Monitoring of Eggshell Breakage and Eggshell Strength in Different Production Chains of Consumption Eggs

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ABSTRACT We first tried to monitor the critical points for eggshell breakage in different logistic chains. Second, we examined whether there was a difference in eggshell strength among eggs produced in different housing systems. Finally, we developed a model to investigate the relation between eggshell strength and the likelihood of an egg cracking during handling and grading. Four logistic chains with different housing systems (battery cages, furnished cages, aviary, and free-range), all housing Bovans Goldline chickens in their mid-lay (45 wk), were compared. In every chain, a randomized set of 1,500 eggs was sampled, and the strength was defined. At every critical point in every logistic chain, the eggs were reexamined for breakage. The classic and furnished cage systems showed the highest percentage of breakage directly at point of lay (6.73 and 10.72%), whereas the other systems showed lower breakage (1.94% in the aviary and 1.99% in the free-range system). Further, in the logistic chain, grading and packing of the eggs generated the second highest percentage of breakage (from 1.50 to 2.65%). Breakage due to transportation ranged from 0.16 to 2.65%. There was a significant difference among the eggshell strength (shell stiffness and damping ratio) of eggs from chickens in different housing systems, showing eggs from chickens in the aviary system to be stronger than cage eggs (classic and furnished) and free-range eggs to be weaker than the other eggs. A significant correlation was found between eggshell strength and the likelihood of breakage in the production chains. In conclusion, it was first shown that, besides the laying, packing of the eggs is a critical point in the logistic chain of consumption eggs; second, the strength of the eggs in the different housing systems differed, and, finally, the eggshell stiffness and damping ratio of consumption eggs are an acceptable measure for rapid eggshell quality assessment and could provide a good predictive value for eggshell breakage in all types of table egg production chains.

Key words: eggshell strength, eggshell breakage, production chain, consumption egg

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INTRODUCTION

The eggshell is the natural packing material for the egg contents, and as a result, it is important to obtain high shell strength, to resist all impacts an egg is subjected to during the production chain (Bain, 1990). Broken eggs cause economic damage in 2 ways: they cannot be sold as first-quality eggs, and the occurrence of hair cracks raises the risk for bacterial contamination of the broken egg and of other eggs when leaking, creating problems with internal and external quality and food safety.

Eggshell strength is generally measured using either direct tests, such as nondestructive deformation (Voisey and Hunt, 1974) or destructive fracture force (Voisey and Hunt, 1967a,b) of an egg under quasistatic compression between 2 parallel plates, or indirect tests, such as the measurement of eggshell thickness (Brooks and Hale, 1955; Voisey and Hamilton, 1976; Ar et al., 1980; Thompson et al., 1981; Bell, 1984; Hunton, 1993) or specific gravity (Olsson, 1934). Many of these methods, however, are destructive, slow, or subject to environmental influences and, hence, are regarded as being unpractical.

Coucke (1998) presented a fast, objective, and nondestructive method for the determination of the eggshell strength, based on acoustic resonance analysis. This technique measured the resonant frequency (**RF**) of the egg and its damping ratio. Based on the RF and the egg weight, the dynamic shell stiffness (**K_{dyn}**) was defined. This technique can also be used to detect cracks in the eggshell (Coucke, 1998; Coucke et al., 1999; De Ketelaere et al., 2000).

Several authors have since shown that the K_{dyn} is a useful eggshell quality measurement. De Ketelaere et al. (2002), for example, investigated the variation of this

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strength parameter in relation to certain production parameters. They proved that, although feed has a major impact on the K_{dyn} measurement, differences among various commercial layer lines exist and are at least as important. A small-scale experiment of Lin et al. (2004) also indicated a decline of K_{dyn} as a result of heat stress. Both Coucke et al. (1999) and De Ketelaere et al. (2002) also found an acceptable correlation between the measurement of K_{dyn} and other measures of eggshell quality, including static stiffness (0.84 and 0.76, respectively) and shell thickness (0.78 and 0.75, respectively). Dunn et al. (2005) reported that K_{dyn} also has a high heritability (0.53) and a high genetic correlation with eggshell breaking strength (0.49), which implies that this measure may be a useful trait in selection programs aimed at improving shell quality. Finally, Bain et al. (2006) showed that K_{dyn} provides a good estimation of eggshell strength in relation to the likelihood of breakage in practice.

