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SIMULATION BASED DESIGN IN THE PACKAGING AND PROCESSING INDUSTRY

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ABSTRACT
In today's competitive global markets time-consuming iterative design processes severely hinder the ability of the packaging industry to respond to rapidly changing market requirements. Material specification changes imposed by packaging waste legislation have impacted the carton industry in particular. Cartons made from thinner board behave less predictably and in some cases fail entirely when processed on existing packaging machines. This motivates the need for greater understanding of the machine-material interactions involved, and the abstraction of this knowledge into simulation based design tools. A finite element computer model was created to simulate the interaction of a carton with machine tooling during its critical transition between flattened and erected states. The model was applied to investigate carton failure through buckling. A parametric study of production rate, tooling orientation and effector positioning showed that distortion in the carton could be predicted with maximum error of 24 %. This was sufficient to identify optimum machine settings and establish performance limits. Traditionally, knowledge pertaining to packaging machinery design has resided in the two divided supply chains of material suppliers and machinery manufacturers. The unique model demonstrated in this paper overcomes this knowledge division and provides the ability to generate information concerning machine-material interactions which was previously unavailable.

Keywords: performance limits, machines, materials, redesign

1 INTRODUCTION
The design of packaging and packaging machinery is based largely on trial-and-error improvement processes. Subtle changes made to the material specification or pack geometry can have serious implications for the efficacy of the packaging process [1]. At present this is overcome through time-consuming production trials and commissioning during which appropriate machine settings can be determined. In today's highly competitive global markets such a time-consuming iterative process is unfeasible and severely hinders the ability of the equipment manufacturer to respond to rapidly changing market requirements.

1.1 The Impact of Packaging Waste Legislation
In order to comply with recently-tightened European Union (EU) regulations on packaging waste [2], packaging is increasingly required to be manufactured from thinner, lighter-weight, and recycled materials. Such materials tend to behave less predictably on existing machines and manufacturers cannot rely on the existing empirical knowledge derived through experience and trial-and-error [3].

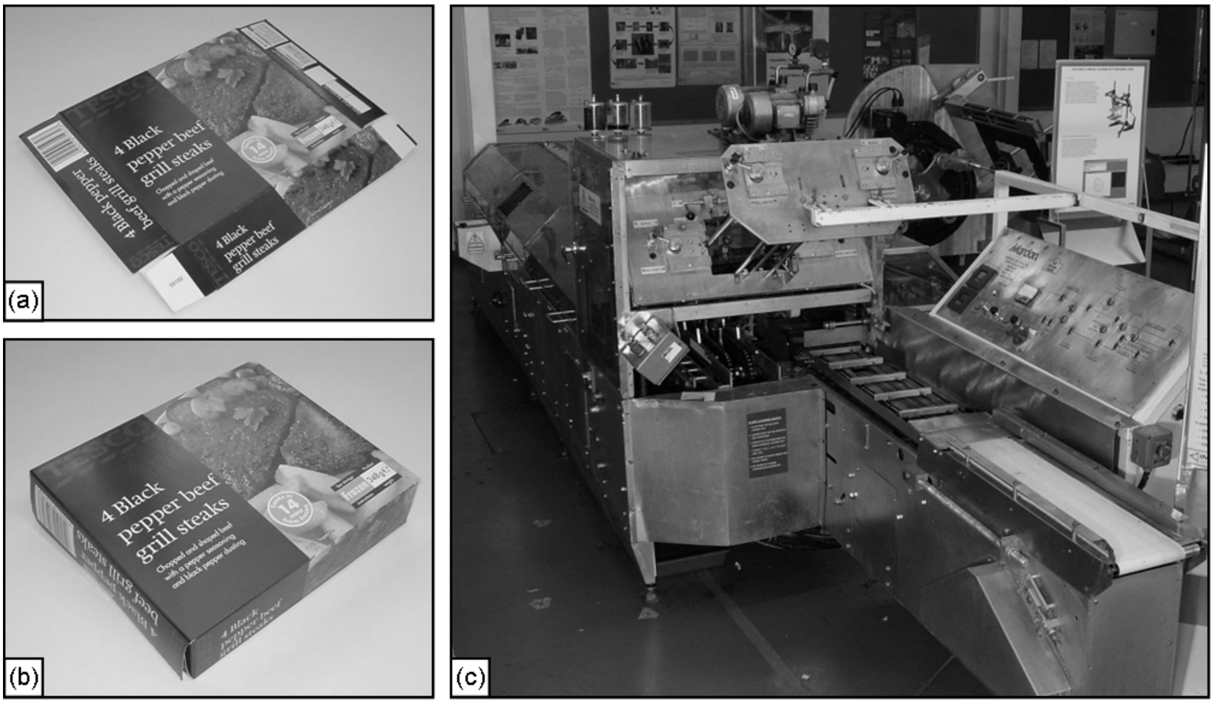

Figure 1. Skillets (a) are erected, filled and sealed to form shelf-ready cartons (b) by automated machinery (c) capable of processing over 250 packs per minute.

