think along and discuss ways to move forward. I want to thank him for his efforts in reading my writings and giving me constructive feedback and suggestions, even through sickness and on short notice. His help and guidance is very much appreciated. I would like to thank Dingena Schott for trusting me with this research and introducing me to Nemag. I want to thank her for her guidance and support helping me finish my research.

Finally I would like to thank my friends and family for their infinite love and support. Especially my little brother for his never ending encouragement, and my aunt who supported me through my entire studies.

Kadir Karaca
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Summary

Nemag, a company based in the Netherlands, designs and manufactures customized grabs for handling various types of bulk material. The interaction of bulk grabs with abrasive materials makes them prone to wear. The consequence of wear is that the grab needs to be put through maintenance. This means the grab can no longer be used for production and therefore is not generating any profits. Nemag wants to increase their grabs tool life by managing their grab's susceptibility to wear. This research focuses on the wear as a result of the interaction between grab and bulk material: abrasive sliding and impact wear. Between these two wear types, the choice is made to focus on the abrasive sliding wear, because this form of interaction is the dominant one. The goal of this research is to increase the grabs tool life by reducing wear on the grab knives, by adjusting the geometrical shape of the grab knives. The performance of the new wear solutions is evaluated by simulation. Simulation is chosen because it is a relatively fast and cheap method that provides detailed information about the results. A simulation model of a grab already exists. This model however needs to be validated for wear.

To determine the wear rate, measurements are performed on a bulk grab prototype: the nemaX®. This prototype is tested at various bulk handling terminals and the amount of bulk material handled by the prototype is carefully recorded. For this reason the nemaX® is used for determining the wear rate. These measurements are used to validate the model.

The simulation is performed with the Discrete Element Method (DEM). There are two contact models capable of wear calculations: The Hertz-Mindlin with Archard wear model and the Hertz-Mindlin Relative wear model.

The simulation of the grab operation cycle in this research consists of two parts: the grab closing to load the bulk material, and the grab opening to unload the bulk material. The material model used is taken from S. Lommen. This model is validated for forces acting on the grab.

The results from the simulation are compared to the measurements on the nemaX®. The wear pattern for the Relative wear model shows no resemblance to the measurements. The wear pattern for the Archard wear model is similar to the measurements. However, the wear rate on the knives is much higher in the simulation. There is a difference between the static friction coefficient (SFC) of the knives and of the bucket. The SFC of the knives is set to 0. A new, small scale simulation is set up to study the influence of the SFC on wear. The results of this study show that the SFC influences the interaction between particles and equipment. This shows that a suitable SFC is necessary to determine the correct wear pattern.

To adjust the model for wear the SFC of the knife is varied between 0,1 and 0,5. The results are once again compared to the measurements. The SFC with wear that matches best is chosen to use. Therefore the Archard wear model with a SFC of 0,4 for the knives is used for all the prospective simulations in this research.

The results of the simulations show that a large portion of the wear occurs when the grab opens to discharge its payload. Concept solutions to reduce wear are designed and tested. The concept solutions aim to reduce wear during opening of the grab by redirecting the flow of material so that no unnecessary contact is made between the knives and the bulk material.

This approach proved ineffective. For the material to be released of the grab, a certain angle of the knives is required. By the time this angle is reached, most of the material is already unloaded. Some concepts however stopped a portion of the bulk material from flowing out of the grab. This way the bulk material was allowed to build up a protective layer, preventing the flowing material to cause any wear and still reduce the amount of wear during opening on the knives.

The adjusted geometrical shape also influences the wear during loading of the grab. The adjusted geometry of some concepts resulted in lower forces acting on the grab, causing less wear. Also, creating a protective layer of bulk material during closing proved very effective for reducing wear.

However, the adjusted geometry also influences and reduces the grabs ability to burrow into the bulk material. For most concepts this reduction in performance is marginal. For one of the concepts this reduction is over 10%. However, this large loss in performance is a result of the large particle size used in the simulation model. This makes the decision making process difficult, since the grab performance is crucial and the concept with the most performance reduction also shows the most reduction in wear in simulation. In reality this performance drop could be less, because the particles would be smaller.

