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Having a crack at bottle scuffing using agent-based mobility

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Abstract

Recent advances in large-scale mobility models have shown that much system-level insight can be gained when modelling at the disaggregate, individual level. Although the focus is often on the movement of vehicles and/or individual people, agent-based simulation modelling is used in this paper to model the mobility of bottles on a conveyor line. More specifically, the model focuses on bottle-to-bottle, and bottle-to-barrier collisions on a conveyor belt and examine the bottle movement trajectories. This paper presents the initial results of modelling the collisions as a function of the relative movement of conveyor tracks and barrier angle and suggests the number and duration of collisions could be used to model bottle scuffing. This is valuable as scuffing is the cause of a number of unwanted effects, including visual degradation of the product, and bottle breakage in both the washing and post-filling pasteurisation processes.

Keywords: bottling; conveyor dynamics; agent-based; scuffing

1. Introduction

The threat of global warming is impacting many industries and reducing the carbon footprint by recycling is becoming more important. One such application is in the beer industry, where consumers are encouraged to return empty beer bottles to the retailer and receive a refund for recycled glass bottles. These bottles are then forwarded to a bottling plant where they are washed and cleaned before being refilled. To meet production targets, new bottles are purchased to supplement any shortfall in the number of recycled bottles. Bottle breakages therefore have a direct cost implication for the bottling plant. On just one production line at SAB miller, broken bottle glass (called *cullet*) amounts to 94.5 tonnes per month, which equates to more than 190,000 bottles [12].

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The question therefore arises as to what causes the breakage. An indication of the number of times a bottle has been recycled, can be seen in the opaque ring that forms around the base and shoulder of the bottle. This is called *scuffing*.

Glass bottles are transported through the bottling plant on multi-track conveyors. See Figure 1 for a typical bottling conveyor configuration. Bottle-to-bottle collisions occur during this transportation process. These collisions cause micro cracks to form, which weakens the bottle structure. When the bottles are then exposed to caustic chemicals during the washing process, the structural integrity of the bottle is further compromised, and this wear is correlated to the amount of visible scuffing. This degradation continues each time the bottle is refilled [9].

The obvious implication of bottle breakage is replacement cost of the bottle. There are, however, a number of other problems caused by breakage that also impact on the plant. Since the bottling process is a fast-moving, continuous process, any stoppages due to breakage have a cost implication because it reduces the output of the plant.

Bottles typically explode or crack in the pasteuriser and filling machine. When a bottle explodes under pressure, it can also cause a chain reaction of secondary breakage of surrounding bottles, which then also need to be replaced by new glass bottles.

Fig. 1: A typical conveyor structure

If the breakage occurs at, or after the filling process, there will be an additional loss of the liquid content. The breakages therefore lead to both material waste as well as loss of production, since cullet needs to be removed from the bottling equipment.

Breakages also have an environmental impact, since most of the cullet is sent to a landfill and not recycled [12]. There is also a safety consideration, since broken and exploding glass in the work environment is hazardous [3].

A further problem is that scuffing distracts from the visual appeal of the packaging. Brand image is linked to quality packaging and unsightly markings on bottles can negatively impact consumer perception of the brand [5]. Companies try to solve this problem by applying special protective coatings to bottles to delay the onset of scuffing and increase the lifespan of the bottle. An alternative or supplementary strategy is to use a coating specially developed to hide the scuff marks. This solution has additional cost implications, not just the coating chemicals but also for the specialised applicator spray equipment [2, 4]

2. Literature

There is surprisingly little published research on scuffing, and even less published on modelling the dynamics and interactions of bottles. Initial research dating from the 1930's and 1950's examined breakages, thermal shock and scuffing in milk bottles [9, 10, 13].

The most recent paper looking at scuffing effects was published in 2001 and measured the amount of scuffing in beer bottles detected via an optical camera. This was related to internal pressure stability and shock resistance [7].

Some researchers considered models describing the complete bottle-filling process, with conveyors connecting the different elements of the process. Al-Hawari et al. [1] use discrete event (DE) modeling to develop a control model. Conveyors are abstracted with a delay time and capacity. Struss et al. [16] applies a flow based model to a bottling plant operation to study the interaction and impact of breakdown between different processing components. The model focus on adjusting the flow rate between these components.

Dilay et al. [5] published a model of a beer pasteurisation tunnel, and deal with generalised mass flow of bottles and heat exchange within the tunnel. The model does not take individual bottles into account but instead aggregate over the number of bottles that passes through the tunnel.

