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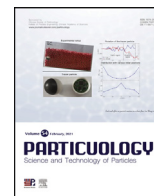
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Large-scale transportation and storage of wood pellets: Investigation of the change in physical properties



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ABSTRACT

The change in physical properties of wood pellets, with a focus on particle size distributions due to pellet breakage and attrition, was studied in a large-scale (~450 ton/h) transportation system. Critical locations with a high probability of breakage through the whole transportation system were chosen and sampled to study the effect of transportation system design and operation on the mechanical properties of pellets. Bulk density, mechanical durability, moisture content, and particle size distribution of pellets were characterized for each sample. Analysis of variance showed that there were significant differences between the percentages of small particles (< 5.6 mm) in the samples taken at different locations, especially at one with a vertical free fall of 7.8 m. On average, this relatively long drop increased the proportion of particles < 5.6 mm in the samples from 8.73% to 14.09%, and that of particles < 3.15 mm from 4.82% to 9.01%. Moreover, the measurements showed a wide deviation in the mechanical durability values, between a minimum of 90.8% and a maximum of 98.7%, which were not correlated to the sampling points but related to pellet properties. It can be concluded that pellet transportation systems require more dedicated design strategies to prevent breakage and attrition.

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Introduction

Worldwide use of wood pellets as a renewable energy carrier has increased sharply, from ~12 million metric tons in 2008 to 56 million metric tons in 2018 (Calderón, Gauthier, & Jossart, 2019). More than 27 million metric tons of wood pellets were consumed in Europe in 2018, more than 45% of them for industrial purposes. However, not all pellets consumed in Europe are produced by European countries. Approximately one-third are imported from the United States and Canada (Calderón et al., 2019).

Due to its inherently high moisture content and its low bulk and energy densities, biomass is usually densified to improve these properties; a process that is advantageous for transportation and handling steps (Tumuluru, Wright, Hess, & Kenney, 2011). Pellets are normally produced under high temperature and pressure

conditions in a so-called pelletization process, which involves the elastic and plastic deformation of particles and the softening of natural binders such as starch, protein, lignin, fat, and fibers to help agglomerate particles (de Souza et al., 2020; Kaliyan & Vance Morey, 2009; Mani, Tabil, & Sokhansanj, 2008; Nanou, Huijgen, Carbo, & Kiel, 2018).

The fragile nature of pellets causes their attrition and breakage throughout the entire logistic chain (Oveisi et al., 2013). As a result, average pellet length may decrease and the amount of generated small particles can increase (Boac, Casada, & Maghirang, 2008). This has consequences for pellet transportation, handling, and storage, such as an elevated risk of dust explosion, fire, segregation, arching and equipment fouling, health issues for people inhaling the dust, and losing a notable portion of the material (Aarseth, 2004; Ilic, Williams, Farnish, Webb, & Liu, 2018; Ramírez-Gómez, 2016). Moreover, pellet breakage and the generation of small particles undermine the pelletization effort by decreasing the bulk density (Sjöström & Blomqvist, 2014).

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The ability of biomass pellets to remain intact during loading, unloading, feeding, and transport is called “mechanical durability” (ISO, 2014). From the definition itself, the mechanical durability can give an indication of the extent to which the material can keep its initial shape. In practice, however, durability is characterized by measuring the amount of pre-defined small-size particles created in laboratory tests. This small size may be different in some of the literature, but a size of between 3 and 5 mm is usually considered (Graham et al., 2016; ISO, 2015). According to the literature, mechanical durability depends on the characteristics of the raw material; specifically, factors such as particle size and moisture content, pelletization process parameters, and storage conditions (Gilvari, de Jong, & Schott, 2019; Shui et al., 2020; Stelte et al., 2012; Whittaker & Shield, 2017).

Undoubtedly, the extent of pellet breakage and attrition very much depends on the type of pellet; the higher the pellet's strength, the lower its breakage and attrition rates are. However, pellets may undergo mechanical degradation due to high impacts and compression forces caused by, for instance, long drops, increased number of handling steps, and poor equipment design (Ilic et al., 2018; Ramírez-Gómez, 2016).

Different breakage mechanisms have been proposed for biomass pellets during transportation and handling, namely breakage into two or more pellets while practically keeping the cylindrical shapes, attrition of pellet surfaces and ends, and crushing of the whole pellet (Boac et al., 2008; Thomas, 1998).

In industry, various equipment is used for the transportation, handling, and storage of pellets. Of these, grabs, belt conveyors, pneumatic conveyors, pipe conveyors, hoppers, transfer chutes, silos, and bins are the most common (Dafnomilis, Lodewijks, Junginger, & Schott, 2018; Larsson, Lestander, Crompton, Melin, & Sokhansanj, 2012). Each of these types of equipment may degrade the pellets mechanically, due to attrition, compression, or impact. Recently, research has been underway to characterize the breakage and attrition of pellets (Boac et al., 2008; Gilvari, de Jong, & Schott, 2020; Murtala, Zigan, Michael, & Torbjörn, 2020; Ochkin-König, Heinrich, & Dosta, 2018). For instance, research on pneumatic conveyors has shown that pellet attrition increases with the increase in particle velocity, which is induced by increasing the air inlet velocity and decreasing the mass flow of pellets. Moreover, a shorter bend radius increases the breakage of pellets (Aarseth, 2004; Jägers, Wirtz, Scherer, & Behr, 2020).

It is known from previous studies that the magnitude of impact force, number of handling steps, and amount of bulk material directly influence the breakage and attrition of pellets (Boac et al., 2008; Kotzur, Berry, Bradley, Dias, & Silva, 2016; Oveisi et al., 2013) investigated the effect of drop height, pellet mass, and repeated handling steps on the degradation of wood pellets during free fall while they placed the pellets in a bag made of synthetic materials. They also studied the effect of pellet mass per bag and of repeated handling steps, concluding that greater drop heights and an elevated number of handling steps increase the amount of fines. Moreover, pellet mass shows a linear correlation with the generated mass of fines as long as the initial mass is kept lower than 1 kg.

