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A quantitative model to characterize granular flow behavior – A measure of grain layer mixing in storage facilities

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ABSTRACT. *Food quality and safety concerns have led to many nations implementing regulation and legislation around acceptable food and feed practices. Traceability systems are one component of food and feed practices that have been a topic of much research in recent years. Traceability tools are useful for ensuring regulations are met and offering metrics for improving company processes. Companies that implement traceability systems reap economic benefits, gain market advantage, and decrease losses from costly food recalls through the ability to more efficiently remove contaminated food from the value chain.*

Bulk commodities, such as grain, greatly increase the difficulty inherent in designing and implementing a traceability system. Comingling grain from various sources is a common practice to transform grain of various quality attributes to achieve an overall higher quality grain for sale to processors. Comingling complicates traceability as granular flow combines all grain sources together with no clear separation point. Previous granular flow research shows that there are two main flow regimes present in a granular material flowing in this manner: 1) Mass flow, where all of the material is in motion and the grain is removed in a mostly first-in-first-out (FIFO) behavior, and 2) Core flow, where the grain forms a natural hopper with some of the grain forced into stagnation and providing a mostly last-in-first-out (LIFO) behavior. The amount of mixing that occurs due to the layering of grain and the flow regimes present as grain is removed has not been previously quantified. Assumptions are made based on the FIFO and LIFO flow regimes but result in a lack of certainty about shipping container composition after the grain is removed from the bin. This lack of certainty leads to costly and inefficient recalls.

This experiment is a first step in the development of understanding how much mixing is occurring in grain storage bins. It consisted of the design and development of a small model similar in structure to a flat-floored cylindrical grain bin. The experimental model presented flow behavior that aligned with expected regimes for flat-floored structures and provided consistent data. These outcomes signify that the model and the method are not causing significant changes in flow behavior and indicate that further testing and scaling should be possible.

Outcomes from this quantification of granular mixing will provide a useful tool in the area of traceability. Given enough data on the mixing between layers of various types of grain probability models can be developed to provide a more precise prediction of what the composition of each shipment consists of on a percent basis.

Keywords. *Bulk grain, grain traceability, granular flow, grain mixing, food security, traceability systems.*

Introduction

Traceability has become an important part of the food supply chain for the following three main reasons: quality and safety regulations and legislative compliance; economic concerns focused processes to increase efficiency, productivity, and profitability; and to increase market competitiveness. Traceability provides: 1) a way to differentiate foods with subtle or undetectable quality attributes; and 2) detailed information about their products to meet the consumer demand for product awareness (Thakur, Martens and Hurburgh, 2011; Golan, Krissoff, Kuchler, Calvin, Nelson, and Price, 2004; Trienekens and Zuurbier, 2008). The grain industry presents unique traceability obstacles, and challenges the methods and technologies used by other industries to track and trace products.

A grain handling organization begins commingling grain they receive by lot as soon as the grain arrives at the elevator from producers. These units will be referred to as source lots in this paper. This commingling practice is due in part to standardization of the commodity value of grain based on quality. If grain is delivered to the elevator in a condition less than the standard the producer is paid a discounted price for the source lot. The grain elevator can then increase the value of the grain by commingling the subpar source lots with higher standard grain to achieve an equilibrium quality value that meets the specifications of their buyers (Laux, Mosher, and Hurburgh, 2015). Grain also mixes unintentionally in storage facilities due to bulk storage methods where grain from multiple farms or regions is stored together in a large bin. Granular flow behaviors add another level of complexity. Much research has been done on granular materials and granular flow due to the importance of such materials in the construction industry (Jaeger, Behringer and Nagel, 1996; de Gennes, 1999; Brennen, 2005). This body of research provides a great deal of information about particle-particle interactions during granular flow and the flow regimes that can be expected under a variety of conditions.