In their paper "Chaos on the conveyor belt", Sándor et al. [14] investigated the dynamics of interacting masses on a conveyor belt. They used a model consisting of a spring-block chain. This study modelled the interactions between

5 wooden blocks interlinked with springs. The model is not suitable for extrapolating to many bottle interactions, and also does not take the interaction with the environment into account.

From the perspective of this paper, the most relevant research was carried out by Do Livramento [6] in his PhD at Delft University. The author developed a detailed 2D discrete element model for bulk bottle behaviour. Bottle-to-bottle contacts were modelled by a linear spring damping system. He developed a computer program to visualise and simulate bottle interactions. Unfortunately the computing hardware available at the time severely limited the practical application of his program, and the size of problem the author could examine. The model verification was limited to bottle dynamics on parallel transition configurations.

3. Model

The key to investigating scuffing is to accurately model the physical movement and interactions of bottles on the conveyor. As indicated in the literature review, most previous modelling approaches tend to aggregate bottle interaction using discrete event (DE) or even Dynamic System (DS) paradigms to model the plant.

A more modern and previously unused approach to model these interactions, is agent-based modelling (ABM). In their paper titled *'Discrete-event simulation is dead, long live agent-based simulation!'* Siebers et al. [15] argue the wide application area of ABM and the utility of applying ABM to cases where the individual interaction of individual entities is important.

There are various definitions for agents and agent-based modelling in the literature [8]. From a practical simulation modelling point of view, we can define agents as decentralised individual entities governed by certain states and rules. These entities can interact autonomously with other agents and their environment. Applying ABM to our case satisfies the four essential characteristics of agents as described by Macal and North [8],i.e. a) self-contained and modular, b) autonomous and self directed, c) a state that varies over time and d) interacts with other agents.

What sets ABM apart from a purely physical micro simulation of collisions, is that one can model the bottle collision interactions as well as the effect of the environment. As in other complex adaptive systems, the agents are carrying with them autonomous behaviour and attributes (existing level of scuffing); the agents can interact with other agents (bottles) on the conveyor; and agents can interact with its environment (temperature differential during the pasteurisation cycle). The environment consists of the conveyor belt, conveyor guides and bottling process equipment. One can therefore model the effect of temperature fluctuations, washing and filling, in addition to physical bottle-to-bottle collisions. This will lead to a model that is closer to the real world, since it is known that scuffing is caused by the accumulated effect and alternation of bottle collisions and chemical attack during the washing phase, and this *memory* needs to be contained within the bottle agent.

Our initial model incorporates bottle-to-bottle and bottle-to-barrier collisions taking place on an accumulation table where bottle movement take place across and along conveyor tracks moving at different speeds. The model abstracts the bottles and conveyor to 2D, with bottle agents represented by circles with the diameter equal to that of the bottle and the centre of mass of the bottle at the centre of the circle. The bottle agent will record a collision or contact if another bottle agent or barrier is detected within the radius.

The model initialises with 24 bottles arranged in an equidistant grid formation of 4 rows by six columns. The conveyor consists of 6 tracks moving from left to right, and the speed can be individually adjusted. A barrier is placed at an oblique angle to the bottle movement and funnels the bottles to the bottom tracks. Figure 2 shows the initial configuration.

When each track speed is larger than that of the preceding track (from the top to the bottom), the initial rectangular grid will be skewed with the bottles on lower tracks reaching the barrier first. In Figure 3 bottles in the first 2 grid rows have not yet reached the barrier, while those in the 3rd and especially the 4th row have collided with the barrier.

The colour red identifies bottles that are in contact with other bottles, green for bottles that previously collided, and grey for bottles that have not yet collided.

It was decided to use a Java programming language open source physics engine JBox2D [11] to calculate the dynamics of the bottles and conveyor. Both linear and rotational interactions due to bottle-to-bottle and bottle-to-barrier collisions are calculated. The rotational effect on a bottle, as it moves across conveyor tracks travelling at different speeds, is modelled by applying a rotational impulse to the bottle that is proportional to the distance between its centre and the boundary between the tracks. The horizontal (positive x-direction) velocity of the bottles is determined by

