ROBUSTNESS OF A MODEL PREDICTING DROP-TESTING PERFORMANCE OF FRUIT PACKS

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SUMMARY

In an earlier investigation a numerical model was defined which summarized the effects on apple packs of multiple drops from different heights. The results suggested that a given package-type could be associated with a "package constant", *k*, characteristic of the package and independent of the drop height and the number of drops. The effect on *k* of change in experimental conditions and material is investigated; it is shown that the model is remarkably robust under such changes, and is equally applicable to pears. The results suggest, however, that *k* may be affected by flesh firmness and state of maturity of the fruit, and this possibility requires further specific investigation. Two methods of calculating *k* are described and compared, and restrictions on the calculations noted; the methods are shown to be in good agreement.

I. INTRODUCTION

The prevention of fruit bruising by adequate package performance to resist the handling environment is of importance to all people concerned with marketing top quality fruit. The prediction of bruising of fruit by dropping boxes from drop heights and number of drops expected in the handling process would enable analysis of whether package performance should be improved or handling hazards reduced in severity. For particular fruit it will then be possible to calculate the cost of alternative packaging or handling procedures.

Schoorl and Williams (1972) described a mathematical model whereby the percentage of apples bruised by dropping boxes could be predicted from the height of the drop in inches, the number of drops, and a "package constant", *k*, which took the value of 0·05 for cases and 0·02 for tray cartons. The concept of a single parameter for summarizing package performance is extremely attractive, but before it can be used with confidence it is essential to investigate the extent to which the value of *k* is invariant under change of experimental conditions and material. There are, in particular, three factors which might be expected to influence the observed value of *k*.

(i) *Variety*.— The results of Schoorl and Williams (1972) suggested that there was no evidence of varietal difference between Jonathan and Delicious apples in packed boxes. However, Mohsenin *et al.* (1962) and Hyde and Ingle (1967) reported that different varieties of apples behave differently in terms of mechanical properties (permanent deformation and energy values at point of bruising) and of size of bruise resulting from impact. There is a discrepancy here which calls for re-examination. Furthermore, it would be of great interest to ascertain whether the model still holds for fruit, such as pears, which are morphologically similar but taxonomically more remote.

(ii) *Fruit condition.*— Fridley and Adrian (1966) reported that, with change of maturity, there is great variation in flesh firmness with peaches and pears, but little with apples. Moreover, the "impact yield" energy required to bruise fruit was found to be markedly dependent on flesh firmness for pears and peaches, but was relatively constant for all flesh-firmness conditions for apples. It might therefore be expected that k would be dependent on degree of maturity in pears, though possibly not in apples.

(iii) *Drop-tester type.*— The drop tester used by Schoorl and Williams (1972) consisted of a rotating cam lifting a package-holder through an arc; when the cam had rotated sufficiently, the package holder fell on to a base. Holt and Schoorl (1973) have recently listed a number of types of drop-machines for impacting boxes, and in particular report on a drop-machine consisting of a platen guided down by rails. The type of machine used might be expected to influence the degree of bruising of fruit, because of differences in the shock characteristics of the impacting surface, and in the flatness of the package drop. This in turn would be expected to influence the observed value of k.

In this communication we report the results of a series of experiments aimed at ascertaining the sensitivity of k to variations in experimental conditions or material. We shall be particularly concerned with (a) a re-examination of the effects of variety, (b) the effect of flesh firmness, (c) the effect of drop-tester type, and (d) the extension of the original numerical model to pears. It should be noted that whereas in our previous paper we were concerned to predict the degree of bruising, in this case we are concerned with the estimation of k. We shall show in the next section that the latter approach poses new numerical problems.

II. THEORETICAL CONSIDERATIONS

If y is the percentage of fruit bruised, h the height in inches, x the number of drops, and k the package constant, the model used by Schoorl and Williams (1972) was

$$\ln (y/(100 - y)) = 2 - 2/(kh + 0 \cdot 2) + 1 \cdot 0818 \ln x \quad \ldots \quad (1)$$

However, this expression was the outcome of a double fitting procedure, the two steps in its formulation being summarized as follows:—

$$\ln (y/(100 - y)) = \ln a + b \ln x \quad \ldots \quad (2)$$

$$(\ln a)/(A - \ln a) = k_1 + k_2 h \quad \ldots \quad (3)$$

where b was found by regression techniques to be $1 \cdot 0818$, k_2 is our package constant k, and A and k_1 were found by sweep techniques to be $2 \cdot 0$ and $-0 \cdot 8$ respectively. In the previous exercise we were concerned, given A, b, k_1, x, h and y, to estimate k_2.