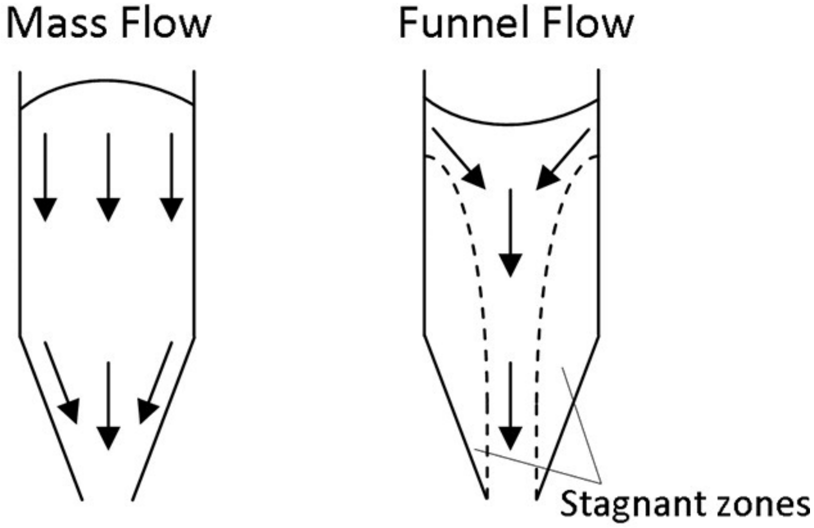


Figure 1 Mass flow and core flow granular behaviors.

All flow behaviors are comprised of some combination of the two main flow regimes shown in Figure 1. Under specific conditions, such as with hoppers specifically designed for the task, granular flow regimes can produce ‘mass flow’, where all the grain in the bin is in motion when gravity flow is under way. Mass flow results in a uniform movement of grain in a First-In-First-Out behavior that is easy to predict. A flat-floored steel bin, however, will generate a ‘core flow’ regime resulting in a mixture of source-lots as each load is removed from the bin and offering a LIFO (last-in-first-out) behavior. Core flow results in the formation of stagnation areas in the angle between the floor and the walls and for some distance up the walls as a natural hopper is formed funneling the top layers of grain down through the center of the bulk. To date, the amount of mixing that occurs as grain is moved through a flat-floored steel bin has not been quantified.

From the point of storage, there are currently two assumptions that can be made to account for grain source-lots moving out of the bin as it is emptied with regard to traceability: 1) the facility can assume that the bin is generating mass flow where the grain is considered to all be in motion every time the loading gate is open, and the resulting source-lot composition is maintained; or 2) the assumption that all source-lots are an equal part of the composition of each draw from the bottom of the bin. Due to the lack of knowledge about the exact composition of the draw during load-out assumption 2 leads to the use of large-lot labeling using a processing time frame, such as a day or week. This leads to waste in the case of a food recall emergency, where all products that may have contaminated grain in them must be destroyed. Large-lot labeling is an imprecise method for traceability that can be very expensive, both in the cost of removal of large amount of food from the value chain, and in the amount of money lost for the company since the products are now not available for consumer purchase (Comba, Belforte and Debbene, 2013). There are three main reasons why neither the mass flow, nor large lot assumptions are effective.

1) Mass flow only occurs in small bins with hoppers that are specifically designed to develop that flow characteristic;

2) Currently the amount of mixing that occurs between source layers during the core flow that is produced by large bins with flat floors is unknown; and

3) The over-bounding approach for lot identification presents weaknesses in immediate identification of the contaminated product lots and results in expensive and highly impacting recalls (Comba et al., 2013).

Criteria and Constraints

Many commercial grain storage containers are cylindrical steel bins, with a flat floor containing a row of mechanical gates that open for grain load-out. The row of mechanical gates in the floor are positioned with one in the center of the bin and, depending on the width of the bin, one or more to either side of the central gate, with the gate furthest from the center being no more than 4 or 5 feet from the bin wall as shown in Figure 2. Grain is generally drawn from the central gate first and the core flow which results from the flat floor creates stagnation areas that start near the edges of the sump. The natural hopper in the grain that is formed by core flow results in deeper grain at the bin walls and shallower grain above the sump. The angle of change in depth is the angle o Next, the gates to the outside of the central gate are opened, and so on until the grain no longer flows and must be manually or mechanically removed. The grain remaining in the bin will be in piles on the floor between the gates, having stopped flowing at the angle of repose as shown in Figures 2-4. Flat floored bins provide more storage space, but do not allow for complete removal of the granular material without manual or mechanical assistance, and therefore, are not beneficial when segregation or product tracking is necessary. It would be difficult to build a hopper that could withstand the weight of grain carried and stored in the larger steel storage bins.