Looking at corn-based animal feed pellets, Boac et al. (2008) studied the effect of the number of handling steps on the quantity of broken pellets (particles passing a sieve with a 5.6 mm mesh) and dust particles (< 0.125 mm) generated. The feed pellets contained 13.2% moisture and had a nominal diameter of 6.4 mm and a durability of 92.9%, according to the tumbling box method. Their test setup included a bucket elevator with a height of 54.9 m, which cycled the pellets from the bottom of storage bins to their top and from a first bin to a second one, then vice versa, with an average flow rate of 59.4 metric tons per hour. They repeated the discharge and loading of the bins eight times and observed a notable increase

in the proportion of particles < 5.6 mm, from 17.5% to 50.2%. The average dust generation was 0.069% per transfer.

As shown above, existing literature regarding the mechanical strength, breakage behavior, and generation of fines and dust of biomass pellets is limited mainly to laboratory or pilot-scale studies. The objective of this paper, therefore, is to quantify small particles at different positions in a large-scale “real world” transportation system (~450 ton/h). This should allow us to determine the major transport steps in which pellet breakage and attrition occur and one can use it as a benchmark for investigating the changes in pellet properties in any other pellet transport system. In addition, the changes in other pellet properties – such as mechanical durability, bulk density, and moisture content – due to multiple transportation steps are studied. For that purpose, a pellet-fired power plant in the Netherlands was chosen as a case study to investigate the breakage and attrition of wood pellets. The transportation system in this power plant consists of a grab unloading system, belt conveyors, and storage in a silo.

Materials and methods

The material for this case study originated with an anonymous company in the USA. A wide range of woody feedstock was used to produce the pellets, including both soft and hard woods. No information about the densification process was disclosed. After their production and local storage in the USA, the pellets were transported in bulk to a local port and loaded into an ocean-going vessel with a capacity of 28,000 metric tons, then shipped across the Atlantic Ocean to the port of Antwerp, Belgium. Here they were transshipped to barges holding ~2,500 metric tons each. Twelve barges were thus required for the entire transatlantic cargo. No information was disclosed regarding changes to the particle size distribution of the pellets up to this stage. The twelve barges proceeded to the port of Rotterdam, where they berthed next to the end user's plant at a rate of one barge per day. The cargo comprised a mixture of seven different types of wood pellets, which differed by color, diameter, and length as shown in Table 1.

Physical properties of the pellets, including their moisture content, bulk density, diameter, length, and mechanical durability, were measured as follows. Moisture content was measured according to EN standard 14774-2 (EN, 2009), using 300 g of pellets that were placed in an oven at 105 °C for 24 h. The moisture content was then calculated based on the difference between the mass of the pellets before and after the test. Bulk density was measured according to EN standard 15103 (EN, 2010) by means of a 5 L steel cylinder using the tap method. The bulk density was calculated from the mass of pellets divided by the volume of the cylinder. Pellet diameters were measured according to EN standard 16127 (EN, 2012) by means of a digital caliper. Twenty-eight pellets were measured in this way: four per pellet type, chosen at random (Table 1). Pellet length distributions were measured according to EN standard 16127 (EN, 2012), using an in-house image processing tool; details of this can be found in our previous publication (Gilvari, de Jong, & Schott, 2020). Mechanical durability was measured according to ISO standard 17831-1 (ISO, 2015), which is a common global method for durability measurement of biomass pellets and is used extensively by researchers in this field (Brunerová, Müller, Šleger, Ambarita, & Valášek, 2018; Dyjakon & Noszczyk, 2019; Gilvari, Cutz et al., 2020; Larsson & Samuelsson, 2017; Stelte et al., 2012; Thrän et al., 2016). The mechanical durability was determined by placing 500 ± 10 g of sieved pellets (round-holed sieve with a screen size of 3.15 mm) in a tumbling can. This was rotated at a speed of 50 rpm for 10 min. After the test, the sample was sieved again using the same sieve, then weighed. Its mechanical durability was calculated by dividing the mass of the material remaining in the

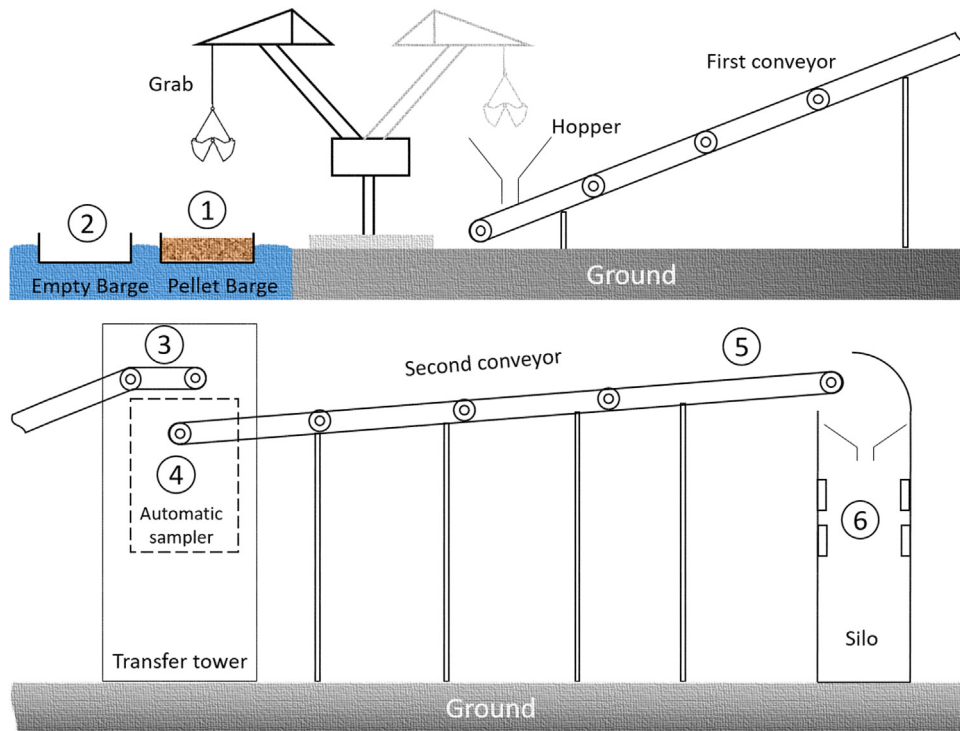
















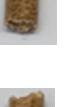
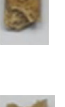

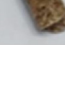
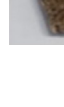









Fig. 1. A 2-dimensional overview of the transportation system. The numbers show the sampling locations. A detailed overview of the automatic sampler is shown in Fig. 2. The size of the equipment may not represent the real case.