One sector of the packaging industry which has been particularly impacted upon by the recent EU packaging waste regulations is cartoning. One of the primary benefits of a carton is that it can be flattened for space-saving transportation and storage (see Figure 1 part (a)), and then erected and sealed (see Figure 1 part (b)) by the fast-moving consumer goods (FMCG) manufacturer at the point of use [4]. Furthermore, cartons can be processed by automated machinery (see Figure 1 part (c)) at speeds over 250 products per minute making them one of the most commonly used classes of packaging material for high speed operations.

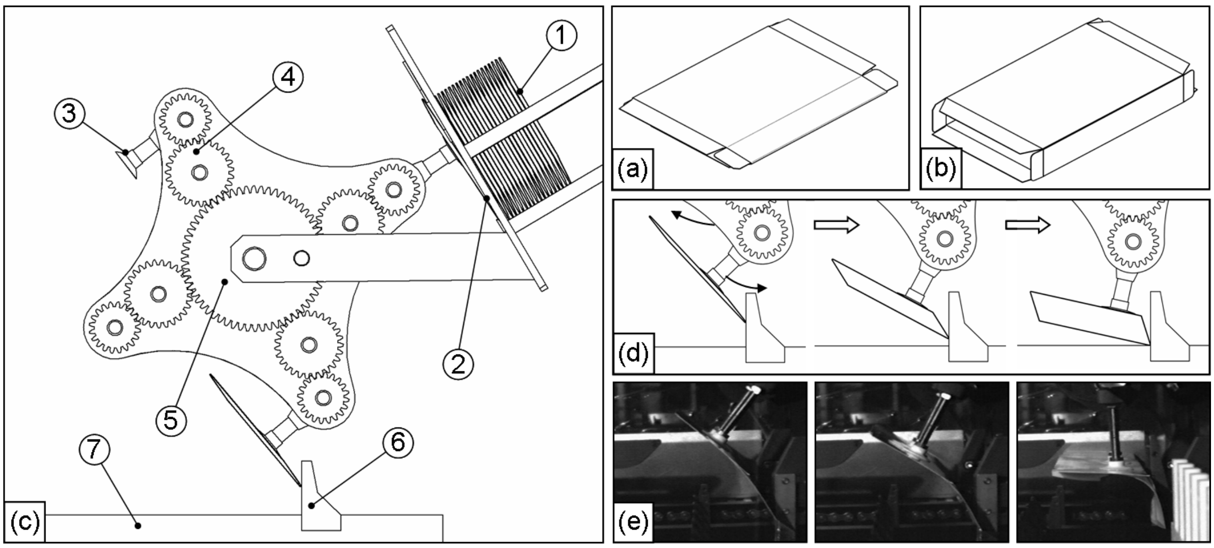

Figure 2. (a) Skillet. (b) Erected carton. (c) Erection mechanism showing skillets (1), feed aperture (2), vacuum cups (3), epicyclic gear train (4), sun gear (5), backstop (6) and fixed rails (7). (d) The mechanism erects the skillet by forcing one edge against the backstop. (e) Frames from high speed video footage of a carton failing in buckling.

With the introduction of new materials, the performance and efficiency of the carton erection process has been compromised, and in many cases fails entirely. This is generally due to buckling of the carton during the critical transition between flattened and erected states (see Figure 2 part (e)). In order to overcome this fundamental issue there is a need to understand the causes of buckling and specify materials, package design and machine design such that the buckling mode-of-failure is eliminated.

1.2 The Role of Computer Simulation

Key to discerning the causes of buckling failure is greater understanding of the relevant machine-material interactions. Determination of this knowledge experimentally is time-consuming and resource-intensive. Furthermore, this approach can reduce the portability of design expertise due to over-reliance on empirical knowledge residing with experienced individuals.

Computer simulation is now a mature and essential part of many design practices that has led to improved designs, reduced development times and costs [5]. Simulation tools offer several advantages such as the ability to adjust design parameters in isolation, high repeatability and reduced dependency on experimental resources. The use of offline methods to obtain design data also avoids blocking of machinery for trial runs and ensures continued revenue generation. Perhaps most importantly, the use of computer simulation minimises reliance on the empirical knowledge of individuals and instead makes this knowledge more widely accessible through abstraction into a common design tool.

1.3 Computer Simulation in the Packaging Industry

Computational tools such as finite element (FE) analysis have been widely used to aid design in, for example, the automotive [6], aerospace [7] and medical engineering [8] industries. The packaging industry is also increasingly turning to computational tools and recent applications of the FE method include analyses of paper cup formation [9], plastic bottle blow moulding [10], plastic bag forming [11], paper forming [12] and protective properties of polyurethane foam [13]. By contrast, relatively little computational modelling work has been carried out for applications in the folding carton industry. Researchers have investigated the case of static loading of palletised cartons [14], crease mobility and panel compliance of cartons erected by a reconfigurable robot [15, 16], and have considered a simplified case of carton erection by end shortening [17], but there exists no other computational tools for modelling the complex machine-material interactions that take place during high speed carton erection. To address this issue, a FE simulation that considers the behaviour of the pack and packaging machine in a common modelling environment was created [18]. The model was recently extended to consider the case of buckling failure [19]. The ability of this model to generate design data is demonstrated here through investigation of the effect on the likelihood of process failure of variation in three key process parameters. These are: the angle of tooling with respect to the carton, the positioning of critical transfer points, and the rate of production.