This creates the opportunity to use K_{dyn} as a new eggshell quality parameter in breeding programs. Because most deformations that cause the eggshell to break in practice are dynamic, this might lead to an increased selection response compared with the classic static techniques, but it still needs to be proven.

Among others, Wells (1967), Bowman and Challender (1963), Thompson and Hamilton (1986), and, mainly, Charles and Strong (1988) investigated the relationship between some measures of shell quality (specific gravity, breaking strength, shell thickness, percentage of shell and shell weight per unit of surface area) and egg breakage in practice. Charles and Strong (1988) assumed that when housing, management, feeding, and the commercial line of the hens were similar, differences in percentage of cracks were primarily due to differences in shell strength. They found that specific gravity and percentage of shell were correlated with percentage of cracks. Also, Britton (1978) investigated the relationship between shell quality, determined by the shell deformation method, and breakage on filler flats. He reported much higher breakage with high shell deformation (poor shell). Thompson and Hamilton (1986), however, stated that defining these traditional measures does not provide adequate prediction of shell breakage during commercial processing.

Thompson and Hamilton (1986) stated that most eggs are broken during transportation, rather than any other step during processing and distribution. Monitoring eggshell breakage in the complete logistic chain from the production unit to the table, however, should include an estimate of breakage in the laying house. Among others, Abrahamsson et al. (1995), Abrahamsson and Tauson (1995, 1998), Leyendecker et al. (2001), Wall and Tauson (2002). and Guesdon and Faure (2004) presented differences in egg quality and the proportion of broken eggs for different housing systems (battery cages, furnished cages, aviary). However, to date, no results are available on possible differences in initial shell strength of eggs produced in these different types of system and how this relates to the incidence of breakage in the rest of the production chain.

The main aim of the research presented in this paper was to monitor the percentage of eggshell breakage in 4 different production and logistic chains, from laying to final destination, to reveal critical points at which breakage occurs. Second, we were interested to see whether there was a difference in eggshell strength (K_{dyn}) and the damping ratio among eggs produced in different housing systems, which could account for any difference in the percentage of breakages. Third, based on the results of Bain et al. (2006), who found encouraging results on the predictive power of K_{dyn}, the data from each system were used to develop a model to investigate the relation between the initial shell strength, defined by K_{dyn}, and the damping ratio and the likelihood of an egg breaking during routine handling and grading.

MATERIALS AND METHODS

Logistic Chains Four different logistic chains for the production of table eggs were investigated. Table 1 gives a summary of the logistic chains and sampling points used in our study. The main difference among each of these chains was the housing system from which the eggs originated: classical battery cages, furnished cages, the aviary, and a free-range system. To minimize bird differences among houses, only farms with Bovans Goldline hens in their mid-lay period, 47 wk of age, were used in our study. The experiments were carried out within a period of 3 wk to minimize seasonal effect. The effect of different feeds could not be controlled, as the farms were all commercial units, but it can be assumed that the basic formulation of different commercial feeds was comparable. For the same reason, effects of other parameters, such as management, stable climate, and health status of the hens, could not be excluded. In our analysis, these parameters were taken together under 1 general parameter, the housing system.