Table 1
Different types of wood pellets shipped from the USA to the port of Rotterdam.

Row	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7
1							
2							
3							
4							

sieve by the mass of the initial sample multiplied by 100. The moisture content, bulk density, and mechanical durability experiments were repeated twice; the reported values are thus the mean values of duplicate measurements.

To determine the change in particle size distributions of the samples, three different sieves with screen sizes of 5.6 mm (square holes), 3.15 mm (round holes), and 1 mm (square holes) were used. The sieve with the smallest screen size determined the amount

of dust (< 1 mm), the medium one determined the amount of fines (1 mm < fines < 3.15 mm), and the largest one was chosen to determine the amount of lumps (3.15 mm < lumps < 5.6 mm). All particles longer than 5.6 mm were considered to be “whole pellets”. Hereafter, all particles smaller than 3.15 mm are referred to as “fines and dust”, and all those smaller than 5.6 mm as “small particles”.

To characterize the classified particles, every sample was first weighed and then sieved manually using the three screen sizes. The masses of dust, fines, and lumps were then weighed and recorded. The percentage of each category was calculated using Eq. (1):

$$P_i = \frac{m_i}{m_t} \times 100\% \quad (1)$$

where P_i is the percentage of category i in a sample, m_i is the mass of category i in the sample, and m_t is the total mass of the sample. The percentage of “whole pellets” was calculated by subtracting the percentage of small particles (< 5.6 mm) from 100.

Sampling locations and methods

Once the pellets had arrived in Rotterdam, they were unloaded by a clamshell grab into a hopper (see Fig. 1). This fed the incoming material onto a covered belt conveyor (hereafter referred to as the first conveyor). The grab's capacity is 10 metric tons and the height of the hopper is 4 m. A dust filter is installed just after the hopper to collect airborne dust before the material is loaded onto the first conveyor. This transported the pellets on an upward incline to the top of a transfer tower with a height of 24.0 m, at a speed of 1.7 m/s. The length and width of the first conveyor are 150.0 and 1.4 m, respectively. It, therefore, has an angle of inclination of 9.2° . At the top of the transfer tower, the pellets were dropped from the first conveyor onto a second one by means of a free fall with a vertical drop of 7.8 m. Between these two conveyors is a chain bucket sampler, which collected samples at a consistent cross-section of the material's stream during its free fall. This is an automatic sampler, already installed in the system for on-site sampling purposes. The samples it took were transferred to a small dosing conveyor (length 3.0 m, width 0.2 m), which in turn fed a rotary tube divider as shown in Fig. 2. The role of the rotary tube divider was to divide a small portion of the samples by rotating the materials in such a way that, eventually, 2 kg of samples were collected every 11 min.

The second conveyor has a length of 500 m and transferred the pellets at a speed of 2.6 m/s to the top of the silo, into which they were dropped via a free fall. Whenever required, pellets are discharged from the bottom of the silo for further processing. The samples for this study were taken on three consecutive non-rainy days in the winter of 2019. Every day, a barge carrying 2500 metric tons of pellets was unloaded into the system. Six different locations throughout the entire transportation system, from the barge to the silo, were identified for the sampling used in this study. Samples were taken at different increments from different sampling locations, and all were analyzed in terms of particle size distribution, mechanical durability, bulk density, and moisture content. A summary of the sampling locations, days of sampling, and number of samples taken at each location is given in Table 2. In total, 77 samples were collected for this study. All were placed in sealed plastic

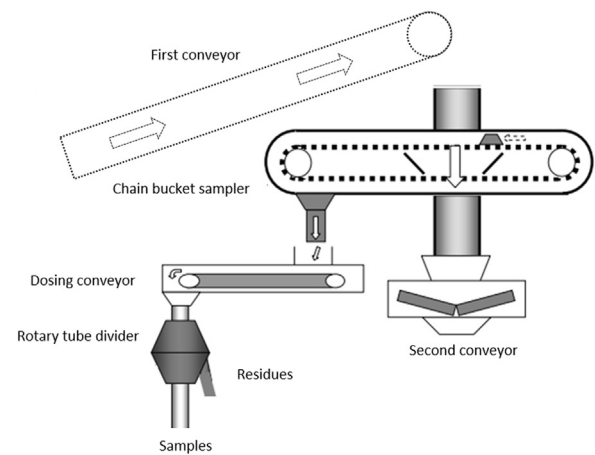


Fig. 2. Detailed overview of the automatic mechanical sampler system in the transfer tower.

bags to prevent moisture uptake and any further changes to pellet properties due to varying environmental conditions. The samples were then transported carefully to a laboratory at the Delft University of Technology for further analysis. The sampling locations are explained in detail below and they are shown in Fig. 1.

Sampling location 1 was situated inside the barge. Samples were collected from the upper surface of the pellet cargo at different time intervals. At this location, the physical properties of the wood pellets can be characterized just before they enter the end user's transportation system. As mentioned before, the pellets were unloaded from the barge using a clamshell grab with a capacity of 10 metric tons. Each grab cycle took approximately one minute, so emptying the entire barge (~ 2500 metric tons) took more than 4 h. To ensure that the samples represent the pellet properties at different layers inside the barge, samples were taken every 30 min. Nine were collected on the first day and eight on the second, using a plastic scoop to gather approximately 6 kg of material per sample.

Sampling location 2 was situated in an extra empty barge (hereafter referred to as the second barge) positioned next to the pellet-loaded barge. Note that no such second barge is used in normal plant operations. However, this sampling location was introduced in order to investigate the effect on the pellet properties of the mechanical forces exerted during grabbing. At this location, one grab of the material was discharged every hour to collect five individual grabs in total. To obtain a representative sample from every discharged grab, the grab contents were dumped onto a flat surface in the second barge, creating a pile of wood pellets. Sampling was then performed according to EN/TS standard 14778-1 (EN/TS, 2005) by taking nine samples of approximately 0.5 kg each from different locations within the pile (Fig. 3), using a plastic scoop.