We first note that the original failure to find any evidence of varietal difference was based on an analysis of variance of the values of ln a from expression (2), where the main effects were height, package type, and variety; the variety mean square was not significant. However, it will be clear from expression (3) that ln is a function of A, k_1, k_2 and h; and it was later found possible to choose values for A and k_1 which were invariant over the entire system. It follows that ln a may be expected to vary less than k_2; moreover, if A and k_1 are declared as invariant from the start all the uncontrolled variation will appear in k_2, which may then exhibit a varietal difference.

There are two possible methods of calculating k_2. The first is to accept expression (1) and, for every observation, calculate k ($= k_2$) by substitution. This would have the advantage that any experiment would provide a series of values of k, so k would be associated with a mean and standard error that would be available for statistical manipulation. Unfortunately, there is also a serious disadvantage. The original curve is asymptotic to 100%; it follows that the calculation of k from observations of high damage would be ill-conditioned, in that small errors in observation would produce large errors in k. In fact, k could apparently become infinite, or even pass through infinity and change sign. It would be possible to "trap", and reject, implausible values of k; but this would introduce a subjective element into the investigation, since it is tantamount to assuming in advance the approximate range within which k must fall. Nevertheless, because of its statistical advantages, we have carried out explanatory calculations by this method. The "trap" used was as follows. We write X for $1 \cdot 0818 \ln x$, and Y for $\ln (y/100 - y))$; we define a quantity such that $D = 2/(2 + X - Y)$; and we reject any observation which does not meet the criterion $0/2 < D < 1 \cdot 5$.

The second method of calculation of k is to take a complete set of results, and to sweep over a range of values of k, selecting that which gives the closest agreement between the observed and calculated value of y, Two simple criteria for closeness of agreement are avaliable. The first is the correlation coefficient between y (calculated) and y (observed), which we have used in our earlier work. However, the correlation coefficient is somewhat sensitive to outlying values at the extremes of its range, and we have come to prefer the root-mean-square percentage error: if d is a difference between an observed and calculated value, and there are n observations, we calculate and minimize $(d^2/n)^{\frac{1}{2}}$. This method of calculating k obviates the need for trapping aberrant values, but it has the concomitant disadvantage that, if the data contain many examples of high percentage bruising, k is liable to be over-estimated.

III. MATERIAL AND METHODS

The fruit used were Jonathan and Delicious apples of $2\frac{3}{4}$–$2\frac{7}{8}$ in. in diameter, and Packham pears of $2\frac{7}{8}$–3 in. in diameter; they were obtained from a commercial packing house, care being taken to select only bruise-free fruit. Two types of pack were used for apples; the first was Anon. (1970) tray-pack cartons of internal dimensions $19\frac{3}{4}$ in. x $11\frac{7}{8}$ in. x $11\frac{1}{2}$ in.; and the second was pattern-packed wooden bushel cases of internal dimensions 18 in. x $11\frac{1}{2}$ in. x $10\frac{1}{2}$ in. Three types of package were used for pears; these were pattern packed, tight-fill and volume-fill telescopic cartons of internal dimensions 18 in. x $11\frac{1}{2}$ in. x $8\frac{1}{2}$ in. (Anon. 1970; Mitchell *et al.* 1968). The tight-fill and volume-fill were packed from pattern-packed cartons just before dropping experiments.

Packages were subjected to a number of flat drops from various heights in randomized trials. The equipment used was that described by Holt and Schoorl (1972); it consisted of a platen guided down by rail with the platen impacting a solid rubber shock programmer. The packages were strapped onto the platen before dropping. Details of heights and numbers of drops used are included in the reports of individual experiments in the next section.

Bruise assessment on each fruit was conducted 3–4 days after dropping, a wedge section being taken out of the bruised area by a sharp knife. The largest bruise on the fruit was measured for the maximum diameter and depth of bruise.

A fruit was considered “bruised” when a bruise of 0·8 in. diameter and 0·2 in. depth was present in either apples or pears, or if either dimension exceeded these values. The data used for calculations were the percentage fruit bruised under experimental conditions.