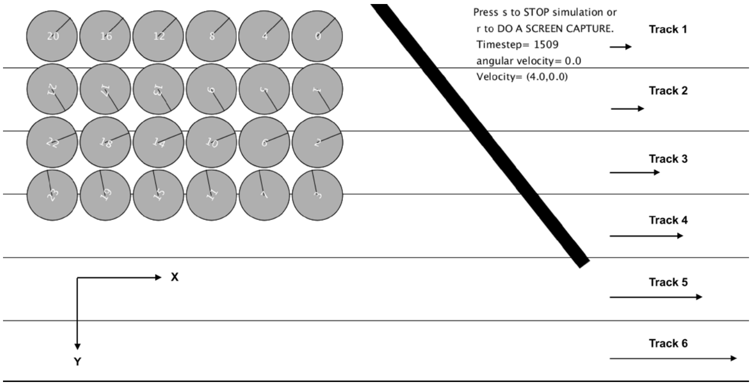


Fig. 2: Initial Bottle position on conveyor

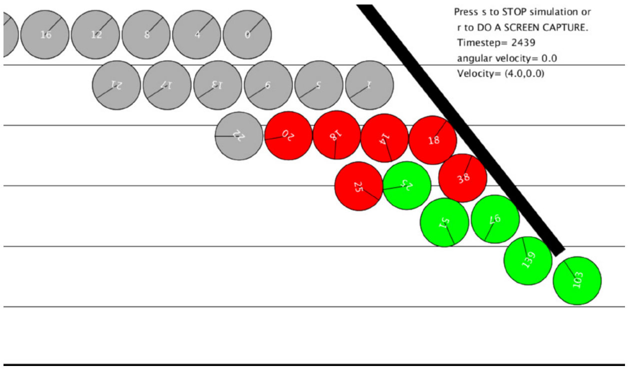


Fig. 3: Bottle position on conveyor and number of collisions

velocity of the track below the centre of the bottle and modified by any collisions. Each bottle agent stores the total number of collisions, as well as the duration of contact with other bottles. The movement trajectory of each bottle agent is also recorded by storing the x and y-coordinates for each model time step.

The model assumptions are that bottle agents will move at the conveyor speed, unless they collide with either a barrier or another bottle. This interaction will change the velocity (strictly the momentum), and the conveyor track will interact to restore the original momentum. This slippage on the conveyor is modelled using a friction constant.

It is also assumed that the barriers are treated with a low friction material that will not contribute towards scuffing. We assume that only bottle-bottle interactions will contribute to scuffing and specifically the length of contact.

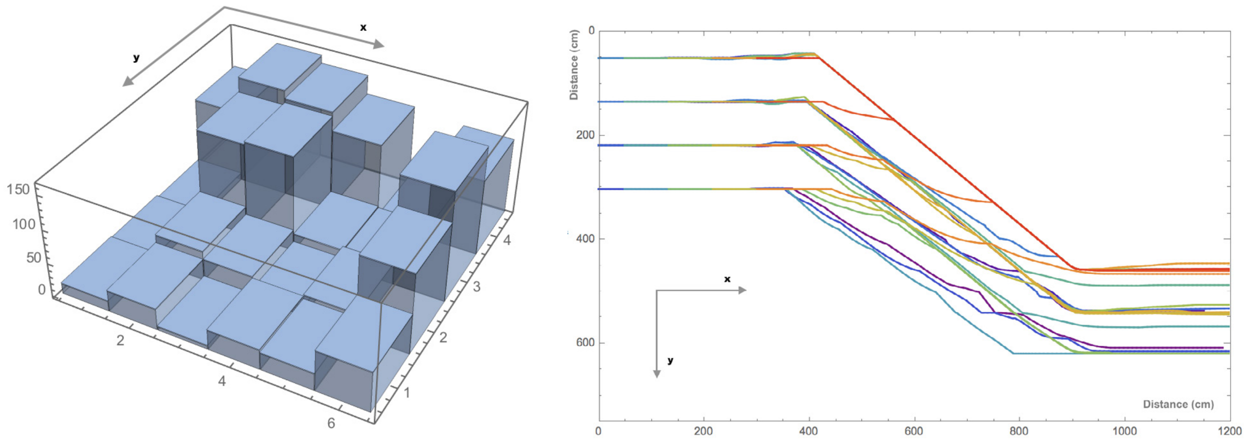
4. Results

Two initial experiments were performed. The model needs to be calibrated with experimental data to determine appropriate vales for model parameters, e.g. the friction constant. It should also be noted that the track velocity values were chosen to be convenient for the experimental runs, and not to be realistic for the actual operation. Contact time measurement values are displayed in units of 10 seconds.