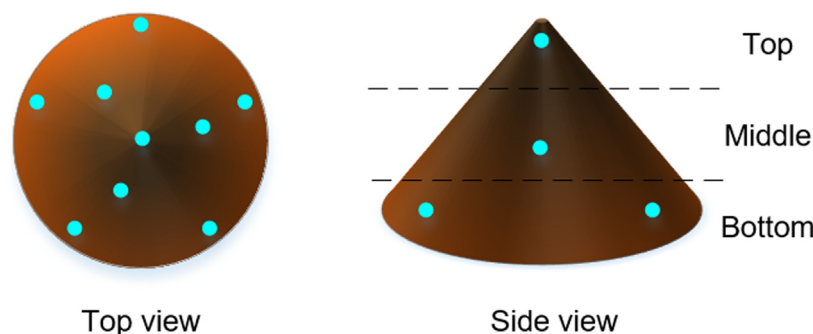


Fig. 3. Schematic representation of the pile of pellets in the second barge and of the samples taken (cyan markers). Note that the real pile deviated from a perfect cone shape.

Table 2
Summary of sampling locations, days of sampling, and number of increments per location.

Sampling location	Location number	Day of sampling	Number of increments
Barge	1	1	8
		2	9
Second barge	2	1	5
First conveyor	3	1	8
		2	9
Rotary divider	4	3	17
Second conveyor	5	1	8
		2	9
Silo	6	3	4
Total	–	–	77

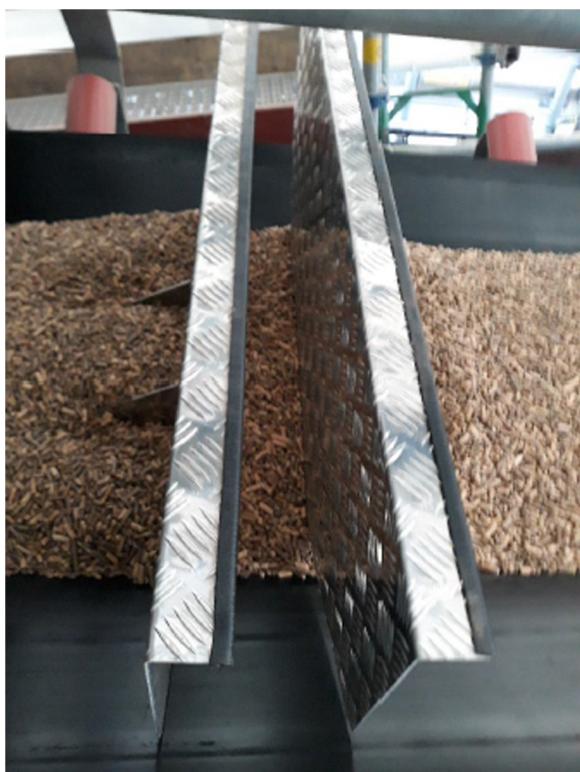


Fig. 4. Isolation of the samples on the conveyor using the stopped-belt method.

These nine samples were collected from the top (one sample), middle (three samples), and bottom of the pile (five samples), and were combined to create one single sample. Sampling at this location was undertaken only on the first day.

Sampling location 3 was situated inside the transfer tower at the end of the first conveyor, which brings the pellets from the hopper to the transfer tower. This sampling location is situated just before the pellets were discharged onto the second conveyor (see Fig. 1). This location was used to estimate the effect on the material's properties of grabbing and of a vertical free fall of 4 m (the hopper's height). Note that in each grabbing cycle, the pellets were dumped at the center of the hopper, and so the effect on them of hopper wall impacts can be considered negligible. This sampling location is useful as a benchmark to check the reliability of the properties of the samples divided by the automatic sampler at location 4. At this location, samples were taken using the stopped-belt method provided for in EN/TS standard 14778-1 (EN/TS, 2005). In other words, the entire transportation system was halted at the sampling times and the samples were taken from the belt conveyor after being isolated from the other material on it by means of two steel plates (Fig. 4). Consequently, all the material on a cross-section of the conveyor belt was collected and labeled as coming from sampling location

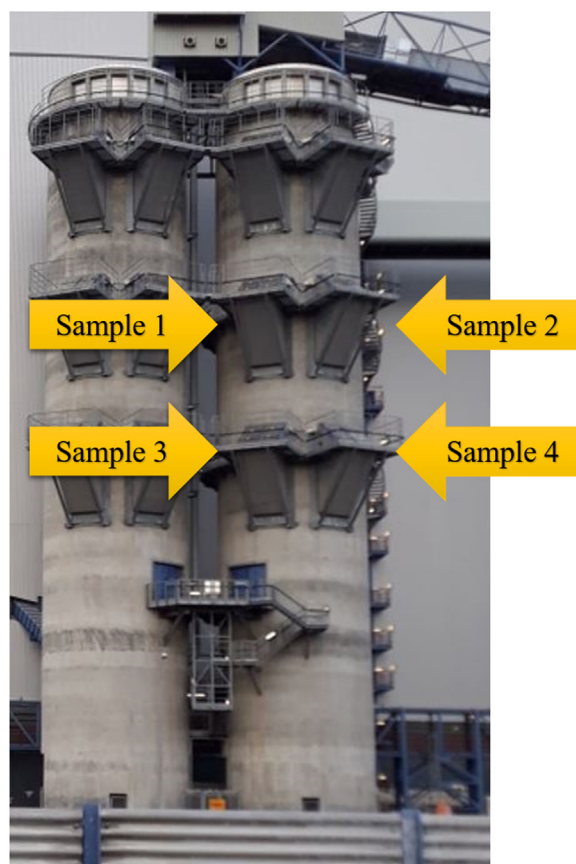


Fig. 5. The silo and sampling ports.

3 at the relevant time. Each sample contained approximately 6 kg of material. As with location 1, sampling at this location was performed on days one and two. Moreover, all the samples here were collected at the same time as those from location 1 (the barge). In all, 17 samples were thus collected at this location.

Sampling location 4 was a part of the automatic mechanical sampler within the transfer tower. Samples taken at this location can be used to investigate the reliability of the material properties provided by the rotary divider with regard to the other locations in the transportation system, e.g. at the end of the first conveyor. Each sample was collected automatically, filling a plastic bag with approximately 2 kg of material within 11 min. Samples were only taken at this location on the third day, in 17 increments.