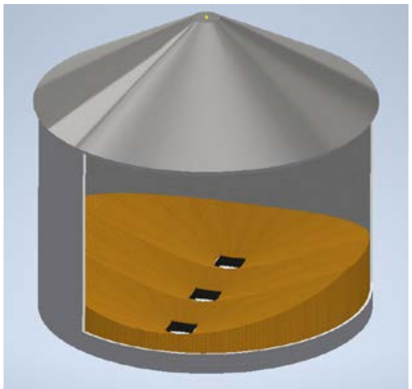


Figure 2 Depiction of a large steel bin having been emptied of grain starting with the central orifice, then the side orifices, with the grain coming to rest at the angle of repose.

A top down view of the grain, as seen in Figure 3, shows the flow pattern sloping down at the angle of repose. The grain at the bin walls is much deeper than it is in the bumps between the orifices because the bin walls are further away.

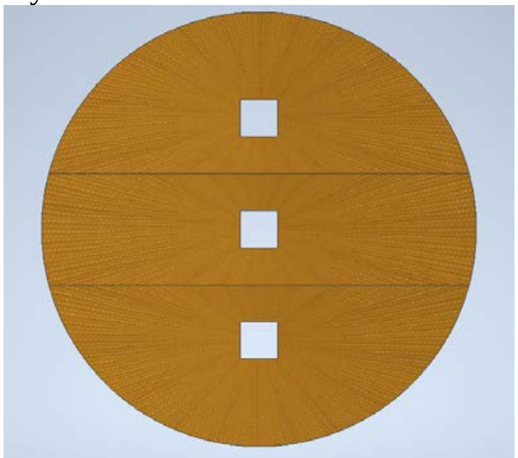


Figure 3 Flow direction of grain in a cylindrical bin with 3 load-out orifices.

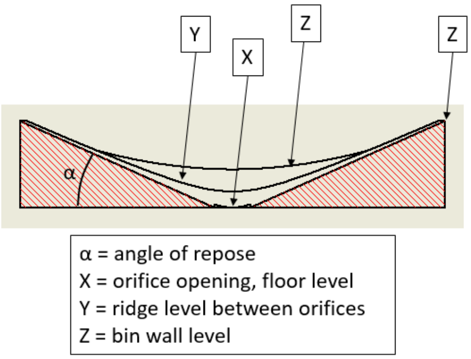


Figure 4 Cross section of grain left in a cylindrical steel bin after gravity load-out has stopped and the grain has come to rest at the angle of repose.

Figure 4 is a representation of the cross section of the grain and shows the various angles and levels of grain left in the bin after gravity feed has stopped. Due to granular flow characteristics, the complexity of the source layer diversity, and the variability in behavior that the bin options allow for, criteria and constraints were outlined for the model. To ensure consistency in data collection and to focus on answering the question of whether the model would be able to provide precise data within the ranges of reasonable expectations, the following model criteria were selected:

- Small bin size for manageable segregation and data sets
- Flat floor with centrally located slide gate for load-out simulation
- Centrally located funnel loading system in the roof
- 8mm glass beads of uniform shape in ten easily differentiable colors.

Materials and Methods

Current research on grain traceability has not addressed or quantified the amount of mixing that occurs as grain is loaded and unloaded from a storage bin. Determining the best approach for adding to the body of knowledge in this area required taking current understandings about granular flow characteristics and the variability inherent in performing those calculations into account. It was determined that the most practical approach to quantifying the level of mixing in a grain bin would be to build a model and record measurements of the mixing between various layers. The model used in this experiment for the quantification of granular mixing consisted of a small, transparent plastic cylindrical bin. The model bin was adhered to a flat plexiglass floor that had a mechanical slide gate in the center for unloading the granular material. A hole in the roof with a funnel affixed was used as the single receiving point for loading the granular material. The model floor was mounted onto a wooden frame that elevated the model above the surface of a table on which a grain grading scale was placed directly beneath the load out gate. A one-liter plastic measuring vessel was placed on the scale for containing and weighing the grain loads as they flowed through the gate opening. The bin was loaded the same way each time with ten layers, each layer a different easily differentiable color, of 8mm glass beads. The layers were placed in the following order each time from bottom to top: green, orange, white, blue, yellow, rust, pink, teal, purple, and black. Each layer of beads weighed 800 grams ± 0.4 grams.