2 CARTON PACKAGING

Folding cartons are delivered to end users in a flattened state termed a "skillet" (Figure 2 part (a)), and are erected (Figure 2 part (b)) at the point of use. Skillet erection, product insertion and carton sealing operations are carried out sequentially on an automated carton packaging machine (e.g. Figure 1 part (c)). This study focuses on the critical erection phase, which is accomplished by forcing one edge of the skillet against a fixed tooling surface. One method commonly used to achieve this is through the use of an epicyclic mechanism (Figure 2 part (c)). In this mechanism, skillets (1) stacked against the feed aperture (2) are drawn into the machine by vacuum cups (3) which are driven by an epicyclic gear train (4) orbiting a stationary sun (5) towards fixed tooling known as a "backstop" (6). As its edge slides against the backstop, the skillet unfolds into a rectangular-cross sectioned sleeve (Figure 1 part (d)). When the vacuum cups reach the bottom-dead-centre position, the vacuum is released and the erected carton is supported by fixed horizontal rails (7) and transported through machines by lugs connected to a chain driven conveyor below the rails (not shown).

2.1 Machine Setup Considerations

In order to allow end users to remain competitive in the face of rapidly changing market demands, manufacturers are increasingly expected to produce packaging machinery capable of handling wide variations in packaging dimensions and material properties. Furthermore, these machines are expected to be capable of rapid reconfiguration in order to increase changeover performance. To achieve the former, machines are equipped with a large number of adjustable settings, while manufacturers are addressing the latter through the introduction of computer-controlled, servo-driven adjustment axes. However, the limiting factor remains the knowledge relating a particular carton geometry or material property to the appropriate set of values for the adjustment set. Certain settings are dictated by geometric considerations alone, for example the positions of guides and sensors relate directly to carton dimensions. Such settings therefore may have clearly-identifiable correct positions with small tolerance bands outside which processing becomes unreliable. By contrast, there exist other parameters having wider tolerance bands within which optimum positions are difficult to identify using carton dimensions alone.

An example of a parameter whose effect on the erection process is poorly understood is the position and orientation of fixed tooling against which the skillet is forced during erection. This tooling, known as a "backstop", may be translated and rotated in order to alter the "angle of attack" and initial contact position of the incoming skillet (see Figure 3 part (a)). A further example is the positioning of the vacuum cups that grip the skillet relative to its upper wall boundary (see Figure 3 part (b). Discussions with machinery manufacturers and visits to end-users carried out in preparation for this study revealed variation in design and setup strategies for both these machine elements.

2.1 Process Failure

The limiting factor in the carton packaging operation is generally the skillet erection phase. Under certain conditions, the skillet adopts a buckling mode instead of opening in the manner of a parallelogram mechanism (see Figure 2 part (e)). The mechanism responsible for buckling is the region of low pressure that forms within the carton as the walls separate at high speed. This causes the walls to remain in intimate contact as the edge of the skillet moves over the tooling surface. This results in permanent deformation of the carton structure, makes product insertion impossible and often necessitates downtime to clear blockages. For a given carton, buckling is more likely to occur at higher production rates and so in practice, operators avoid the problem by reducing machine speed. However, this results in under-utilisation of machine capacity and limits productivity. A more effective approach is to more closely examine the fundamental causes of buckling in terms of material properties, pack geometry and machine set up. Computational tools represent an increasingly effective way to achieve this.

3 AIMS AND OBJECTIVES

The overall aim of the work reported in this paper is to create a computational simulation of the complex behaviour of folding cartons during processing in order to support improvements in machine design and set up. The objective of the study presented here was to use the computer simulation to investigate the effect on the likelihood of buckling failure of two key machine settings. These were the orientation of fixed tooling with respect to the skillet, and the location of points of contact between the skillet and the moving machine elements.

4 MATERIALS AND METHODS

4.1 Modelling Carton Structure

A three-dimensional finite element (FE) model of the folding carton and packaging machine mechanism was created using ABAQUS/Standard 6.5 [20] (see Figure 3 part (c)). Mechanical testing was performed to determine the material properties of the carton board and creases. Carton walls were represented in the model as elastic shell elements with orthotropic, perfectly elastic material properties. Non linear material behaviour was accounted for in the creases, which were represented by torsional spring elements with user-defined stiffness characteristics. Preload was added to the two folded creases in order to generate "plim", the term used in the carton industry to describe the initial distance of separation between the skillet walls. Contact interactions between the internal walls of the carton itself were applied in order to simulate air inrush suction, which as previously stated is the physical mechanism responsible for buckling. Air-inrush suction was measured experimentally using specially-designed apparatus and was incorporated into the FE simulation through the use of contact damping interactions applied to the internal surfaces of the folded carton [19]. The contact damping coefficients, expressed in terms of pressure per unit separation velocity, are summarised together with other key material properties in Table 1.