Sampling location 5 was situated at the end of the second conveyor, just before the material was discharged into the silo. Sampling at this location can demonstrate the effect of a 7.8 m vertical free fall (between the two conveyors) on pellet properties. The effect of the conveyor's vibrations on the pellet properties

Table 3
Pellet properties at different locations on different days of sampling. Numbers in parentheses show the standard deviations.

Property	Location	Day of sampling	Average value
Moisture content (%)	All	All	5.9 (0.3)
Bulk density (kg/m ³)	All	All	640 (25)
Mechanical durability (%)	All	All	97.6 (1.3)
Diameter (mm)	3, 4	2, 3	7.11 (0.59)
Length distribution ^a (mm)	1,	1,	50% < 13.40
	3,	2,	99% < 32.70
	4	3	100% < 42.10

^a Based on the pellet length distributions of samples shown in Fig. 7.

was assumed to be negligible. The stopped-belt method with the same type of steel-plate isolators as at sampling location 3 (Fig. 4) was used here, too. Samples were taken at this location on days one and two only, each weighing approximately 6 kg. On average, these were collected three minutes after each of those at location 3, since that was how long it took for the pellets to be transferred from there to location 5 on the second conveyor.

Sampling location 6 was situated at the storage silo (with a height of 31 m and a diameter of 9 m) and was used on the third day. Four samples have been collected from the four hatches installed at the wall because sampling inside the silo was impossible at the time of the experiments. These hatches were located at two levels, and two samples were taken at each level (see Fig. 5).

Results and discussion

Mechanical durability, bulk density, and moisture content

Fig. 6 shows the pellet properties with regard to the sampling locations and days. Analysis of variance (ANOVA) of all 77 samples revealed that there was no bias in the results for pellet properties at different locations or on different days ($\alpha = 0.05$, i.e. 95% confidence interval). From Fig. 6, it can be seen that mechanical durability, bulk density, and moisture content are independent of the day of sampling and of the sampling location. Moreover, there was no correlation between bulk density and moisture content. However, the mechanical durability varied between 90.8% and 98.7% in all locations, and this exceeded the 2% repeatability limit set by the standard (ISO, 2015). The average values of pellet properties measured at different locations on three different days of sampling can be found in Table 3. This table implies that although a large devi-

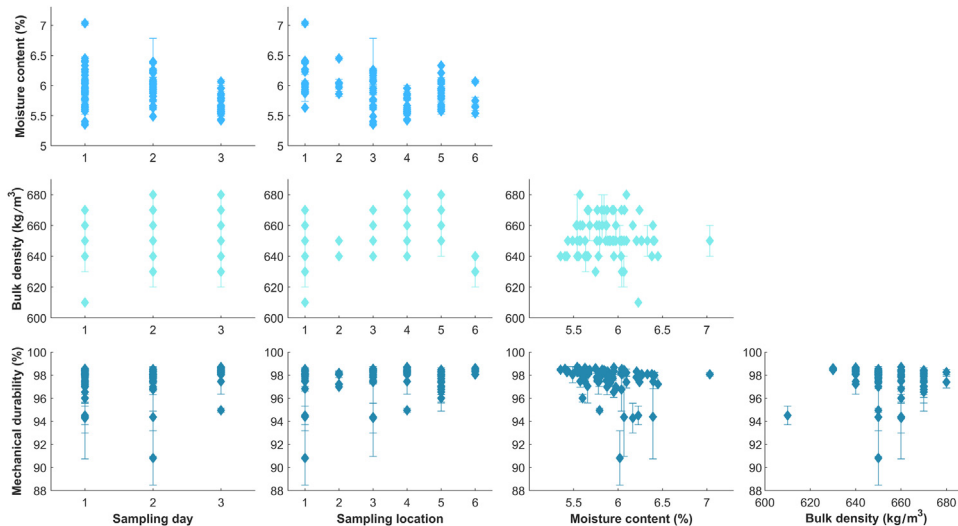


Fig. 6. Pellet properties measured at different sampling locations and on different sampling days. The error bars show the standard deviations.

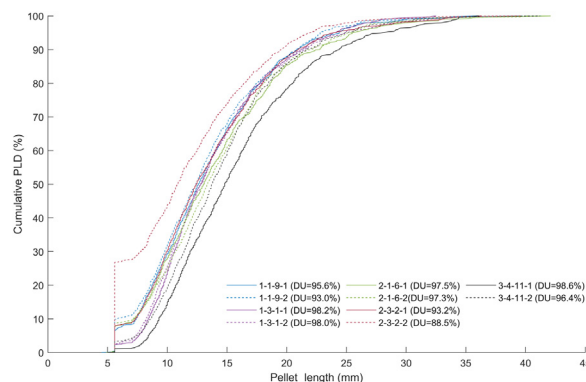


Fig. 7. Pellet length distributions of different batches of pellets used for mechanical durability (DU) test (legend: digits from left to right = sampling day - sampling location - number of increment - repetition number).

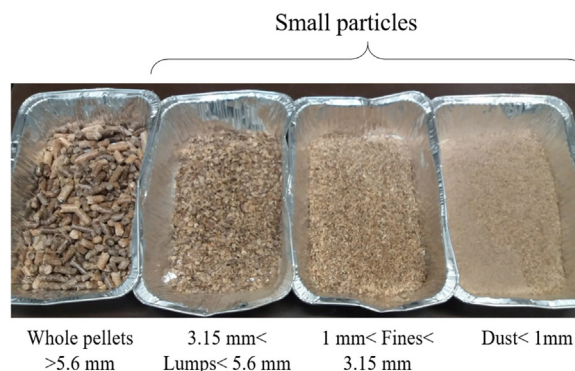


Fig. 8. Size-classified particles after sieving.

ation in durability, only a few samples widely diverge from the average value and that the average durability can be considered as reliable data in our study.