In the first chain, a total of 28,800 hens were housed in a Specht 4-tier battery cage system (Specht-TenElsen GmbH, Sonsbeck am Niederrhein, Germany). The hens in this system were fed with feed A. The eggs in this system were transported out of the hen house on a rubber conveyor belt and were then collected by a belt consisting of coated iron bars, rolling in a direction perpendicular to the rubber belt. In this way, the eggs were conveyed into the egg storage room, next to the hen house, where the eggs were automatically collected and packed in cardboard trays of 30 with a Moba farmpacker (MOBA b.v., Barneveld, The Netherlands). These trays were then stacked up in piles of 6, which were placed in a rolling container. Such a rolling container can be considered as an open iron cupboard on wheels with 5 shelves (65×95 cm with 40 cm intershelve space) and can contain 180 trays in total. This container was the mean to transport the egg trays to the packing station where they were sorted by weight class and packed in commercial cardboard boxes of 6 eggs. These small boxes were put into a large cardboard box of 120 eggs, in which they were transported to the retail store.

Table 1. Survey of the different operations from which each logistic chain consists[1]

Item	Chain 1 (Battery cages)	Chain 2 (Furnished cages)	Chain 3 (Aviary)	Chain 4 (Free-range)
Housing	[K_{dyn}, % crack]	[K_{dyn}, % crack]		
Egg collecting	[% crack]	[% crack]	[K_{dyn}, % crack]	[K_{dyn}, % crack]
Transport to packing station	[% crack]	[% crack]	[% crack]	[% crack]
Grading and packing	[% crack]	[% crack]	[% crack]	[% crack]
Transport to central depot of department store	X	X	X	[% crack]
Transport to retail	[% crack]	[% crack]	[% crack]	[% crack]

[1]X = the absence of the operation in the chain; the measurements performed in each operation are noted between brackets. K_{dyn} = dynamic shell stiffness.

In the second chain, the housing system consisted of furnished cages, equipped with perches, a laying nest (with synthetic grass mats as laying nest material), and a scratching space. Dimensions and occupation of the cages (by the 2,460 hens) met the European standards (average of 40 hens/cage). The eggs were transported into the egg storage room by a standard Specht (Specht-TenElsen GmbH) conveyor belt. To encounter the different levels of the cages, a collecting lift brought the eggs to the level of collecting (1.20 m). The eggs were then manually collected and packed into cardboard trays of 30 eggs. Similar to the first chain, these trays were stacked in a rolling container for transport to the packing station where the eggs were sorted by weight and packed with 12 in each cardboard box. For transportation to the retail store, these small boxes were put into a large cardboard box of 180 eggs.

The aviary, in the third chain, was divided into 4 compartments, each housing 500 hens. The laying nests, with Astroturf XPNP laying nest material (Jansen Poultry Equipment, Barneveld, The Netherlands), were located on the 2 lateral sides of the compartments. At the back of the nests, the slanting surface came out on a perforated conveyor belt that transported the eggs into the egg storage room. These perforations of the belt minimized egg rolling and interegg contacts. From this point on, the eggs from the aviary followed the same track as the eggs from the furnished cages, with the distinction that they were packed into small boxes of 6.

The furnished cages housing system and the aviary were located at the same farm and in the same building. The hens in the furnished cages and half of the hens in the aviary were fed the same feed (feed B), yet for the other half of the hens in the aviary, a supplement of corn cob mix was added to feed B (feed C). The housing in the last chain was a free-range system with 13,500 layers. Every day from 1100 h untill dusk, the hens had access to an outside free-range meadow. The hens were fed with feed D.

In the hen house, 2 rows of laying nests (with Astroturf XPNP laying nest material) were placed at a height of 67 cm. At the back of the nests, the slanting surface came out on the conveyor belt that transported the eggs out of the hen house into the egg storage room. This conveyor belt was perforated with holes to minimize egg rolling. After arrival in the storage room, the eggs were collected and packed manually in trays of 30, put into rolling containers, transported to the egg packing station where they were first sorted by weight, and then packed in groups of 4 into small cardboard boxes. These were put into large boxes of 120 eggs. As these eggs were destined for sale in a large department store, the boxes with the eggs were first transported to a central depot before final transportation brought them to the store.