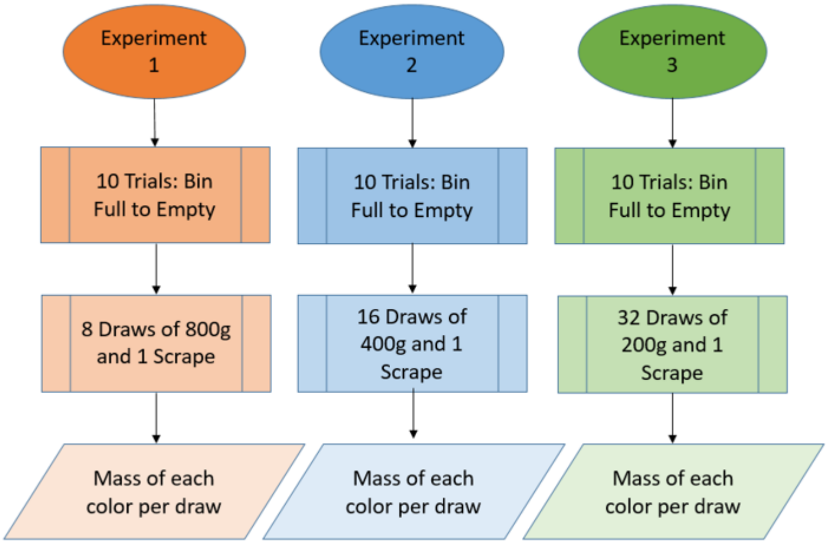


Figure 5 Experimental design of the three experiments conducted.

As shown in Figure 5 there were three experiments performed with ten trials per experiment. Each trial is the collective data from the bin being first filled according to the prescribed method, and then completely emptied using incremental draws from the gate in the bottom of the bin. The first ten trials were performed using draws of approximately 800 grams simulating a facility where the receiving transportation mode and the load-out transportation mode were the same (i.e. semi-truck loads, etc.). Trials 11-20 were performed using draws of approximately 400 grams, and trials 21-30 were approximately 200 grams. The second and third sets of trials were completed to provide more data points, and the ability to see when certain layers began to enter the mix, and when they ceased their appearance. The final draw of each of the 30 trials was a scrape, or clean-out draw, to remove all the material that would have remained in the bin due to the flat floor.

Results

The experiments answered two research questions:

1. Is the behavior seen in the experiment consistent with the expected behavior, given an understanding of granular flow in a bin with no hopper?
2. Does the model provide consistent data so that the results are similar across the trials?

The model produced the expected core flow regime and the results show that the LIFO (last-in-first-out) behavior expected was indeed present. Figure 6 below shows the average mass of each of the colors present in each of the draws in 800-gram increments for all 30 trials. The image clearly shows that the average of all but the top two layers are present in the first 800 gram draw which would indicate that the funnel through the granular material was still forming. The presence of each of the bottom 7 layers immediately drop off as the lower layers are forced into stagnation except for some small amount of slippage. The visible trend seen in the graph is that once the layer above begins to diminish, the layer below peaks, showing that once the funnel is formed the layers exit in a top down fashion. The top layer (Layer 10) denoted by the black line clearly shows a very early peak in flow and then is depleted by the time there is just under 3000 grams of beads remaining in the bin. Layer 9, denoted by a purple line, is the second layer to be completely removed from the bin and is gone by the time there is approximately 2000 grams remaining in the bin.