4.1. Variation of track speed.

We initialised the experiment with the 24 bottles as illustrated in Figure 2 . The barrier angle was fixed at 51.5°

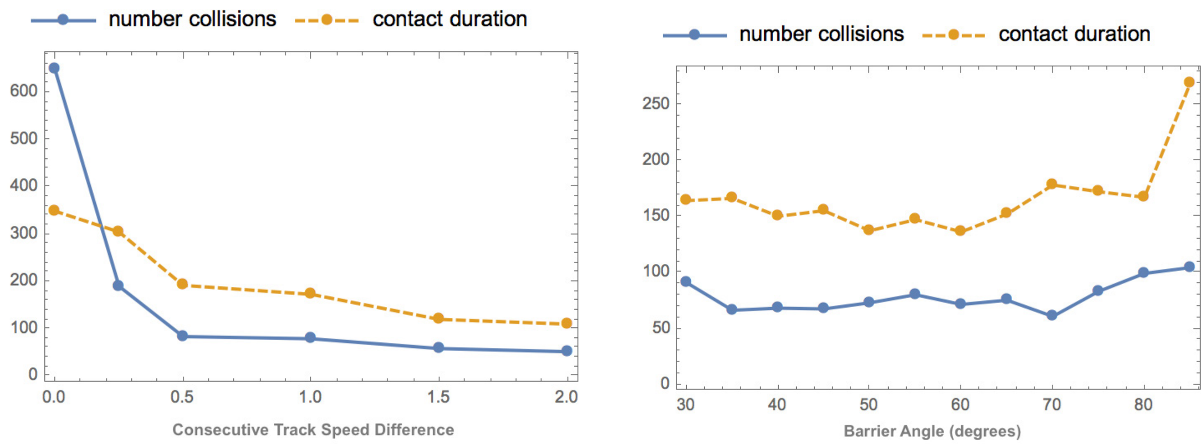
as measured from the horizontal direction, and the track speeds were varied during 6 experimental runs. For the first experiment all track speeds were set at 4 m/s (the inter-track speed difference was 0). For the second experiment track1 was set at 4 m/s, track2 at 4.25 m/s(speed difference 0.25), track3 at 4.5 m/s etc.



(a) Number of collisions per bottle

(b) Bottle movement trajectory

Fig. 4: Number of collisions and trajectories at barrier angle 75°.



(a) Collisions and contact time vs relative track speed.

(b) Collisions and contact time vs barrier angle.

Fig. 5: Number of Collisions and trajectories for variation in track speed and barrier angle.

The number of collisions experienced by each bottle, as well as the contact time with other bottles are stored within each bottle agent. Figure 4a shows a typical result: the height of the bars is proportional to the number of collisions and the position of the bars correspond to the initial grid layout pattern of the bottles. The number of collisions can vary greatly, depending on the position of the bottle. The mean of the values for both number and duration of collisions were recorded and plotted in Figure 5a.

4.2. *Variation of the Barrier Angle.*

The experiment was conducted with the same configuration of 24 bottles. The barrier angle was varied from 30° to 80° in increments of 5°. The track speeds were set from 4 to 9 m/s in increments of 1 m/s.

Figure 4b plots the bottle trajectories as bottles move from left to right on the conveyor. The initial linear tracks result from the undisturbed bottle configuration. As the first column of bottles come into contact with the barrier, bottle movement is directed downwards by the barrier and collisions occur with the next column. After the barrier is cleared bottles once again move in a straight horizontal track.

These results were obtained looking at just one element of the conveyor structure: the accumulation table. We also only introduced 24 bottles to facilitate ease of visualisation and explore the agent-based modelling paradigm. Initial experimental runs have shown the current model to work with 10,000 bottle agents, which proves the scalability of the model.

Further research will focus on building a test rig to examine the scuffing and to calibrate the model parameters. Mounting cameras on the rig will enable the logging of bottle trajectory and rotations which will be used to calibrate the model. In addition bottles may be equipped with accelerometers that will log the number of collisions. By running the test rig continuously in a closed circuit configuration, the physical scuff marks on the bottles can then be correlated to the model.

5. Conclusion

Examining Figure 5a these initial results indicate that the maximum number of collisions and contact occur when all tracks move at the same speed, and that even a small inter-track speed difference is sufficient to reduce the number of collisions and contact. At larger relative speeds the change become less dramatic.

The barrier angle increase only shows an increase in contact time and after about 75° there is a sharp increase, and the number of collisions increase only slightly over the range of angle increase.

We postulate that there is a relation between scuffing and the number and length of rotational contact between the bottles. Initial experiments show that modifications to the conveyor operation and setup will have an effect on collisions and contact. Agent-based modelling was shown to be a rich paradigm to employ in this setting and will be even more valuable when larger sections of the bottling line is incorporated in the model.

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