Measurement Points

In each chain, there were 5 measuring points, except for chain 3 (aviary), which had only 4. In the first measurement point (as early as possible in the chain), a sample of 1,500 test eggs was randomly picked throughout each housing system. A power analysis was carried out to calculate this sample size for the detection of a difference of 1% in the percentage of breakage among the investigated chains. As shown in Table 1, this first measurement point differs for the different logistic chains. In both the classical and furnished cage system, this point is situated directly after laying. While in the aviary and free-range system, the first measurement point is situated after collecting the eggs, which gives an additional risk for breakage caused by the collecting system. The reason for this difference in initial measurement point was the fact that it was practically impossible to take the eggs out of the laying nests in the last 2 systems. Further measurements were carried out in each subsequent operation of every chain, as shown in Table 1.

Measuring Method

In the first measurement point (as early as possible in the chain), a sample of 1,500 test eggs was randomly picked throughout each housing system. The collected eggs were numbered (with reference to their origin) and tested with a crack detector. This crack detector used the acoustic resonance technique to derive the RF of the egg. This RF was then evaluated to detect cracks in the eggshell. (De Ketelaere et al., 2000). Subsequently, K_{dyn} and the damping ratio of the intact eggs were measured as described by Coucke (1998) and Coucke et al. (1999). The damping ratio is derived directly from the RF, whereas the K_{dyn} is calculated using a formula that combines the RF and the egg weight. The intact eggs were then placed back in the chain and followed the rest of the chain, along with the remaining untested eggs of that day's production. Here the same test eggs were retrieved, and the percentage of cracked eggs was calculated. All cracked eggs were removed, and the remaining intact test eggs again continued their journey along with the untested eggs. This process was repeated until the eggs had reached the end of the logistic chain.

Statistical Analysis

Statistical analysis of the data was performed using SAS Version 8.2 (SAS Institute Inc., Cary, NC). For the investigation of the possible effect of housing system on K_{dyn} and total breakage percentage, a GLM was applied, treating housing system as covariate and K_{dyn} or total breakage percentage as dependent variable. For breakage percentage, an arcsine transformation was applied first. An overall F-test was performed and, if significant differences were noticed, was followed by a post hoc test correcting for multiple comparisons (Tukey's multiple comparison procedure). To check for significant differences among operations in a chain and among the chains in an operation, the Marascuilo procedure for comparison of multiple proportions was used.

To check whether the initial K_{dyn}, damping ratio, and, eventually, their crossproduct had any predictive capacity for egg breakage in the logistic chain, a logistic regression was used. A Hosmer and Lemeshow goodness-of-fit test was performed to assess model adequacy. The logistic regression model fits the log of the odds as a function of the explanatory variables (Hosmer and Lemeshow, 1989)

$$\log it(\pi) = \log(\pi/1 - \pi)\ \alpha_i + \sum_{j=1}^{m} \beta_i X_{ij} + \sum_{j=1}^{m}\sum_{k=1}^{m} \beta_{jk} X_{ij} X_{ik}$$

where X = the explanatory variables (e.g., K_{dyn}, damping ratio); j and k = the number of the explanatory variable; π = the probability defined by the proportion of cracked eggs, given a set of m explanatory variables (K_{dyn}, damping ratio, $K_{dyn} \times$ damping ratio); α_i = the intercept parameter for logistic chain i; β_j = the slope parameter for the jth explanatory variable; and X_j = the observation for the jth explanatory variable. The odds are defined as the ratio of the probabilities of event (cracked) to nonevent (not cracked). The odds ratio is calculated by exponentiating the parameter estimate for the explanatory variable (Agresti, 1996). An odds ratio can range from 0 to infinity. A value of 1 indicates that the variable has no influence on the incidence of the disorder. For this analysis, a global data set was made consisting of the 4 separate datasets from the 4 logistic chains. The effect of housing system was incorporated into the model by allowing each housing system to have a different intercept in the logistic regression model (α_i). This allows for a shift in the shell strength – breakage curve, to incorporate possible different input levels in the different logistic chains. However, the slope coefficients (β_j) were chosen to be independent of housing system, because it is assumed that, overall, a unit increase in shell strength, given the housing system, will result in a fixed probability change of breaking.