All in all, this research has shown that the wear on the knives of a bulk grab can be reduced by relatively small changes in the geometrical shape of the knives, without significant loss of performance. By changing the geometrical shape, lower normal forces and lower sliding distances can be achieved, reducing the amount of wear on the grab knives.

For improving the accuracy of the model and increasing the design options, for further research it is advised to: Reduce particle size, add particle rolling, and add particle adhesion to the model.

Samenvatting

Nemag, een in Nederland gevestigd bedrijf, ontwerpt en produceert grijpers op maat voor de overslag van verschillende soorten bulkmaterialen. De interactie van bulk grijpers met abrasieve materialen maakt dat ze sterk onderhevig zijn aan slijtage. Het gevolg van slijtage is dat de grijper onderhoud moet ondergaan. Dit betekent dat de grijper niet meer gebruikt kan worden voor productie en dus geen winst oplevert. Nemag wil de standtijd van hun grijper verlengen door de gevoeligheid voor slijtage van de grijper te beheren. Dit onderzoek richt zich op de slijtage als gevolg van de interactie tussen grijper en bulk materiaal: abrasieve glij- en stootslijtage. Tussen deze twee soorten slijtage is de keuze gemaakt om te concentreren op de abrasieve glijslijtage, omdat deze vorm van interactie de dominante is. Het doel van dit onderzoek is om de standtijd van de grijpermessen te verlengen door de slijtage van de grijpermessen te verminderen. Dit door de geometrische vorm van de grijpermessen aan te passen. De prestaties van de nieuwe slijtageoplossingen worden geëvalueerd door middel van simulatie. Simulatie is gekozen omdat het een relatief snelle en goedkope methode is die gedetailleerde informatie geeft over de resultaten. Er bestaat al een simulatiemodel van een grijper.

Om de slijtagesnelheid te bepalen, worden metingen uitgevoerd op een bulkgrijperprototype: de nemaX®. Dit prototype wordt getest op verschillende bulk terminals en de hoeveelheid bulkmateriaal die door het prototype wordt verwerkt, wordt zorgvuldig geregistreerd. Om deze reden wordt de nemaX®® gebruikt voor het bepalen van de slijtagesnelheid. Deze metingen worden gebruikt om het model te valideren.

De simulatie wordt uitgevoerd met de Discrete Element Methode (DEM). Er zijn twee contactmodellen die slijtageberekeningen kunnen uitvoeren: De Hertz-Mindlin met Archard wear model en het Hertz-Mindlin Relative wear model.

De simulatie van de grijpercyclus in dit onderzoek bestaat uit twee delen: het sluiten van de grijper om het bulkmateriaal te laden en het openen van de grijper om het bulkmateriaal te lossen. Het gebruikte materiaal model is afkomstig van S. Lommen. Dit model is gevalideerd voor krachten die op de grijper werken.

De resultaten van de simulatie worden vergeleken met de metingen op de nemaX®. Het slijtagepatroon voor het Relatieve slijtagemodel vertoont geen gelijkenis met de metingen. Het slijtagepatroon voor het Archard wear model is vergelijkbaar met de metingen. De slijtage van de messen is echter veel hoger in de simulatie. Er is een verschil tussen de statische wrijvingscoëfficiënt (SFC) van de messen en van de emmer. De SFC van de messen is op 0 gezet. Er is een nieuwe, kleinschalige simulatie opgezet om de invloed van de SFC op slijtage te bestuderen. De resultaten van deze studie tonen aan dat de SFC de interactie tussen deeltjes en apparatuur beïnvloedt.

Hieruit blijkt dat een geschikte SFC nodig is om het juiste slijtagepatroon te bepalen. Om het model voor slijtage aan te passen wordt de SFC van het mes gevarieerd tussen 0,1 en 0,5. De resultaten worden opnieuw vergeleken met de metingen. Er is gekozen voor de SFC die het waarvan de slijtage het meest overeenkomt met de metingen. Het Archard wear model met een SFC van 0,4 voor de messen wordt gebruikt voor alle volgende simulaties in dit onderzoek.