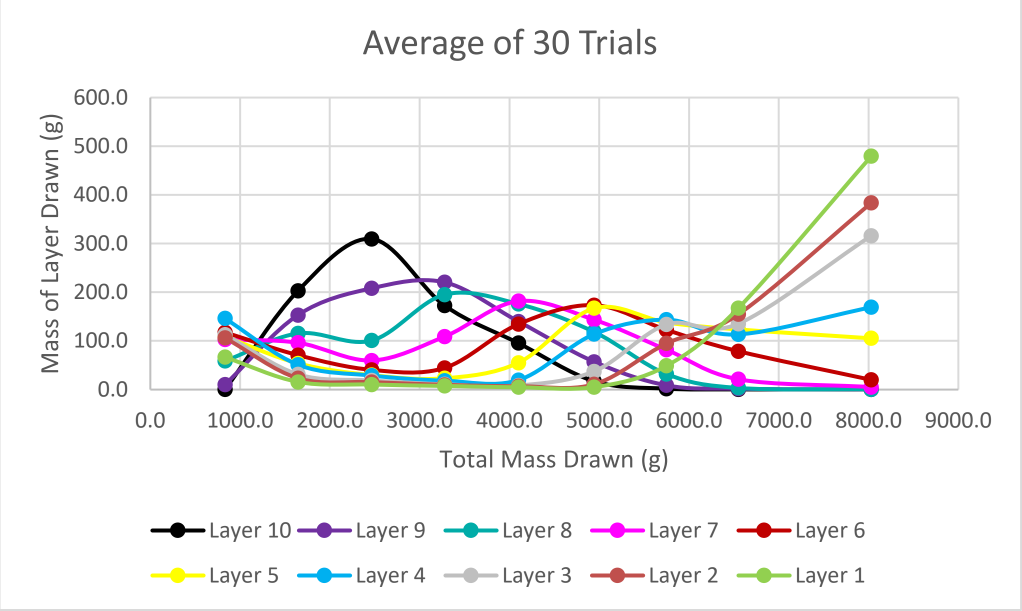


Figure 6 Average granular flow by mass of all 10 layers as they moved through a cylindrical bin with a flat floor across 30 trials.

Layers 8 and 7 have a short spike early, when the funnel core is forming. The spikes fall off while the upper layers pour through the funnel. The spike for each color emerges again when the top of the funnel reaches the level of that color and it begins to pour through the center core. Similarly, the bottom seven layers have immediate presence and flow readily in the first 800-gram draw while the funnel through the center is forming, diminish in presence a great deal as they are forced into stagnation, and begin to show larger masses as the upper layers have been depleted and the top of the funnel reaches those layers. The large spike at the 8000-gram mark represents the final draw, which is a scrape or clean-out draw, and is the physical removal of the beads remaining in the bin once gravity flow has ceased.

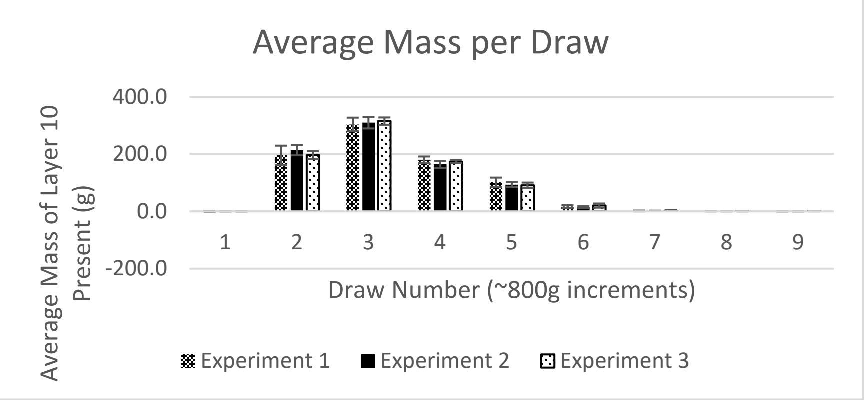


Figure 7 A comparison of the appearance of Layer 10 at 800-gram increments across 3 experiments.

Figures 7-8 are a comparison of the average mass of one specific layer for 800-gram draw increments and for all three experiments. These graphs show that across all 30 trials the behavior of the layer was very similar, and each has their own specific pattern of appearance, flow, and dissipation. Figure 7 contains the data for Layer 10, showing that for all 3 experiments the majority of Layer 10 is nearly extinguished between draws 2 through 5. Figure 8 is representative of Layer 8 and shows what looks more like a normal distribution where the appearance of that layer in larger amounts happens more gradually, and therefore dissipates over the course of more draws than were shown in Layer 10. Layer 10 had one draw that averaged at least 300 grams for all three experiments, but Layer 8 has essentially no draws where more than 200 grams are present.