4.2 Modelling Machine Elements

The simulation was based on an end-loading carton packaging machine with a four-station epicyclic skillet erecting mechanism, as shown in Figure 1 part (c). The FE model considered a single epicyclic station consisting of two vacuum cups connected by rigid beam elements representing the rotating epicyclic carrier and the planet gear. The movement of the vacuum cups followed a cycloidal path generated by applying appropriate rotational velocities to the joints between mechanism elements. The 44 mm diameter vacuum cups themselves were modelled using isotropic linear elastic solid elements and their grip upon the carton was achieved by applying uniform pressure to the rear surface of the cup and to the inside of the upper carton wall. This allowed a flexible connection to be established between the carton and the rigid elements of the packaging machine. Dynamic and static friction coefficients were measured and incorporated into the interactions defining sliding contact between the skillet and backstop surface, which was represented as a rigid surface (see Table 1).

4.3 Skillets

The skillets investigated in this study were of a type used to hold six aluminium foil-encased sweet pastry pies arranged in a 3 x 2 matrix on a plastic tray insert. Export grade skillets made from high quality cartonboard were chosen for the study in order to minimise variation in material properties and hence improve repeatability. In order to simulate the worst-case scenario of skillets exposed to adverse storage conditions and hence to increase the tendency of the skillets to buckle, samples were environmentally conditioned in an atmosphere of 38 C, 90 % relative humidity for three days prior to stabilisation at room conditions for at least six days [21]. Cartons prepared in this manner have previously been shown to have a repeatability error of ± 8 % on the cross sectional area at the prescribed sampling point in the erection cycle [18].

4.4 Experimental Procedure

Experiments carried out for this study were performed first in the FE model and were then reproduced on a carton packaging machine adapted for the purposes of validating the simulation results using high speed video. For the study of backstop angle adjustment, this paper compares experimental and predicted results of trials performed at three angles: θ_b = 0, 15 and 30 degrees. Care was taken to ensure that the point in its trajectory at which the skillet first made contact with the backstop, and hence its approach velocity, was the same for all angles tested. This was achieved by rotating the backstop about a point (denoted "p" in Figure 3 part (a)) such that the angle θ_a remained at 50 degrees, which was the existing setting on the machine. For the study of vacuum cup position, the distance between the common centreline of the cups and the edge of the upper skillet panel, d_v, was adjusted in three increments of 8.0 mm (see Figure 3 part (b)). The vacuum cup centre-to-centre distance remained unchanged throughout. The typical appearance of the FE model at the two extreme values of backstop angle and vacuum cup position is shown pictorially in Figure 3 parts (e) and (f) respectively. For the experimental results, a side-view of the erection phase was obtained using high speed digital video with a frame rate of 500 frames per second, exposure time of 1/5000 seconds and resolution of 640 x 480 pixels. This paper presents results obtained using production rates of 150, 175, 200 and 225 cartons per minute.

Table 1. Material properties and process parameters. E_x = Elastic moduli in direction x; t = cartonboard thickness; $C_{d\ x}$ = contact damping coefficient for internal wall interactions at distance x; μ_s , μ_s = static, dynamic friction coefficients for carton-tooling interactions.

E_1 [MPa]	E_2 [MPa]	E_3 [MPa]	t [mm]	$C_{d\ 0.0\ mm}$ [Nsm^{-1}]	$C_{d\ 1.2\ mm}$ [Nsm^{-1}]	$C_{d\ 6.0\ mm}$ [Nsm^{-1}]	μ_s	μ_d
4460	2385	22	0.5	1500	260	100	0.3	0.2

