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GENERATING RULES FOR THE IMPROVED DESIGN OF PACKAGING MACHINERY

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1. Introduction

The fast moving consumer goods (FMCG) sector is particularly reliant upon the effective design of high-speed machinery in order to produce and package high quality competitively priced products [MTA, 2005]. For these reasons the manufacturers of packaging and processing machinery are required to develop machinery that is capable of ever-increasing production rates and larger range capabilities. At the same time these machines are expected to deliver greater production efficiency, reduced changeover and run up times, and be right first time. Achieving these requirements poses some difficult challenges for the machinery manufacturer. In particular, there is the need to understand the complex interactions between the machine and the product, and relate this understanding to machine design and machine setup.

In the past it was common for machinery to be fine tuned or even refined at the customer's premises. Furthermore, repeat orders could be incrementally changed using the understanding gained from the first generation machine and the products that it processed. However, in today's fast moving global markets there is rarely the opportunity to refine a particular machine. Rather each machine can be considered to be largely a one-off. Although the platform may remain unchanged a large number of machine assemblies and tooling elements may change depending on the properties of the materials and the product. In addition to this a multitude of machine settings may also need to be altered.

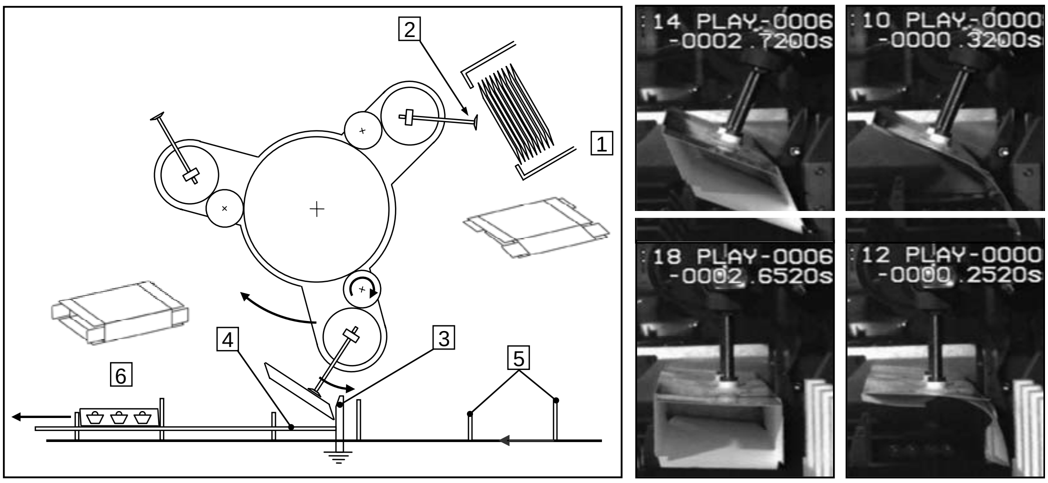
The need to understand machine-material interaction is becoming of increasingly important as material converters are required to meet European legislation [EU directive, 2004]. In order to comply with the new regulations, FMCG manufacturers are required to use thinner, lighter-weight materials and materials with a greater proportion of recycled content. This has significantly impacted upon the convertibility of carton board and in particular pre-folded, flattened cartons. More specifically the behaviour of such materials during processing with present designs of packaging machines is less predictable [Hicks et al., 2004] and many processes have become highly sensitive to changes in machine settings. This is further frustrated by the fact that many packaging machines are set up on a trial-and-error basis since the understanding necessary to relate a particular pack geometry and material, to the optimum machine setup, is not well established.

There is a fundamental requirement to create supportive tools and techniques that aid in generating an understanding of machine-material interaction, and to convert this understanding into design rules and machine settings. One way of achieving this is to simulate the process using computational tools. The work reported in this paper considers the creation of an environment which simulates the behaviour of a carton as it is processed within a packaging machine. In particular this study explores the process by which a flattened carton is opened up or "erected" into a rectangular sleeve. This paper demonstrates the use of the model for investigating the sensitivity of the erection phase to variation in machine setup and production rate. The understanding gained is then used to determine the optimum machine setting.

2. Background

This paper considers the design of machinery for the processing of folding cartons. The folding carton is a successful packaging solution that is used to pack a wide variety of FMCG products. It is economical in terms of materials and manufacturing costs, can be flattened for space saving transit, and has minimal environmental impact upon disposal. The folding carton industry occupies the largest sector of the European paper-based packaging industry, has a turnover of £4.5 billion and employs around 57,000 workers [Pro Carton Europe 2005].