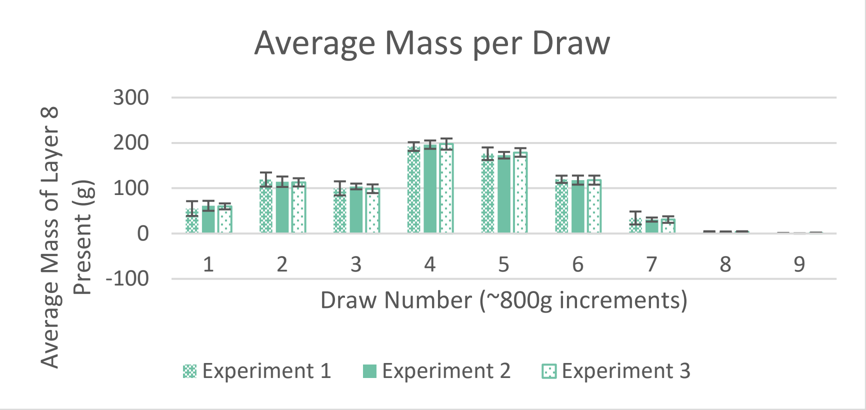


Figure 8 A comparison of the appearance of Layer 8 for 800-gram increments across 3 experiments.

Figure 9 shows a comparison of the behavior of Layer 1, the bottom layer, for 800-gram increments across 3 experiments. This figure shows approximately 10% of Layer 1 is removed in the first draw as the funnel forms, is then forced into a mostly stagnant behavior until nearly 5000 grams of grain have been removed, and that nearly 500 grams of Layer 1 remain in the bin after gravity feed has ceased.

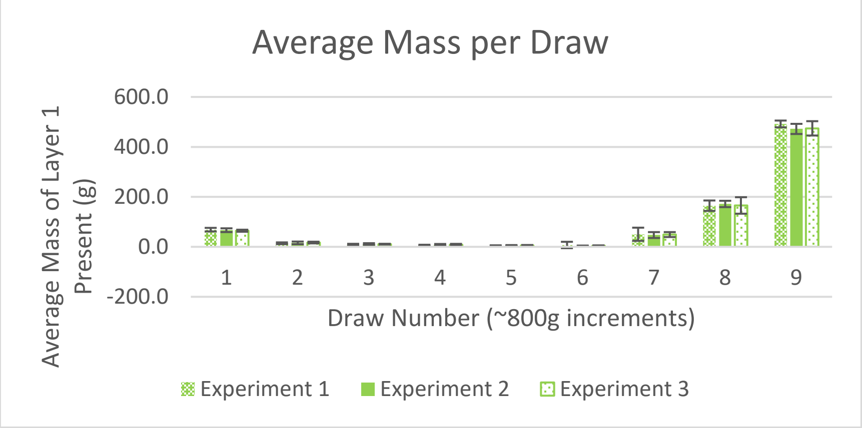


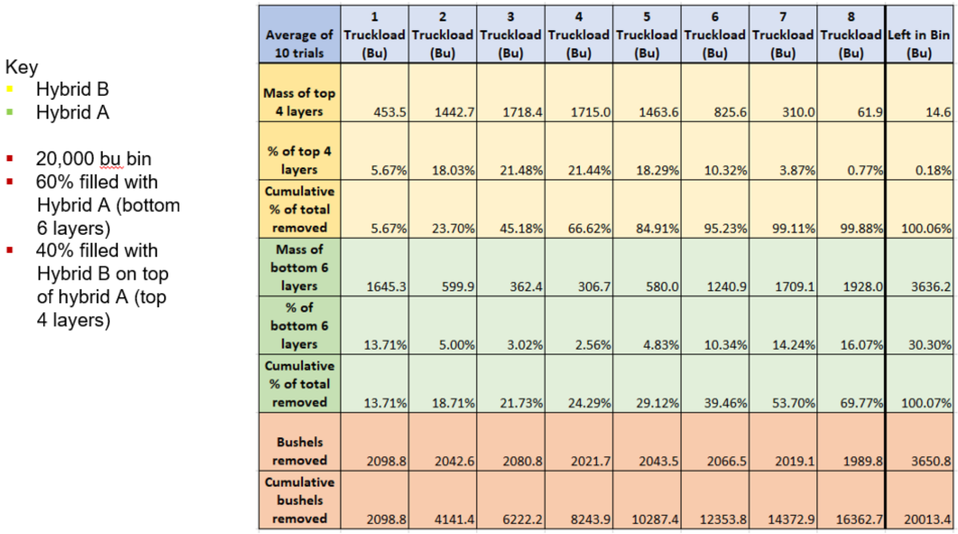
Figure 9 A comparison of the appearance of Layer 1 for 800-gram increments across 3 experiments.