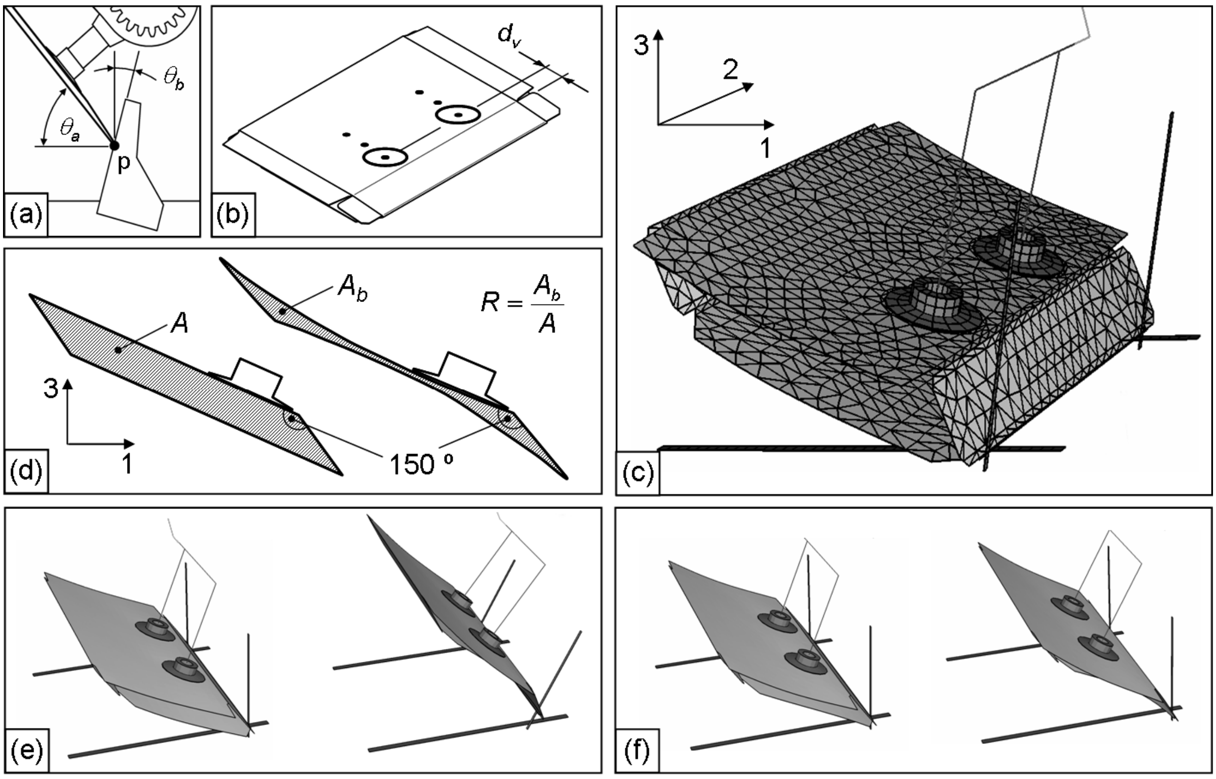

Figure 3. (a) Backstop orientation. (b) Vacuum cup locations (not to scale). (c) FE model of the carton and packaging machine. (d) Opening ratio calculation. (e) Typical appearance of the FE simulation with backstop at 0 (left) and 30 degrees. (f) Views of the FE simulation with vacuum cups positions closest (left) and furthest from the crease.

4.5 Results Evaluation

The results of the FE simulation were compared to experimental results qualitatively and quantitatively. For qualitative comparison, the deformed shape of the skillet predicted by the FE simulation at a prescribed point in its erection cycle was superimposed over that from the corresponding frame of the high speed video of the experimental case. The comparison was made at the point where the included angle of the crease on the upper wall nearest the vacuum cups had reached 150 degrees. The quantitative comparison was made by calculating the cross sectional area of the skillet at this point. This measurement was made independent of skillet size by dividing by the cross sectional area of an undistorted skillet at the measured crease angle. This quantity was termed the "opening ratio", *R* (see Figure 3 part (d)). An *R* value of 0.0 therefore represented the case of a skillet whose walls fully coalesced, while a skillet whose walls remained planar and hence opened normally produced an *R* value of 1.0. Observations of high speed video have shown that inward curvature of the lower carton wall indicative of buckling begins at *R* values around 0.6. *R* can exceed 1.0 if the skillet walls bow outwards sufficiently. The most suitable configuration for a given carton is therefore that which maximises *R*.

5 RESULTS

As previously stated the effects of variation in two key machine settings were investigated. Each of these is now discussed.

5.1 Backstop Angle

Figure 4 illustrates the effects of variation in backstop angle for the highest and lowest production rates considered in this paper. The deformed shapes of the skillet predicted by the FE simulation for three backstop angles are compared in the figure with the corresponding high speed video frames. With the exception of the θ_b=30 degrees position at 150 CPM, a close correlation exists between the actual and predicted deformed skillet shapes. The distortion in the carton is shown to increase with increasing backstop angle, and buckling is in general more pronounced at the higher of the two production rates shown in the figure.