One of the most critical operations during the conversion of folding cartons is the process of “erection”. This involves the unfolding of a flattened, pre-folded section of carton board known as a “skillet” into a sleeve. A common method of achieving this is by forcing one edge of the skillet against a fixed plate. Skillets are commonly erected using an epicyclic mechanism. A three-station configuration is shown schematically in Figure 1. The mechanism is capable of achieving production rates in excess of 200 cartons per minute (CPM). In operation, a skillet is drawn from a feed magazine (1) and is held securely by vacuum cups (2). It is then rotated anticlockwise towards a fixed backstop (3). The leading edge of the skillet is forced into contact with the backstop and this initiates erection. Once opened, the skillet rests on the fixed horizontal guide rails (4) and is transported through the machine by the moving lugs (5) to the product insertion point (6).



(a) (b) (c)

Figure 1. (a) Simplified diagram of an epicyclic carton erection mechanism. (b) Normal carton erection. (c) Buckling failure

Skillet erection is generally a reliable process but it can fail and the reasons for this are not fully understood. During a failure, the skillet walls effectively stick together instead of separating, which causes the structure to buckle (see Figure 1 part (c)). The physical mechanism thought to be responsible for buckling is the region of low pressure that forms within the skillet due to air-inrush as the walls separate. However the sensitivity of this phenomenon to variation in machine settings and carton properties is not well known. Hence, to avoid failure, machinery operators will reduce production rates until acceptable process efficiency is achieved.

This approach can significantly reduce overall production capacity which can be costly to the FMCG manufacturer and ultimately the machinery manufacturer. To overcome this, there is a need to improve the understanding of machine-material interaction and generate the fundamental design knowledge necessary to improve machinery and tooling design. Such understanding cannot be easily obtained through practical studies. It therefore follows that the aim of this work is to construct a detailed simulation of the carton conversion process as an aid to establishing rules that will help to optimise the design and operating parameters of the carton conversion process. In the construction of this simulation a variety of complex motions, nonlinear materials properties and complicated interactions need to be represented. Furthermore, these aspects need to be represented in an integrated manner such that the behaviour of the carton can be reliably predicted and design changes evaluated.

In order to illustrate the importance of machine-material interaction and demonstrate the generation of important design knowledge through the modeling of such interactions, an industry based design scenario is considered. This involves examining the effect on conversion efficacy of variation in the position of the vacuum cups on the carton surface. This is a particularly important design issue since opinion in the packaging industry differs over the ideal position for the cups due to a lack of objective analysis of the problem.

3. Methods

As previously stated, to simulate the carton conversion process it is necessary to represent and simulate a variety of machine elements, complex motions, nonlinear materials and complicated interactions. To achieve this, a system model was created using ABAQUS/Standard 6.5 (ABAQUS Inc.) finite element analysis software (see Figure 2) and validated for the case of normal conversion [Sirkett et al. 2006]. The key elements of this system model are summarised in the following sections.

3.1 Machine elements

An epicyclic conversion mechanism, as shown in Figure 1, was created in ABAQUS using design data supplied by a machine manufacturer. The analysis that follows considers the portion of the erection cycle from the point at which the skillet first makes contact with the backstop through to the point at which it first contacts the rear moving lug.

3.2 Materials

Mechanical testing was performed to determine the material properties of the wall sections and the folding/unfolding characteristics of the creased regions. This used techniques previously developed by the authors [Hicks et al. 2004]. Overall material properties for the carton material were obtained from the results of previous studies [Mann et al. 1980, Baum et al. 1981] and through direct mechanical testing where necessary. These properties are summarised in Table 1.

The walls of the skillet were modelled as quadrilateral shell elements having non-isotropic material properties. The crease regions were modelled using hinge-type connector elements incorporating non-linear torsional stiffness. Mechanical folding and unfolding tests were performed on crease samples in order to determine the relationship between torque and angular displacement. The four creases interacted to produce an equilibrium state in which an initial separation between the long walls, termed “plim” in the carton industry, arose.

3.3 Interactions

Within the system model the vacuum cups were represented as circular rubber discs against which the skillet was held by a constant pressure load applied to the underside of the wall. Contact interactions incorporating a static/sliding friction formulation were applied between the walls of the skillet and the fixed backstop, the moving lugs, and the fixed horizontal rails of the packaging machine. These interactions are highlighted in Figure 2.