IV. EXPERIMENTAL RESULTS

(a) Apple-dropping Experiments

(1) Re-examination of 1971 Results

Our previous exercise (Schoorl and Williams 1972) used two varieties of apple (Jonathan and Delicious) and two package types (cases and cartons); the drop-tester was the rotating-arc type. These data were re-examined from the point of view of the determination of *k*. The basic relationship (expression (1) of Section II above) was accepted, and *k* calculated by the two methods outlined in that section. Method 1 was the back-calculation of individual values of *k*, aberrant values being “trapped” and rejected; method 2 was the “sweep” method, with the root-mean-square percentage error criterion for agreement. The results are given in Table 1; their discussion will be deferred until after presentation of the 1972 results.

TABLE 1

Values of *k* Calculated by Two Methods for Two Varieties of Apple and Two Package Types in Two Years

Parameter	Cases		Cartons	
	Jonathan	Delicious	Jonathan	Delicious
1971 Experiments				
Method 1				
k (mean)	0·049	0·065	0·022	0·026
Standard error of mean	0·0033	0·0052	0·0010	0·0016
No. observations accepted	20	20	32	32
No. rejected	16	12	2	2
No. > 85% damage	17	15	6	6
Method 2				
k	0·048	0·059	0·021	0·024
r.m.s. error	6·25	11·01	8·62	10·48
1972 Experiments				
Method 1				
k (mean)	0·040	0·037	0·030	0·026
Standard error of mean	0·0025	0·0014	0·0013	0·0012
No. observations accepted	25	22	29	23
No. rejected	7	2	3	0
No. > 85% damage	10	3	6	0
Method 2				
k	0·040	0·037	0·028	0·024
r.m.s. error	12·43	7·90	6·98	7·12

(2) 1972 Results

The experimental design was of the same two varieties, dropped from 5 heights at the following numbers of drops: 6 in. and 12 in., 1, 3, 9 and 27 drops; 18 in., 1, 3, and 9 drops; 24 in., 1 and 3 drops; 48 in., 1 drop. Each observation was replicated once. The drop-tester was the falling platen type; *k* was again calculated by both methods, and the results are included in Table 1.

(3) Discussion

Comparison of methods of calculation.—The two methods are in remarkably good agreement. In 6 out of the 8 pairs of values, the method-1 result is marginally higher; the mean difference is 0·0018, and is significant at the $P<0{\cdot}05$ level ($t = 2{\cdot}60$ with 7 d.f.). However, the bulk of the difference lies in the single large discrepancy associated with 1971/Delicious/cases, and for all practical purposes the methods can be regarded as true alternatives; the method-1 result then has the considerable advantage that it provides, for each condition, a replicated set of k values which can be used for statistical comparison. It should be noted, however, that the standard errors are abnormally low; the experiments are, from this point of view, over-replicated and a fairly stringent test of significance will be desirable.

Effect of high percentage damage.—The table shows the number of observations rejected by the method-1 "trapping" procedure, and also the number of observations with more than 85% bruising. The two sets of figures are in substantial agreement; this suggests that 85% would be an acceptable upper limit for the degree of bruising that can safely be used for the determination of k, though "trapping" will still be necessary.

Comparison of k values.—The method-1 values have been compared in all possible pairs by a t-test. As expected, all but 4 of the 28 comparisons are significant at at least the $P<0{\cdot}05$ level, and for clarity we have therefore elected to work at the $P<0{\cdot}01$ level. The individual t values are of no intrinsic interest, and only the level of significance is shown in Table 2.

TABLE 2

STATISTICAL COMPARISON OF k VALUES FROM METHOD 1 CALCULATIONS

	Cases				Cartons			
	1971		1972		1971		1972	
	Jon.	Del.	Jon.	Del.	Jon.	Del.	Jon.	Del.
Cases								
1971 Jonathan ..	−	−	−	+	++	++	++	++
Delicious ..	−	−	++	++	++	++	++	++
1972 Jonathan ..	−	++	−	−	++	++	++	++
Delicious ..	+	++	−	−	++	++	+	++
Cartons								
1971 Jonathan ..	++	++	++	++	−	−	+	+
Delicious ..	++	++	++	++	−	−	−	−
1972 Jonathan ..	++	++	++	+	+	−	−	−
Delicious ..	++	++	++	++	+	−	−	−