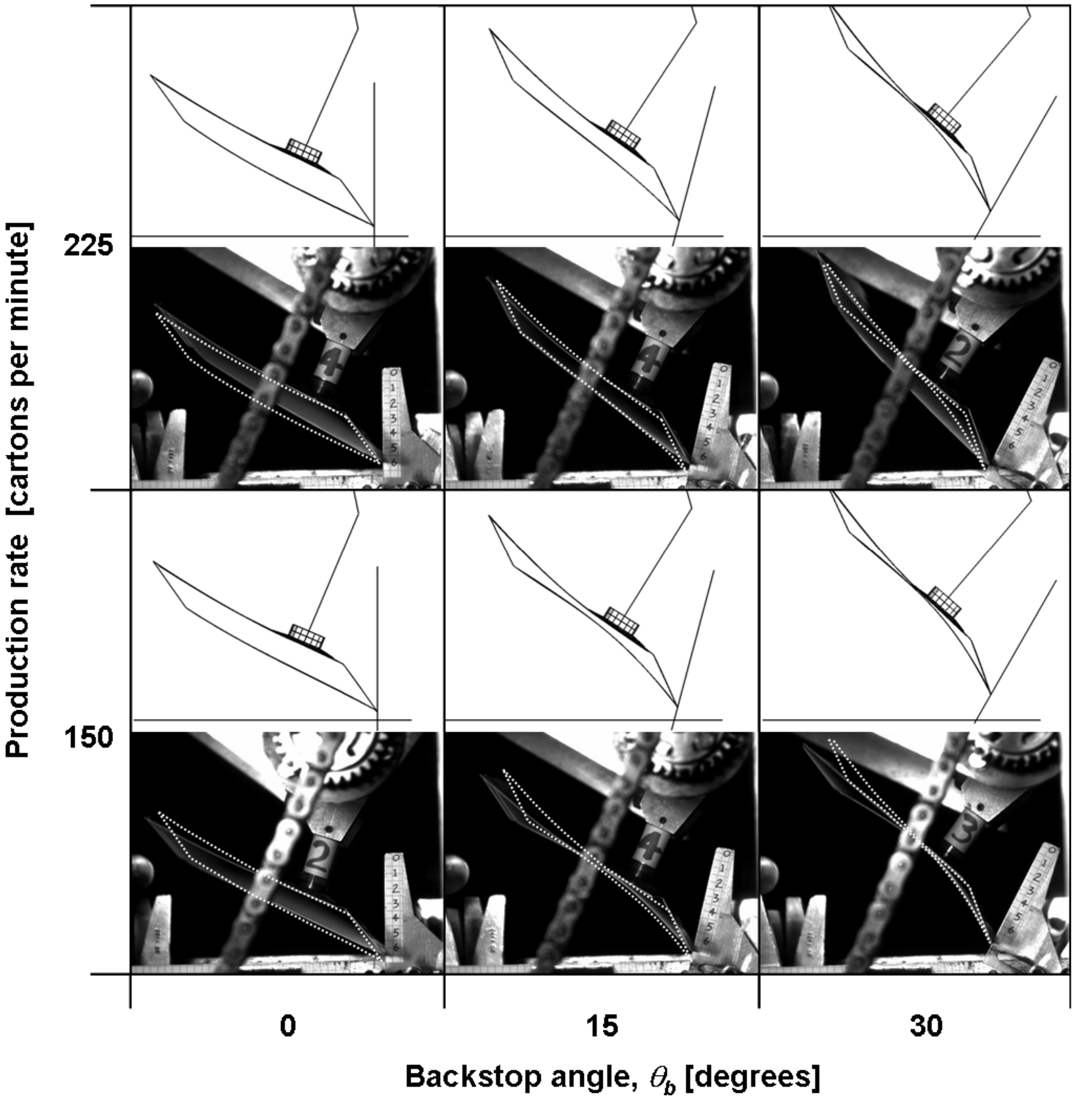

Figure 4. Comparing simulation results with high speed video footage of skillet erection at the three backstop angles considered. Predicted results are shown above corresponding frames from high speed video. Predicted results (dotted line) are superimposed on the high speed video images.

Quantitative results for the adjustment of the backstop angle are shown later in Figure 6 part (a). The figures show the opening ratio as a function of production rate for the three backstop angles considered. The error bars associated with the (single replicate) experimental values show an estimated repeatability based on ten trials at the worst-case operating point [18]. Points falling below the R=0.6 threshold indicate those configurations in which buckling is most likely. Both predicted and experimental results show that with increasing backstop angles, the tendency to buckling increases, as evidenced by comparing the number of points falling below the buckling threshold. For the case of θ_b =30 º, buckling occurred in the experimental results at all production rates higher than 150 CPM. By contrast, at 0 º degrees, production was reliable up to the maximum production rate of 225 CPM. The positive correlation between production rate and likelihood of buckling is also demonstrated in both data sets, but for the extreme case of θ_b = 30 º, is more pronounced in the experimental results. The error on the predicted results presented here, averaged over all operating points and expressed in absolute terms was +0.01, or + 1 % of the opening ratio for an undistorted carton, with a standard deviation ± 18 % about this value.