No correlation was found between the mechanical durability of the pellets and the number of handling steps they underwent. Nevertheless, there are two explanations for the variation we found in mechanical durability. First, in our previous study (Gilvari, De Jong et al., 2020) we showed that pellet length distributions (PLDs) can be a contributing factor in the measured mechanical durability

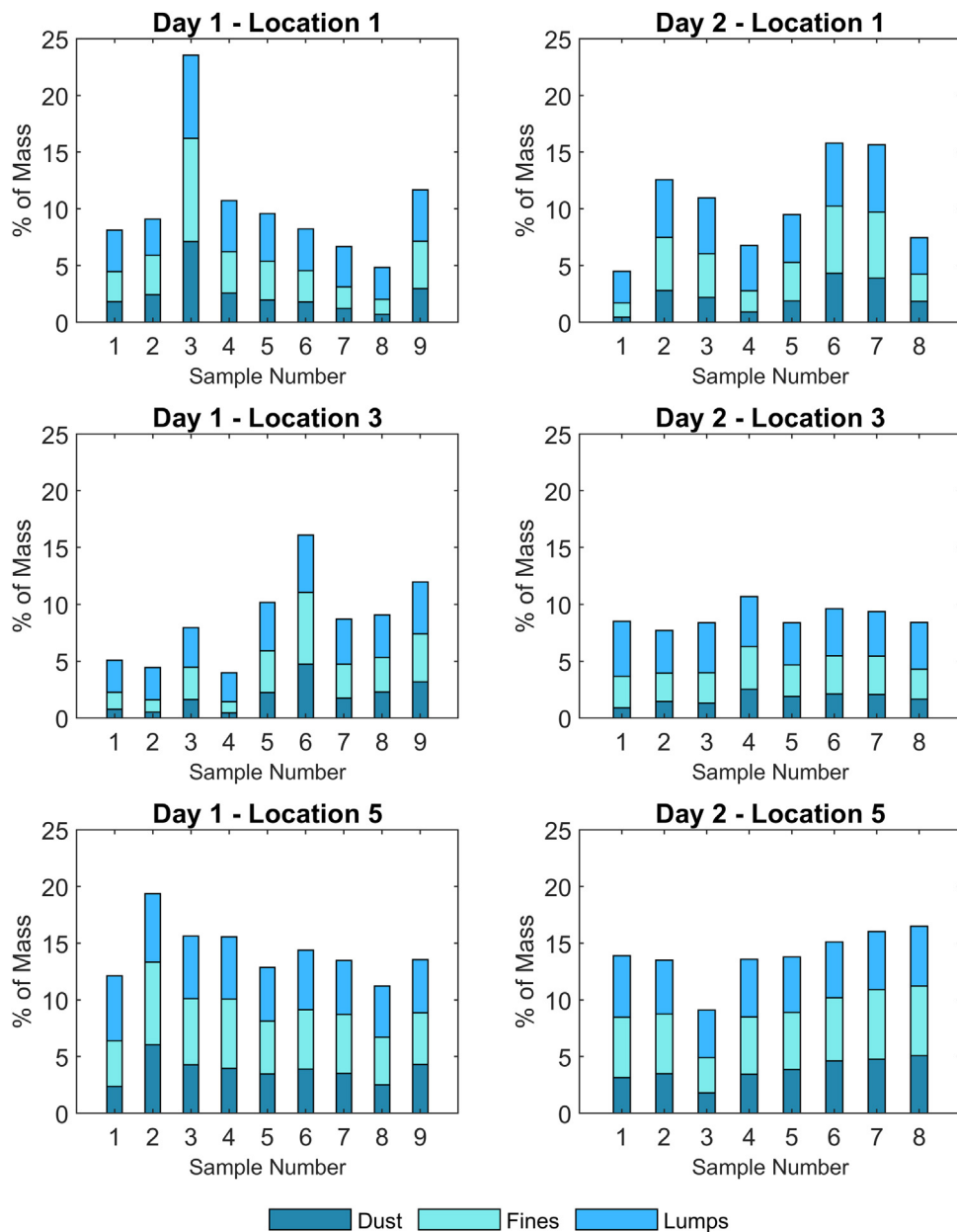


Fig. 9. Sieving analysis at locations 1 (first barge), 3 (end of the first conveyor), and 5 (end of the second conveyor). The sample numbers correspond to the sampling order.

value, which increases with greater pellet lengths. To study this effect, the PLDs of ten samples (five out of 77 samples, with two replications each) were determined before durability tests (Fig. 7) using our self-developed in-house image processing tool (Gilvari, De Jong et al., 2020). As can be seen in Fig. 7, a sample containing the highest quantity of small particles (< 5.6 mm) showed the lowest mechanical durability value. Take, for example, samples 2-3-2-1 and 2-3-2-2 in Fig. 7. These samples were two randomly selected 500 g from the initial 6 kg sample that was taken on day 2 at location 3 as the third increment. However, their durability values differ by 4.7%. This relatively high deviation can confirm the effect of length distributions. Second, as the share of each pellet type in each sample was not counted here, it is suspected that other factors such as the share of pellet type may cause a bias in the results.

Particle size distributions

Fig. 8 shows a sample image of the classified particles. In this, it can be seen that all particles longer than 5.6 mm are whole pellets retaining their cylindrical shape.

As explained in section 2, samples at locations 1 and 3 were collected at the same time and each discrete sample at location 5 was collected on average three minutes after each collection at locations 1 and 3. Therefore, it is likely that all corresponding samples originated from the same location in the barge. Hence, the effect on the particle size distributions at these locations of different transportation units can be investigated with regard to their original particle size.

Fig. 9 shows the results of sieving analysis at locations 1, 3, and 5 (the main transportation stream) on the first and second days of

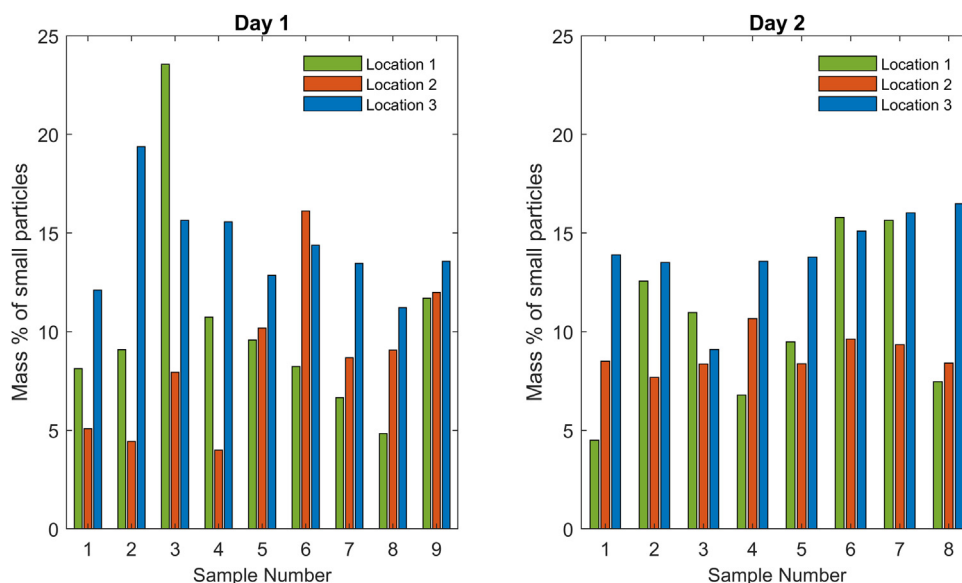


Fig. 10. Percentages of small particles (< 5.6 mm) at different locations on the first and second days of sampling.