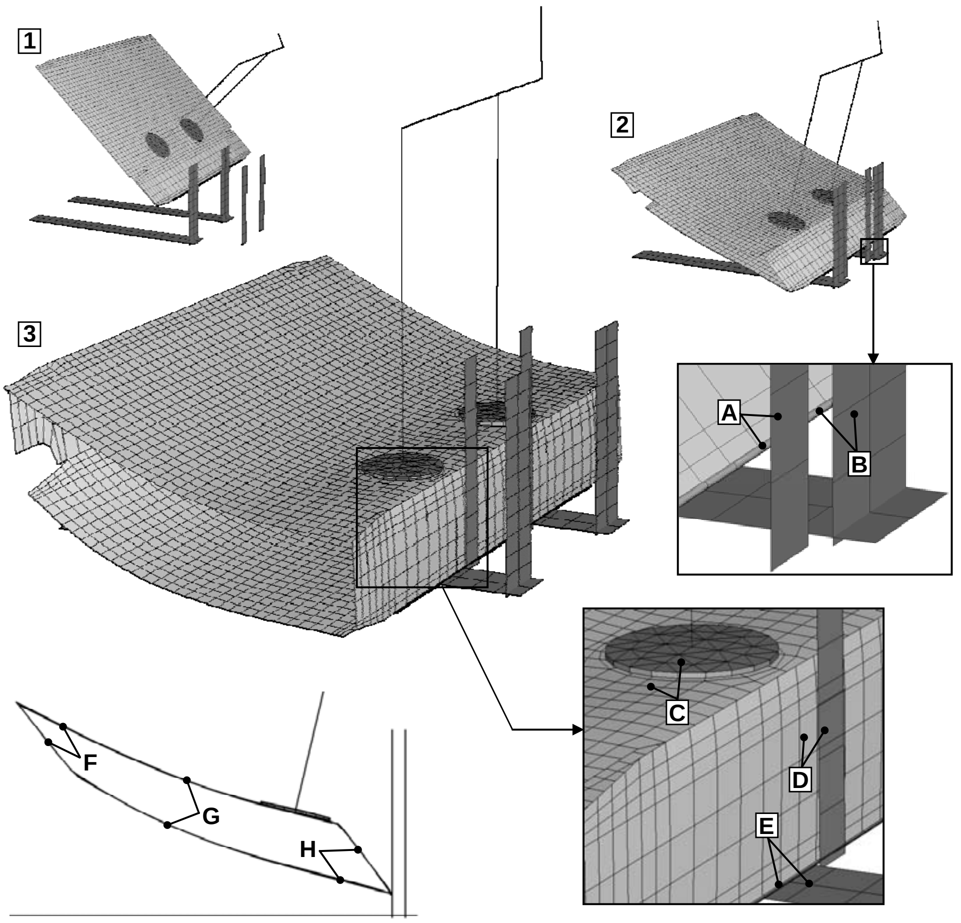


Figure 2. Views of the simulation at the start (1), mid-point (2) and at the end (3) of the conversion cycle. The five machine-material interactions are: (A) Crease on moving lug, (B) Crease on backstop, (C) Vacuum cups on upper wall, (D) Carton wall on moving lug, (E) Crease and lower wall on horizontal rails. Also shown are the three pairs of interacting surfaces on the interior of the carton (F,G,H)

Table 1. Overall material properties for the carton material. t=thickness, E=elastic modulus, G= shear modulus, ν=Poisson's ratio, μ_s, μ_d= static, dynamic friction coefficients

t [mm]	E_x [MPa]	E_y [MPa]	E_z [MPa]	G_{xy} [MPa]	G_{xz} [MPa]	G_{yz} [MPa]	ν_{xy}	ν_{xz}	ν_{yz}	μ_s	μ_d
0.415	5278.6	2606.0	20.7	2891.3	96.9	74.5	0.32	1.52	1.84	0.29	0.20

The effects of suction pressures which develop within the skillet as its walls separate were modelled using a contact damping formulation applied to internal wall surfaces. In this manner a negative pressure was developed as a function of both the separation between the surfaces and their velocity of separation. A peak suction pressure of 1000 Nm^{-2} per ms^{-1} was applied at zero separation distance, decaying linearly to zero at a separation distance of 3.0 mm. These values were estimated based upon the observed buckling behaviour of cartons during conversion.