Conclusion

The data provided by the model are promising because the two desired outcomes are evident in the resultant data. Expected outcome 1 is that the core flow behavior results in a flushing of the material in the center column of the bin and mixture between some or all the layers throughout the entire process, followed by the top layers pouring through the core to be depleted first. Expected outcome 2 is that consistency between trial data sets showing that the model is able to provide precise data about a pattern of behavior of granular flow from a flat-floored cylindrical bin.

Further data collection and analysis will provide more precise characterization of granular mixing behavior. Ultimately the behaviors can be examined statistically to provide a method for calculating the amount of grain from each depth that will be present in a load and with what degree of confidence that claim can be made. A diligently maintained internal traceability system would have records of the mass of any source lot received. The masses can be used to describe the physical shapes of the source layers in the bin. Characterization of granular behavior can be used to develop a method for calculating the amount of grain from each source layer that would be present in a particular load, and the degree of confidence with which that claim can be made. The clarification of the probable composition will need to include any lots that could possibly be present but will refine the number of sources identified in a large-lot labeling method, increasing response effectiveness, and decreasing the impacts and overall expense of an emergency recall.

Figure 10 shows how the data obtained in this experiment could be used to identify the amount of mixing that has occurred due to unloading. The bin was being loaded with hybrid A and was 60% full when it was accidentally topped off with hybrid B. Applying the percentages of layer removal seen in the experiments to the layers in this bin shows the "contamination" level of each load removed from the bin.



Key
- 🟨 Hybrid B
- 🟩 Hybrid A

- 20,000 bu bin
- 60% filled with Hybrid A (bottom 6 layers)
- 40% filled with Hybrid B on top of hybrid A (top 4 layers)

Average of 10 trials	1 Truckload (Bu)	2 Truckload (Bu)	3 Truckload (Bu)	4 Truckload (Bu)	5 Truckload (Bu)	6 Truckload (Bu)	7 Truckload (Bu)	8 Truckload (Bu)	Left in Bin (Bu)
Mass of top 4 layers	453.5	1442.7	1718.4	1715.0	1463.6	825.6	310.0	61.9	14.6
% of top 4 layers	5.67%	18.03%	21.48%	21.44%	18.29%	10.32%	3.87%	0.77%	0.18%
Cumulative % of total removed	5.67%	23.70%	45.18%	66.62%	84.91%	95.23%	99.11%	99.88%	100.06%
Mass of bottom 6 layers	1645.3	599.9	362.4	306.7	580.0	1240.9	1709.1	1928.0	3636.2
% of bottom 6 layers	13.71%	5.00%	3.02%	2.56%	4.83%	10.34%	14.24%	16.07%	30.30%
Cumulative % of total removed	13.71%	18.71%	21.73%	24.29%	29.12%	39.46%	53.70%	69.77%	100.07%
Bushels removed	2098.8	2042.6	2080.8	2021.7	2043.5	2066.5	2019.1	1989.8	3650.8
Cumulative bushels removed	2098.8	4141.4	6222.2	8243.9	10287.4	12353.8	14372.9	16362.7	20013.4

Figure 10 Grain traceability scenario with accidental loading of two different hybrids in a 20,000-bushel bin.

Next steps include scaling the model bin to a size that represents a large portion of grain storage containers, experimenting with the new model to assure that the behavior is consistent, running trials with various grain types to see if the behavior remains the same with grain instead of glass beads, and performing statistical analysis to identify the probability that a layer will be present in a given draw. Comparison of the results of this future work to and EDEM simulation would provide a practical verification of the theoretical methods applied in the software. Further research will need to be conducted using larger scale bins to verify that the probabilities calculated using the smaller models hold true when the scale is changed.

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