Table 4
Average share of categorized particles at locations 1, 3, and 5 on the first and second days of sampling.

Location	Sampling day	% of small particles(< 5.6 mm)	% of fines and dust(< 3.15 mm)	% of dust(< 1 mm)
1 (first barge)	1	10.28	6.11	2.50
	2	10.40	5.93	2.27
3 (end of first conveyor)	1	8.61	4.91	1.95
	2	8.87	4.73	1.74
5 (end of second conveyor)	1	14.24	9.05	3.81
	2	13.93	8.98	3.77

sampling. According to these results, on each day the barges contain a notable amount of small particles at different sampling times prior to unloading. This also shows that different layers of the barge’s cargo (from top to bottom) contain different particle size distributions. However, no evidence was found regarding the accumulation of small particles in one specific layer or at one specific location in the barge. The results (Table 4) show that, on average, the share of each size category on day one is consistent with the results on day two.

The statistical analysis shows a significant difference between the amount of fines and dust in the samples collected at different locations ($\alpha = 0.05$, i.e. 95% confidence interval). The measured *p*-value for one-way ANOVA analysis between the sampling locations and the amount of fines and dust (< 3.15 mm) was zero, which means that there was a significant difference in the average values. On average, the proportion of fines and dust was 6.02% at location 1 (first barge), 4.82% at location 3 (end of the first conveyor), and 9.01% at location 5 (end of the second conveyor) on the first and second days.

A similar trend to that for fines and dust (< 3.15 mm) is observed for all small particles (< 5.6 mm) as well, since the ANOVA analysis shows significant differences between the percentages of these by sampling location. The average proportion of small particles (< 5.6 mm) on days one and two was 10.33% at location 1 (first barge), 8.73% at location 3 (end of the first conveyor), and 14.09% at location 5 (end of the second conveyor). This indicates that a significant quantity of small particles (< 5.6 mm) is generated throughout the entire transportation system, from the barge to the end of the second conveyor just before the material enters the silo.

One interesting result is the reduction in the number of small particles (< 5.6 mm) after the pellets are grabbed and discharged onto the first conveyor, i.e. between locations 1 and 3 (Fig. 10). The

proportion of small particles decreased relatively between these two locations by up to 16.24% on the first day and 14.71% on the second day. There are two explanations for this. Firstly, a number of small particles escaped from the grab into the air while the grab was loading in the barge and shifting upwards towards the hopper. Secondly, the dust filters at the beginning of the first conveyor removed some dust; however, the accumulated dust in those filters was not measured in this study. On the other hand, by comparison with location 3 (end of the first conveyor), the average proportion of small particles (< 5.6 mm) at location 5 (end of the second conveyor) increased from 8.61% to 14.24% on the first day and from 8.87% to 13.93% on the second day, showing a relative increase of 65.74% and 57.04%, respectively. Assuming that the effect of conveyor vibrations on the generation of small particles (< 5.6 mm) is negligible, all of these extra ones must have been generated due to the vertical free fall of 7.8 m at the transfer point between the two conveyors. Boac et al. (Boac et al. (2008)) observed an average increase of 3.83% in the number of particles smaller than 5.6 mm in one transportation cycle of feed pellets in a bucket elevator and silo feeding system for pellets with the durability of 92.9% and a nominal pellet diameter of 6.4 mm. In this study, however, an average 5.36% increase in the number of particles smaller than 5.6 mm was observed solely due to a free fall of 7.8 m. This is probably related to the compression and impact forces associated with the amount of material being transported, which was around 450 ton/h in the present study and 54.9 ton/h in the work of Boac et al. (Boac et al. (2008)).

The results show that the average proportion of small particles at location 2 (second barge) was 6.56%, with a 1.51% standard deviation. This was lower than the figure for location 1 (10.34%). During grabbing from the first barge to the second one, it was observed that a portion of small particles was released from the grab due to