4. Design analysis

As previously stated the design focus dealt with in this study involves the position of the vacuum cups (Figure 1 (2)). Preliminary studies revealed that the position of the vacuum cups has a significant impact on the latter stages of the process and in particular the point at which the skillet makes contact with the backstop (Figure 1 (5)) until the point of full opening. For the process considered successful processing is deemed to have taken place when the skillet behaves like a parallelogram mechanism, its cross section transforming smoothly from flat to rectangular. In contrast to this, under certain conditions, the skillet adopts an overall buckling mode. Buckling is deemed to have occurred if, by the point at which the moving lug has drawn level with the backstop, or the point at which the leading edge crease first contacts the horizontal rails (whichever occurs first), the carton walls have coalesced and, or the lower carton wall is hogging. In addition to qualitative observations of the deformed shape, it was possible to determine which of the two modes were adopted by monitoring the principal in-plane bending stress occurring in a small region of the lower carton wall

The simulation was performed for a variety of positions of the vacuum cups on the upper wall of the skillet. The position of the vacuum cup centres was adjusted over six equal increments starting at the leading edge of the skillet and moving toward the centre. In order to represent the fundamental limits the worst-case scenario pack condition was considered [Berry et al, 2005]. This is when the plim (initial separation) is 1.5 mm. For each vacuum cup position considered, simulations were performed at seven different process speeds in order to assess the sensitivity of each configuration to production rate.

The effect of vacuum cup position and production rate on the stress in the lower wall are shown in Figure 4. Figure 4a shows that at a production rate of 125 CPM, vacuum cup positions 1, 2 and 3 are characterised by an initial increase followed by a sharp decrease (e.g. A) in compression in the lower wall. For these three cases, the carton opened normally. However for positions 4, 5 and 6, the compressive stress increased sharply at the point at which the leading crease contacted the horizontal rails (e.g. B). This indicated an inward curvature of the lower wall and for these three cases buckling failure was observed.

Figure 4b shows that with the vacuum cups fixed in position 2, normal opening is achieved for production rates of 100, 125, 150 and 175 CPM. This is indicated by the sharp rise in tensile stress at point (A). From point (A) onwards, the lower wall of the carton was observed to bow outwards, thereby increasing the tensile stress in the outer surface of the wall. For production rates of 200, 225 and 250 CPM, the compressive stress increased sharply at the point of contact with the moving lugs (B), indicating that the inward curvature of the wall had increased and the structure had taken up a buckling mode.

Table 2 shows the bounds on performanc of the erection cycle with respect to vacuum cup position and production speed. Limiting cases are highlighted and represent configurations in which the simulation became unstable and terminated before it was possible to determine which mode had been adopted.

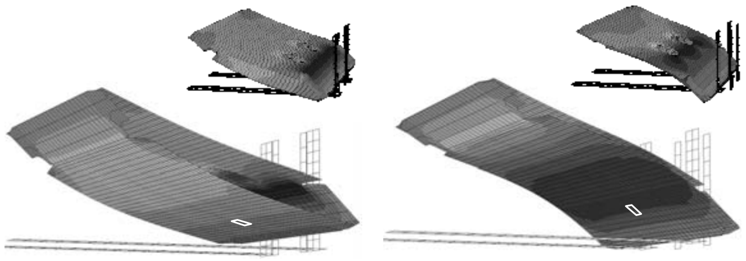
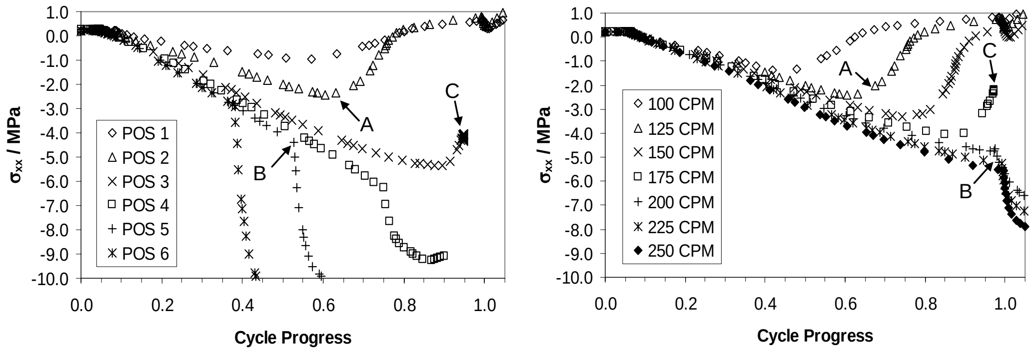