De resultaten van de simulaties tonen aan dat een groot deel van de slijtage optreedt wanneer de grijper zich opent om zijn lading te lossen. Concept oplossingen om slijtage te verminderen worden ontworpen en getest. De concept oplossingen zijn erop gericht om de slijtage tijdens het openen van de grijper te verminderen door de materiaalstroom te manipuleren, zodat er niet onnodig contact wordt gemaakt tussen de messen en het bulkmateriaal.

Deze aanpak is ineffectief gebleken. Om het materiaal los te maken van de grijper is een bepaalde hoek van de messen vereist. Tegen de tijd dat deze hoek is bereikt, is het grootste deel van het materiaal al gelost. Sommige concepten hebben echter verhinderd dat een deel van het bulkmateriaal uit de grijper stroomde. Op deze manier kon het bulkmateriaal een beschermende laag vormen, zodat het stromende materiaal geen slijtage veroorzaakt en toch de slijtage tijdens het openen van de messen vermindert.

De aangepaste geometrie van sommige concepten resulteerde in lagere krachten op de grijper, waardoor er minder slijtage optreedt tijdens het sluiten. Ook het creëren van een beschermende laag bulkmateriaal tijdens het sluiten bleek zeer effectief om slijtage te verminderen, maar de aangepaste geometrie heeft ook invloed op- en vermindert het vermogen van de grijpers om zich in het bulkmateriaal te graven. Voor de meeste concepten is deze prestatievermindering marginaal.

Voor één van de concepten is deze reductie meer dan 10%. Dit grote prestatieverlies is echter het gevolg van de grote deeltjesgrootte in het simulatiemodel. Dit bemoeilijkt het besluitvormingsproces, aangezien de grijperprestaties cruciaal zijn en het concept met de meeste prestatievermindering ook de meeste reductie van slijtage simulaties laat zien. In werkelijkheid zou deze prestatiedaling minder groot kunnen zijn, omdat de deeltjes kleiner zouden zijn.

Al met al heeft dit onderzoek aangetoond dat de slijtage van de messen van een bulkgrijper kan worden verminderd door relatief kleine veranderingen in de geometrische vorm van de messen, zonder significant prestatieverlies. Door de geometrische vorm te veranderen, kunnen lagere normaal krachten en lagere schuifafstanden worden bereikt, waardoor de slijtage van de grijpermessen kan worden verminderd. Om de nauwkeurigheid van het model te verbeteren en de ontwerp mogelijkheden te vergroten, wordt voor verdere onderzoek geadviseerd: Vermindering van de deeltjesgrootte, toevoegen van deeltjesrollen en toevoegen van deeltjesadhesie aan het model.

Contents

A

Research Paper

Evaluation of the suitability of a material model, validated for payload performance, to assess wear performance

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Keywords: Discrete Element Method, DEM, Wear, Archard, Static friction coefficient

Abstract: DEM simulation is used to model the behaviour of bulk materials and their interaction with bulk handling equipment. In large scale applications, due to the large number of particles, the simulation run time can become too long, making the use of simulation inefficient. To reduce this run time, particle size can be increased. This results in less particles for the same volume. However, increasing particle size influences its interaction with the equipment. Adjusting parameters, such as the static friction coefficient (SFC), can correct this particle size influence. A material model for the interaction of iron ore with bulk grabs was created this way, and validated to assess the grab payload. It is unknown whether the validated model for payload can be used to assess a different performance indicator: wear. In this study the effects of this adjusted SFC on wear is investigated. This is done by simulating a piece of equipment moving through a bed of material and varying the SFC. The results show that for a different SFC, the amount of wear is also different. Analysis shows that the SFC influences the forces on the equipment during penetration and also the velocity of the particles in direct contact with the equipment. This shows that the SFC influences the interaction between geometry and particles. This could in turn affect the flow of the material and therefor the wear pattern. In conclusion, a model cannot just be used to assess a different performance indicator. Although a model is validated for payload performance, the adjustments can influence the models behaviour causing incorrect results for wear performance. The model should therefore be validated for each performance indicator.