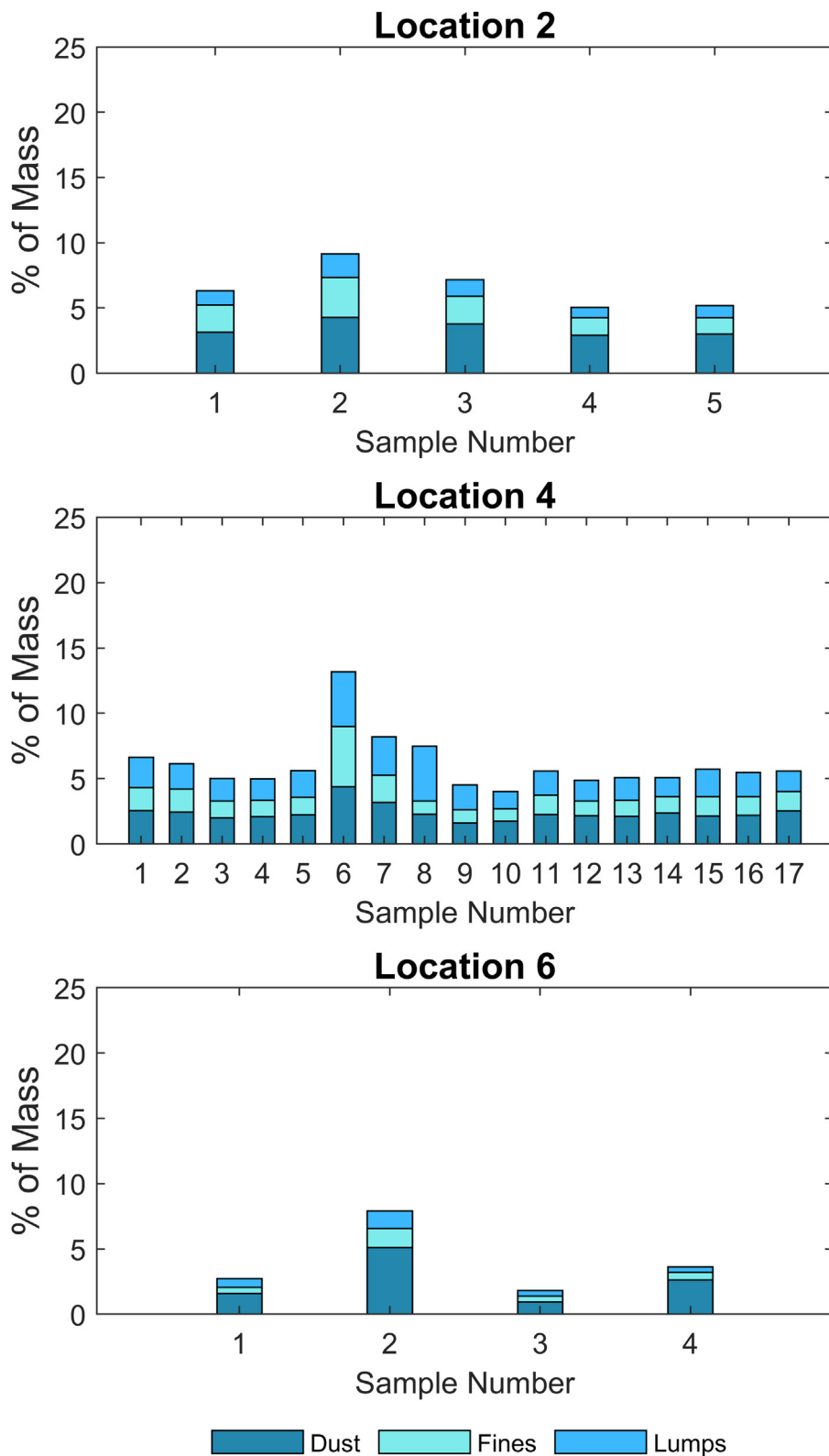


Fig. 11. Share of small particles at locations 2, 4, and 6.

leakage. Because of this, the measured small particles are not representative for the whole particles and the effect of grabbing on the generation of small particles remains unclear.

Fig. 11 shows that the percentage of small particles at location 4 (automatic sampler) on the third day was 6.05%, with a standard deviation of 2.04%. As discussed earlier in this section, the

results from the first two days show a high repeatability in terms of generating small particles at each sampling location. Therefore, the share of small particles at each location on days one and two can be postulated to be similar to that on the third day. Based on this assumption, the results for the first and second days at location 3 (end of the first conveyor) can be compared to the results for the

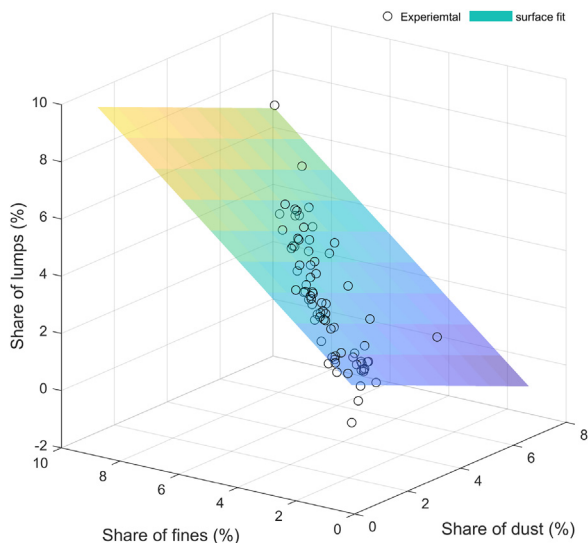


Fig. 12. Correlations between classified small particles.

third day at location 4 (automatic sampler). The average proportion of small particles at location 3 on the first and second days was 8.73%, while at location 4 it was 6.05%. Thus, on average, the number of small particles decreased between these two locations by 2.68%, showing that the automatic sampler (location 4) does not produce similar particle size distributions when compared to location 3. A possible reason for this is the segregation of bigger particles due to the rotation of particles in the rotary divider, which separates larger particles from the smaller ones in such a way that the latter are rejected as residue (see Fig. 2).

The average percentage of small particles (<5.6 mm) at location 6 (silo) is shown in Fig. 11. On average, these made up 4.00% of the samples taken from the silo hatches. Comparing the proportion of small particles here with that at location 5 (end of the second conveyor), it can be concluded that the whole pellets accumulated at the silo walls. This can be explained by percolation segregation, whereby the smaller particles are captured in the voids and bigger ones move down the slope towards the walls.

Thomas (Thomas (1998)) showed that pellet fragmentation and attrition are the two major mechanisms for physical degradation of pellets. Fig. 12 shows the share of lumps, fines, and dust in all the samples taken from different locations and includes a surface fit that is the best fit for all the samples. Although the breakage mechanism was not studied in this work, Fig. 12 shows that the shares of dust, fines, and lumps at different locations and on different sampling days are correlated to one another with an R^2 value of 0.866. In other words, in all samples, the quantity of each size-classified particle was increased by increasing the amount of other size-classified particles.

Conclusions

In this study, we have investigated the change in the physical properties of commercial wood pellets with a focus on breakage and attrition behavior during large-scale (~450 ton/h) transport and storage in a pellet-fired power plant in the Netherlands. Our main conclusion is that transferring the wood pellets via a free fall from a height of 7.8 m (the transfer point between two conveyors) increases the proportion of small particles (< 5.6 mm) from 8.74% to 14.09%, on average, and the amount of fines and dust from 4.82% to 9.01% for pellets with an average mechanical durability of 97.6% (based on ISO standard 17831-1). This emphasizes the importance of equipment design and operation with respect to material

degradation. The mechanical durability of the samples taken at different locations differed by up to 7.9%, while no correlation was observed between moisture content, bulk density, sampling location, or day of sampling and mechanical durability. This suggests that other properties, most probably pellet length distribution, play a significant role in the measured mechanical durability value.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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