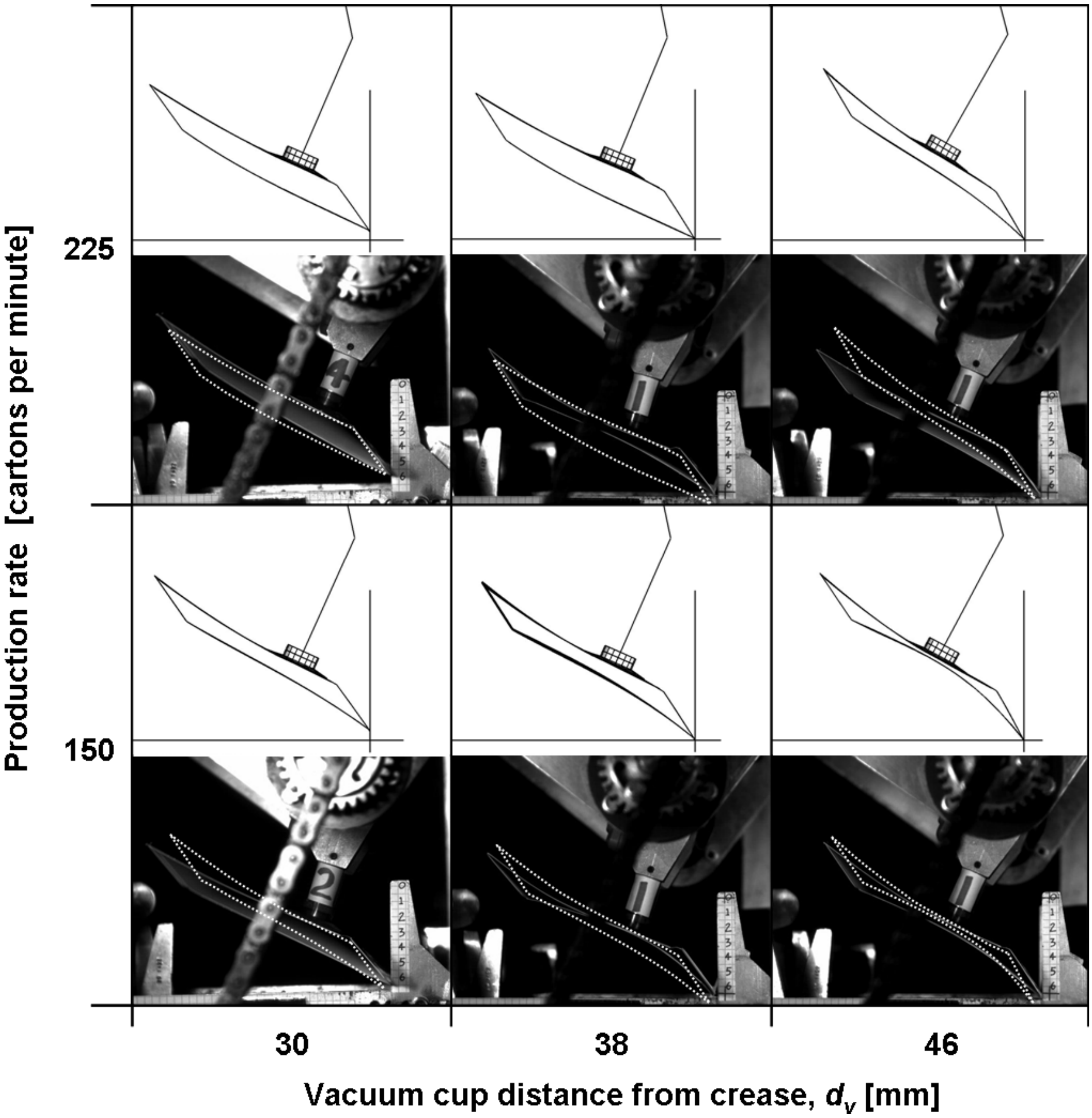

Figure 5. Comparing simulation results with high speed video footage of skillet erection at the three vacuum cup positions considered. Predicted results are shown above corresponding frames from high speed video. Predicted results (dotted line) are superimposed on the high speed video images.

5.2 Vacuum Cup Position

The effect of variation in vacuum cup position is shown in Figure 5. The overall pattern observed is that buckling becomes more likely as the vacuum cups are moved further from the edge of the skillet wall. For the cases where this distance, d_v, is 30 mm and 46 mm, the results of the FE simulation are in agreement with the observed deformation. For each change in d_v, it was necessary to alter the phasing of the moving conveyor system with respect to the epicyclic mechanism such that the skillet was transferred to the moving lugs at the same point in the erection process. For the d_v = 38 mm case an unforeseen alignment error occurred, which resulted in the skillet being transferred to the moving lugs before the crease had opened to the prescribed sampling point of 150 degrees (see Figure 3 part (d). This resulted in exaggeration of any buckling already present in the skillet at this point and hence explains the discrepancy between experimental and predicted results for the d_v = 38 mm position. The error on the predicted results, excluding the case of d_v = 38 mm and expressed in absolute terms, was -12 % of the opening ratio for an undistorted carton, with a standard deviation of ± 12 %.

Figure 6 part (b) shows how the opening ratio is affected by variation in vacuum cup position and production rate. The figure shows that when the vacuum cups are positioned closest to the skillet wall edge, the likelihood of buckling is minimal, with all experimental and predicted results lying above the *R*=0.6 threshold. However, with the vacuum cups located 16 mm further from the crease the limiting production rate has fallen from 225 to 150 CPM.