1 INTRODUCTION

The Discrete Element Method (DEM) is a method to model individual particles. The method can be used to model the behaviour of bulk materials, such as rocks and ores, and their interaction with bulk handling equipment. Research at the Department of Transport Engineering and Logistics at the Delft University of Technology is conducted on DEM in large scale applications. This research has led to a simulation model that describes the behaviour of a bulk handling grab interacting with iron ore pellets. These bulk handling grabs are capable of handling dozens of metric tons of material.

In DEM simulation spherical particles are used to model and represent the bulk material. The large size of the bulk handling grab requires a large volume of particles to be modelled in the simulation. This leads to extremely high computational times of over a year, making the use of simulation inefficient. One way of reducing the computational time is by applying the coarse graining technique. This is a technique where the radius of a particle is scaled up to increase the size of the particle. By increasing the size of the particles, less individual particles are required to accommodate the same volume.

The material model developed by TU Delft makes use of the coarse graining technique. Research on the effects of this have shown that the resistance on the tip of the grab during penetration of the bulk material was higher compared to particles without coarse graining. This has been compensated by reducing the static friction coefficient of the tip to 0. This approach is validated by comparing the forces on the grab in the simulation with the forces acting on a real grab. With this validated model, the performance of a grab regarding its payload can be assessed [1].

1.1 Aim

The aim of this study is to determine whether a simulation model validated to assess the performance of a bulk grab on payload, can be used to assess a different performance indicator: wear.

Being able to assess multiple performance indicators with the same model can give a better insight in the performance of a design. This way the design can be optimized based on multiple criteria.

1.2 Wear

Wear is defined by the ASTM as: Damage to a solid surface that involves progressive loss of material, due to relative motion between a surface and a contacting substance or substances [2].
Wear can occur through various wear processes. These wear processes are categorized in wear modes according to the wear mechanism. The major mechanical wear modes are abrasive wear, adhesive wear, and fatigue wear [3]. These wear modes can be further classified into subgroups according to their contact type: sliding wear, rolling wear, impact wear etc [4] [5]. Abrasive sliding wear is the dominant form of wear in the grab, therefore this wear mechanism is the focus of the research.

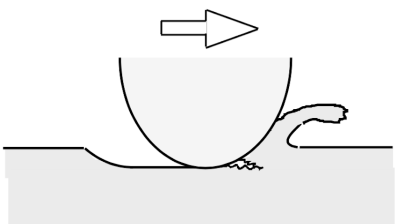

Figure 1: Abrasive sliding wear

1.2.1 Abrasive wear

When two materials are in contact, the harder material creates scratches in the softer material. Due to this scratching, a certain amount of material is removed. The material that causes the wear on the material/object that is to be preserved is considered the abrasive. For example, in grab operations, the grab needs to be preserved in order to have a longer lifespan and the bulk material it handles is considered the abrasive (Fig. 1).

1.2.2 Archard wear model

The model to determine the volume of material removed by abrasive sliding wear is created by J.F. Archard. The principle behind the model is that the amount of wear on a surface is determined by the friction work done over a certain distance. The model is given by the formula [6]:

$$V = K\frac{F_n}{H}d \tag{1}$$

Where:

- V = Wear volume
- K = Wear coefficient
- F_n = Applied normal force
- H = Hardness of the softest material
- d = Sliding distance

The wear coefficient K is a proportionality number equal to the wear volume per unit sliding distance with the applied normal force equal to the hardness of the softer material. The wear coefficient K is determined for a wear system by experiment [7].