Figure 3. Deformation behaviour and in-plane principal bending stress distribution for two vacuum cup positions at 125 CPM. Darker shading indicates higher compressive stress. Sampling region used to create graphs shown in Figure 4 is highlighted in white. With vacuum cups in position 2, the carton opens normally (a) but when moved to position 4, a buckling failure occurs (b)



(a) (b)

Figure 4. Variation in principal in-plane bending stress (tensile +ve) for six different vacuum cup positions at a production rate of 125 CPM (a) and seven different production speeds at vacuum cup position 2 (b). The point 1.0 on the x-axis refers to the point at which the moving lugs draw level with the backstop. Points A = typical behaviour at onset of normal opening. B = typical behaviour at onset of buckling failure. C = points at which the solution became unstable and terminated before it was possible to determine whether normal opening had occurred

Table 2. Summary of simulation outcomes

Speed (CPM)	Vacuum Cup Location					
	1	2	3	4	5	6
100	■	■	■	■	□	□
125	■	■	▨	□	□	□
150	■	■	□	□	□	□
175	■	▨	□	□	□	□
200	■	□	□	□	□	□
225	■	□	□	□	□	□
250	▨	□	□	□	□	□

■ Normal opening
▨ Unstable solution
□ Buckling failure

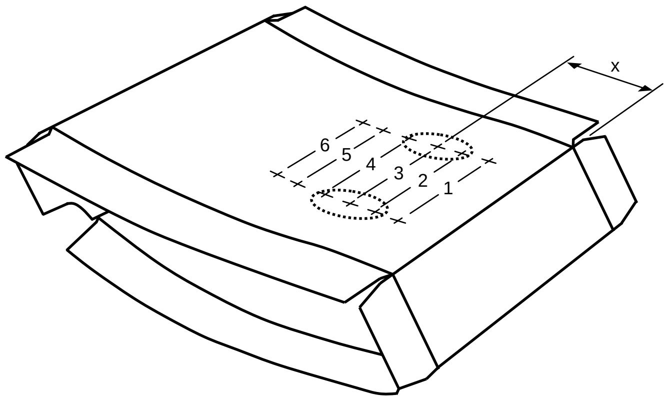


Figure 5. For the six vacuum cup positions tested, the computer simulation predicted that for a given rate of produciton, the likliehood of buckling failure diminished as distance x became smaller

5. Design rules

The work has shown that tooling design and machine setup has a significant impact on the efficacy of the carton conversion process. Different manufacturers tend to adopt different strategies for positioning the vacuum cups on their machines since there is a lack of objective analysis of the relevant machine-material interactions. The results of this study however tend to dispute the practice of placing the vacuum cups a fixed distance from one end of the carton wall or proportionally at a predetermined location along the carton, and instead support positioning that is as near as possible to one end (see Figure 5). With such an arrangement, buckling failure is less likely to occur and furthermore, the bending stress in the lower carton wall is minimised. From a production point of view, this allows higher rates of production to be achieved and increases the tolerance of the conversion process to cartons that are in poor condition.

In addition to determining the required setup for maximising production rate, the results of the simulation can be used to determine the production envelope available for a different size carton without changing the setup of the feed hopper. Such knowledge will increase productivity further by allowing unnecessary changeovers and setting adjustments to be eliminated.

This paper has demonstrated the use of the model in investigating the effect of a change in a machine setting. However, it is also possible to generate design rules that relate machine design and variation in material properties such as crease and wall stiffness, as well as pack geometry.

6. Conclusion

Much of today's machinery and processes are governed or even limited by machine-material interaction. The importance of understanding these interactions for improved design has been highlighted and the need to develop models to represent interactions and explore design changes has been presented. In order to illustrate the creation of a model that represents machine-material interaction and the generation of design knowledge from this model, an industry based case study is presented. This case study involves the process of carton conversion. which is becoming increasingly unpredictable due to a reduction of favourable material properties imposed by recently-tightened packaging legislation. The system model was used here to perform a systematic study of variation in a critical machine (design) parameter that was found to directly affect the efficacy of the conversion process. As a result, quantitative design knowledge was gained regarding the setup and tooling design of the packaging machine. While previously trial and error has been used to determine such design knowledge, in today's fast-moving production environments this approach is becoming increasingly less economically viable. Therefore there exists an increasing need to determine this knowledge offline through computer simulations such as that reported in this paper.

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