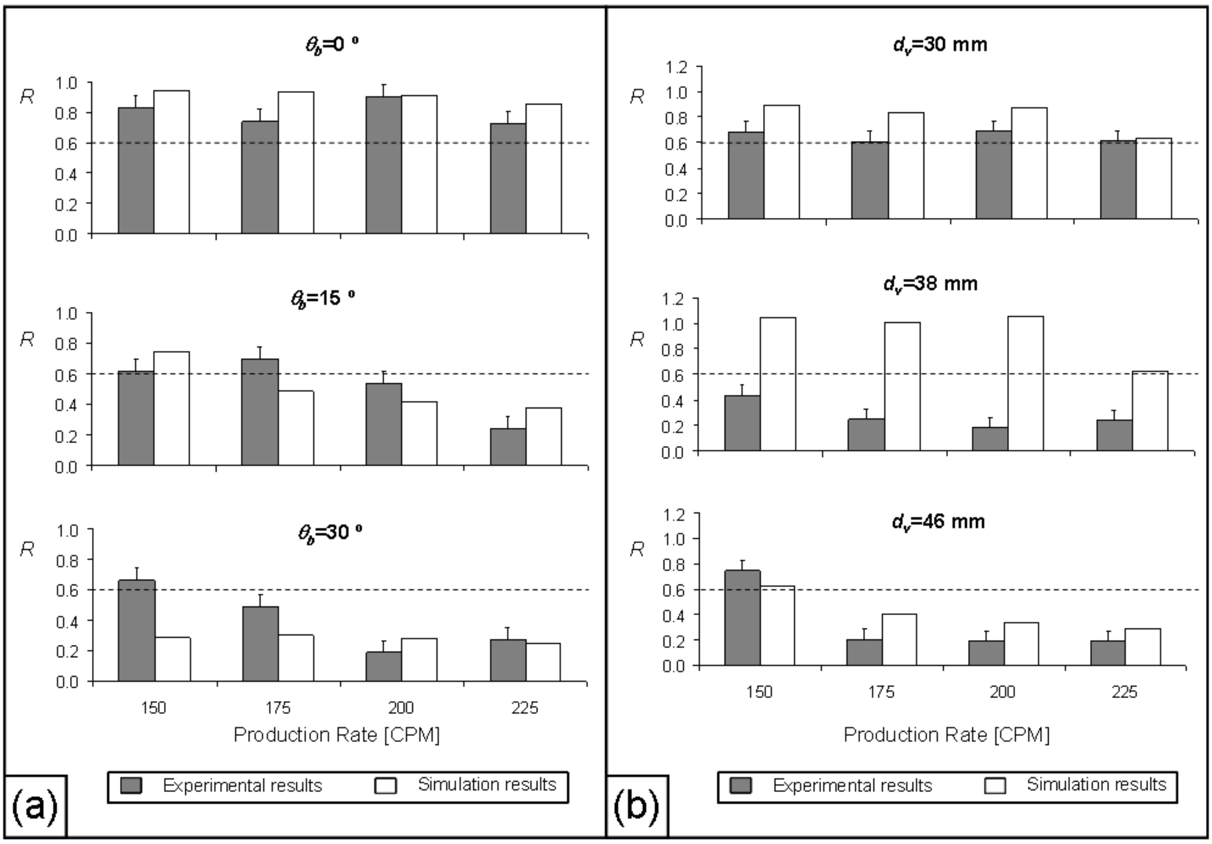

Figure 6. Comparing predicted and experimental values of opening ratio for all backstop angles (a) and vacuum cup positions (b) at all production rates considered. R values below 0.6 indicate operating configurations in which buckling is in evidence.

5.3 Results Discussion

Skillet erection is a complex process consisting of multiple concurrent contact and sliding interactions, rate-dependent effects, large deformations, and non-linear behaviour. Despite these difficulties, the FE simulation of the process showed a good overall agreement with experimental results. For the case of backstop orientation, both sets of results clearly showed that carton performance was maximised when the backstop angle was set to the vertical position. Negative backstop angles were found to be impractical due to the heightened risk of fouling the lower skillet wall. In the light of these findings, it may be argued that the angular adjustment is redundant and that machines should be supplied with the backstop fixed in a vertical orientation. For the case of effector positioning, the results indicate that it is desirable to locate the vacuum cups close to the crease. The sensitivity of the erection process to variation in this distance is highlighted by the fact that moving the cups by just under one cup radius further from the crease can result in a drop in reliable production rate of more than 30 %. The cup-to-crease distance can increase through slippage of the vacuum cups against the cartonboard surface as the skillet is drawn through the feed aperture. The purchase of the cup on the board therefore represents a potential avenue of future research and exemplifies the need for increased understanding of the fundamental machine-material interactions involved in packaging operations.

6 CONCLUDING REMARKS

The study demonstrates the feasibility of simulating a very complex carton erection process using commercially-available finite element software. Results show that the FE simulation is capable of reproducing the shape a folding carton adopts during the critical transition between flattened and erected states both for the case of normal opening and buckling failure. The model correctly predicts the effects of adjustments in backstop angle, vacuum cup position, and production rate, and can identify limiting factors or conditions with a worst-case accuracy of ± 24 %.

The recommendations of this study are that in order to minimise the likelihood of carton buckling and thereby maximise production rate for a given carton:

- The backstop should be oriented in the vertical position
- The vacuum cups should be located as close to the edge of the carton wall edge as possible

The use of simulation based tools for machinery, process and materials design have not been widely used in the FMCG industry. Rather materials and machinery knowledge has always resided within the two supply chains (materials supply and machinery manufacturers). This unique model overcomes the division of knowledge and provides the ability to generate information concerning the machine-material interaction which was previously unavailable. Such knowledge and understanding is critical for FMCG manufacturers and machinery manufacturers to compete in today's highly competitive global markets.

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