2 METHOD

The model that was researched has been adjusted to reduce computation time. This has been done by coarse graining and adjusting the static friction coefficient (SFC). In this research the effects of the SFC on wear in a DEM simulation was determined. This was done by simulating a piece of equipment moving through a bed of material and varying the SFC between 0 and 0,5 with steps of 0,1. Each SFC was simulated three times. The average of these three simulation runs were used as final results.

Various software packages implementing DEM are available. The package used in this research was EDEM.

2.1 DEM Simulation

A DEM simulation consists of individual elements representing the bulk material and of equipment geometries. The elements have a default spherical shape with a radius set by the user (Fig. 2).

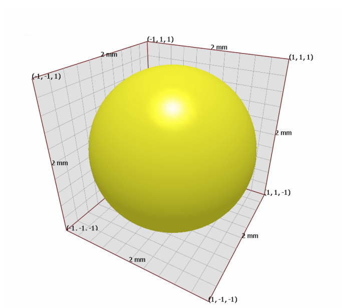

Figure 2: DEM particle

The equipment geometries can be simple static containers holding the bulk material or moving bulk handling equipment that interacts with the bulk material.

During a simulation the DEM follows an algorithm which can be divided into four stages. Figure 3 shows an overview of the stages of the DEM algorithm. This algorithm is looped until the simulation is finished.

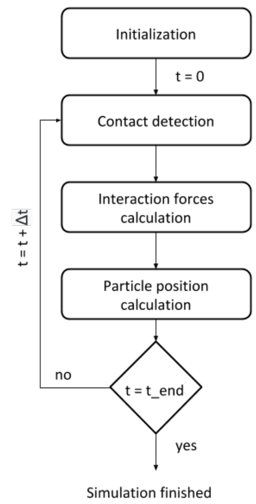

Figure 3: Simulation algorithm [8]

Timestep

The time between each iteration of the four stages is set by a timestep Δt. After each iteration this Δt is summed to the total time. The duration of the simulation is pre-set. After each iteration the total time is compared to the pre-set duration of the simulation. The algorithm keeps repeating until this duration time is reached.

The timestep determines the amount of iterations needed. A small timestep produces more data points, with very detailed results. A small timestep also results in more iterations. More iterations means more calculations, which influences the real time it takes to finish a simulation. Therefore the timestep should be chosen as large as possible.

A timestep that is too large however can result in inaccurate calculations. The large timestep can result in an overlap that is too large. This leads to very large interaction forces, resulting in particles moving erratically.

This means the chosen timestep influences the results of the simulation. This can be a problem if two simulations need to be compared with each other. Therefore, once a timestep is chosen, it should be kept constant.

The timestep can be chosen as a percentage of the Rayleigh time step. The Rayleigh time step is the time taken for a shear wave to propagate through a solid particle. The Rayleigh timestep is based on the size of the smallest particle. EDEM recommends the use of a timestep which is 20% of the Raleigh timestep. This was also the time step chosen for the simulations in this research. [9]

2.2 DEM Contact models

In EDEM, there are two contact models capable of wear calculations: The Hertz-Mindlin with Archard wear model and the Hertz-Mindlin Relative wear model. The Archard wear model is capable of giving quantitative information on the amount of material removed due to wear. Therefore this model was used. This section will give a brief overview of the Hertz-Mindlin contact model and the Archard wear model.

The Hertz-Mindlin contact model is the default model used by EDEM. This contact model determines the interacting forces. These interacting forces are then used to determine the particle positions. The contact between particles and between particles and geometry is modeled by a set of springs, dashpots and sliders. The contact between particles is illustrated in Figure 4. The normal and tangential forces are determined by [10]:

$$\begin{aligned} F_n &= k_n \delta_n^{\frac{3}{2}} + c_n \dot{\delta}_n \\ F_t &= k_t \delta_t \sqrt{\delta_n} + c_t \dot{\delta}_t \sqrt{\delta_n} \end{aligned} \quad (2)$$

Where:

- F_n, F_t = normal, tangential force
- k_n, k_t = normal, tangential spring stiffness
- c_n, c_t = normal, tangential damping coefficient
- δ_n, δ_t = normal, tangential overlap