Key:	
$P > 0{\cdot}01$	−
$0{\cdot}001 < P < 0{\cdot}01$	+
$P < 0{\cdot}001$	++

We first note that the superiority of cartons over cases is amply confirmed; for both years and both varieties the difference is highly significant, with an overall mean of 0·048 for cases and 0·026 for cartons. We further note that, at the level we have chosen to work, there is within any one year no varietal difference, either for cases or for cartons. There are, however, significant inter-year differences; and comparison of Tables 1 and 2 shows that these are due to the abnormally high value for 1971/Delicious/cases (and, to a less extent, the high value for 1971/Jonathan/cases) and to the abnormally low value for 1971/Jonathan/cartons. In these experiments the effect of year is confounded with type of drop-tester.

We have carried out a small-scale comparative trial of the two testers (1972/Delicious/cartons; 24 in., 1 drop, 3 replicates); the values of k obtained were 0·016 for the rotating-arc tester and 0·026 for the falling-platen tester. This result suggests that the inter-year carton difference may well be attributable to the drop-tester used. It has not been practicable to carry out a similar test with cases, and the possibility that the rotating-arc tester may give higher values of k for cases must remain open.

There is, however, also the possibility of an effect due to flesh firmness. The 1972 apples were examined by the Magnus Taylor pressure-tester with $\frac{5}{16}$ in. tip; the results were Jonathan 9·0 lb., Delicious 11·0 lb. No firmness data were available for the 1971 apples, but observation suggested that the firmness would have been comparable to the 1972 Jonathan, i.e., 9·0 lb. The 1972 Delicious was an exceptionally firm apple, and the marked fall in k from 1971 to 1972 may well reflect this. Furthermore, the 1972 Jonathan were showing signs of internal breakdown, which may similarly have been partly responsible for the rise in Jonathan/cartons. We suggest that in future investigations more attention should be paid to firmness, and to other mechanical properties such as sheer stress (Miles and Rehkugler 1971; Horsfield, Fridley and Claypool 1970).

(b) Pear-dropping Experiments

The drop-heights and numbers of drops used were identical with those for the 1972 apple experiments (see A.2 above); all three package types were processed as before on the falling-platen drop-tester. However, referring to Section II above, we can no longer assume that expression (1) will hold, for this assumes values of the three parameters A, b and k_1 in expressions (2) and (3). As a first step, therefore, we took the entire set of results and carried out a quadruple sweep over plausible ranges for these three parameters and k_2. As with apples very high values of the calculated/observed correlation coefficients ($r > 0 \cdot 9$) were obtained with $A = 2 \cdot 0$, $b = 1 \cdot 1$, $k_1 = 0 \cdot 8$. It follows that expression (1) is equally applicable to pears.

TABLE 3

VALUES OF k FOR PEARS

—	Pattern Pack	Tight-fill	Volume-fill
Method 1			
k (mean)	0·016	0·016	0·031
Standard error of mean	0·0022	0·0017	0·0018
Method 2			
k	0·016	0·019	0·031
r.m.s. error	14·81	9·21	11·29

The values for k ($= k_2$) for three package types calculated by both methods are given in Table 3. It will again be observed that the two methods of calculation are in good agreement. The volume-fill pack is clearly inferior to both the others; its k value lies about midway between the 1972 cases and cartons values for apples, and at the $P < 0 \cdot 01$ level does not differ significantly from either. The values for the other two packs are remarkably low, and are in fact highly significantly lower than the best values obtained for apples in the main experiment. It follows that, although pears are as sensitive as apples to the *number* of times they are dropped (since b is unchanged), they are less sensitive in the better packs to the height from which they are dropped.

V. CONCLUSIONS

The most gratifying feature of these results is the evident robustness of the numerical model originally proposed; it remains applicable when the type of drop-tester is changed, and is as satisfactory for pears as it is for apples. There seems little doubt that the concept of a single "package constant" is viable; the results do suggest, however, that the mechanical condition—i.e. the stage of maturity—of the fruit is more important than has hitherto been realized, and this possibility requires more critical examination by experiments specifically designed to this end.

The two theoretically possible methods of calculating the package constant are in such good agreement that either can safely be used in practice. However, the method of direct back-calculation has the double advantage that it produces a string of replicated values, and is fairly easily amenable to hand-calculation. The results also suggest that the calculation of k becomes ill-conditioned in the region of 85% bruising, and future experiments should be designed so that this figure is not exceeded.

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