The the tangential force F_t is limited using the Coulomb friction law:

$$F_t \leq F_n \mu \quad (3)$$

Where:

- μ = static friction coefficient

Hertz-Mindlin with Archard wear model

The Archard wear model is an extension of the Hertz-Mindlin contact model. The Archard wear model in EDEM is based on the wear model created by J.F. Archard. The model calculates the wear on a geometry surface per mesh element. The result of this model

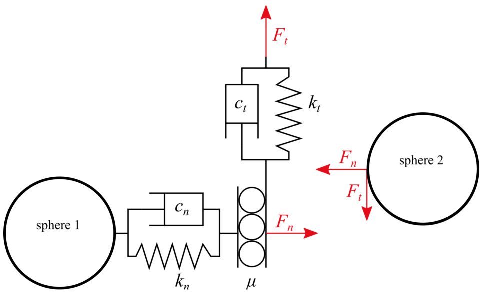

Figure 4: Overview of Hertz-Mindlin contact model [11]

gives the depth of the sliding wear per element. The wear equation used by EDEM is given as:

$$wear\ depth = \frac{W F_n d_t}{A} \tag{4}$$

Where:

- W = Wear coefficient
- F_n = Applied normal force
- d_t = Sliding distance
- A = Area of element

The wear coefficient W of EDEM combines two variables used in the original Archard wear model. The wear coefficient W is given as:

$$W = \frac{K}{H} \tag{5}$$

Where:

- K = Wear coefficient
- H = Hardness of the softest material

2.3 Material model

The material model used in EDEM was taken from S. Lommen [1]. Lommen experimentally determined the parameters to be used in EDEM to represent iron ore pellets. The model is validated for forces acting on the grab by comparing the simulation results with measurements on a real bulk grab. Table 1 gives an overview of the validated parameters.

2.4 Simulation set-up

The set-up to test the influence of the SFC on wear is shown in Figure 5. The set-up consists of a knife shaped geometry which moves through a bed of material at 1,5 m/s. The knife is parallel to the XZ-plane

Parameters	**Value**
Material	
Poissons Ratio	0,25
Shear Modulus	$1 * 10^8$ [Pa]
Density	3700 [kg/m3]
Particle radius	27,5 [mm]
Angular velocity limitation	Capped at 0 [rad/s]
Interaction	
Coefficient of Restitution	0,6
Coefficient of Static Friction	0

Table 1: DEM parameters for iron ore pellets

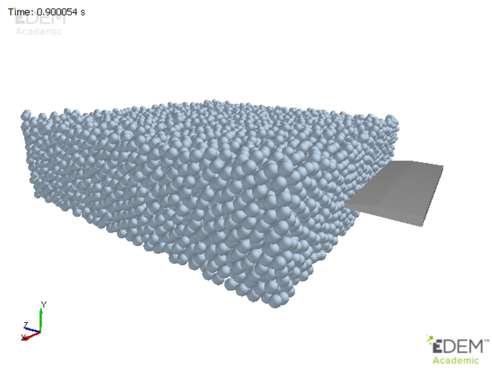

Figure 5: Set-up

and moves in the Z-direction. The material bed is 2m wide, 2m long and has a thickness of 0,5m. The wear coefficient is set to 1.

Equation 4, the Archard wear model, has four variables: wear coefficient W, the applied force F_n, the sliding distance d_t and the area of an element A. W and A are constants. This means that the SFC affects either the applied force or the sliding distance. To investigate this a geometry bin was created around the knife geometry, that moves along with the knife through the material (Fig. 6). The size of the geometry bin was chosen so that only one layer of particles, the ones in direct contact with the knife, are measured.

3 Results and discussion

The results for a varying SFC on wear are shown in Figure 7. These results show that the SFC does in fact influence the wear rate.

Figure 8 shows the velocities of the particles in contact with the knife. The velocity is shown for movement in the same direction as the knife (Z-direction). It is clear that the velocity of the particles was different for every SFC. A higher SFC means a higher resis-

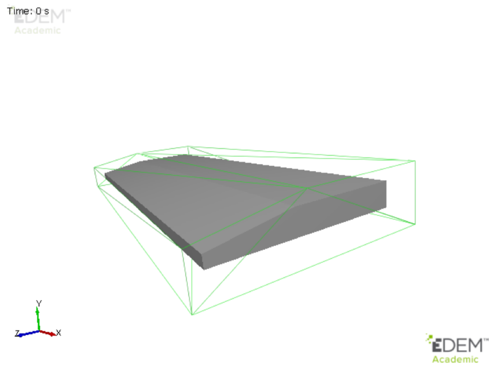

Figure 6: Geometry bin

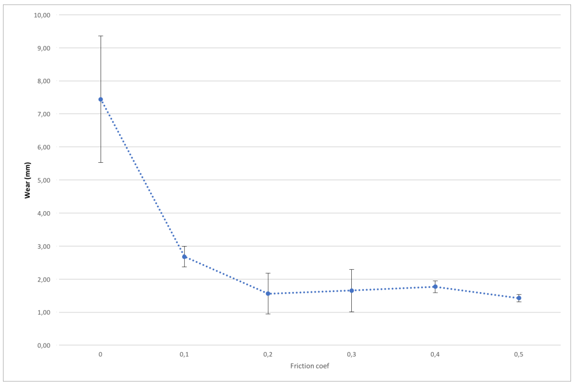

Figure 7: Wear for different SFC

tance for sliding. Because of this, with a higher SFC the material tends to move along with the knife longer, resulting in a lower sliding distance. This shows that the SFC influences the sliding distance of particles. The SFC influences the interaction between geometry and particles. Which could in turn affect the flow of the material and therefor the wear pattern.

Figure 9 shows the forces acting. During the steady state movement through the material the difference in forces were negligible. During penetration the forces were different for each SFC. This shows that the SFC has an influence on the forces.

4 CONCLUSIONS

The results in this research showed that the SFC influences the amount of wear on a piece of equipment. This shows that a simulation model, that has been adjusted from reality through coarse graining and validated for one performance indicator, cannot just be used to assess a different performance indicator. Although a model is validated for payload performance, the adjustments can influence the models behaviour causing incorrect results for wear performance. The

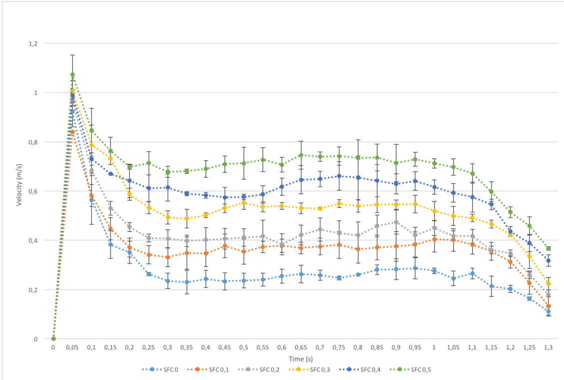

Figure 8: Particle velocities

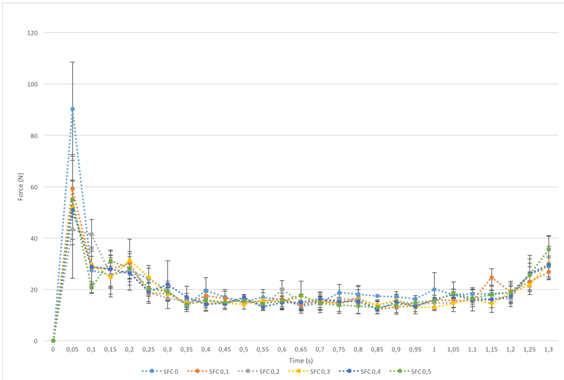

Figure 9: Particle forces

model should therefore be validated for each performance indicator.

In this research, only the SFC was considered. The influence of the increased size of the particles should also be investigated in further research.

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