To compare the percentages of cracked eggs in the different measurement points of the different chains, and to compare values for egg weight, K_{dyn}, and damping ratio, a GLM was used.

RESULTS

Critical Points for Breakage

When analyzing the egg breakage in the different chains, the classical and furnished cage systems (chains 1 and 2) showed a relatively high percentage of breakage after lay, 6.73 and 10.72%, respectively. Furthermore, the collecting belts in chain 1 generated an extremely high percentage (36.85%) of broken eggs due to technical problems. The aviary and free-range system (chains 3 and 4) (1.94 and 1.99%) had a similar total breakage after collecting the eggs. As shown in Table 2, grading and packing of the eggs seems to be the second critical point in the logistic chain after laying and collecting. Although only a significant difference for chain 4 was found when comparing the packing operation with the transportation of the eggs to the packing station (2.11 and 0.28%, respectively), the higher breakage percentages of the packing operation indicate a possible higher risk at this point in the logistic chain. The packing operation in chain 1 resulted in the highest percentage of breakage (3.44%), whereas in chain 2 the lowest (1.50%) percentage of breakage was generated ($P < 0.005$). Breakage due to transport varied from 0.16 to 2.65%. There was also a significant difference ($P < 0.01$) in the percentage of broken eggs between transport to the packing station (average breakage of 1.37%) and transport to the retail store (average breakage of 0.21%).

Eggshell Strength

In Table 3, the average values of K_{dyn} and damping ratio are compared for the eggs produced in the different housing systems. Compared with the other 3 groups, the free-range system displayed a significantly ($P < 0.0001$) lower dynamic stiffness (11,403 N/m) and a higher damping ratio (4.26%). For the other groups, the eggs from hens in battery cages and furnished cages displayed a lower dynamic stiffness ($P < 0.05$) than the ones from the aviary. The same ranking was found for the values of damping ratio, but they were inversed. The values for the 2 groups in the aviary were equal. There was a difference between the values for both dynamic stiffness and damping ratio for the furnished cages (13,419 N/m and 3.99%) and part of the aviary where the birds were known to have been fed the same feed (14,140 N/m and 3.48%).

Relation Between Eggshell Strength and Breakage

The analysis of the influence of eggshell strength on the likelihood of an egg breaking during handling and

Table 2. Percentages of broken eggs given for the different operations of the investigated production chains

Item	Chain 1 (Battery cages)	Chain 2 (Furnished cages)	Chain 3 (Aviary)	Chain 4 (Free-range)
Laying	$6.73^{b,x}$	$10.72^{a,y}$	—	—
Collecting	$36.85^{a,x}$	$3.83^{b,y}$	$1.94^{a,z}$	$1.99^{a,z}$
Transport to packing station	$2.65^{c,x}$	$1.25^{c,x}$	$1.31^{a,x}$	$0.28^{b,y}$
Grading and packing	$3.44^{c,x}$	$1.50^{c,x}$	$2.17^{a,x}$	$2.11^{a,x}$
Transport to depot warehouse	—	—	—	0.86^{ab}
Transport to retail store	$0.25^{d,x}$	$0.16^{d,x}$	$0.21^{b,x}$	$0.22^{b,x}$
Total	44.63^{x}	16.61^{y}	5.47^{z}	5.36^{z}

a–d Percentages within a column lacking a common superscript differ ($P < 0.05$).
x–z Percentages within a row lacking a common superscript differ ($P < 0.05$).

grading pointed out that K_{dyn} as an independent parameter did not show a significant predictive capacity ($P > 0.18$). The damping ratio, on the other hand, proved to have a very significant capacity ($P < 0.0001$). When both parameters were incorporated into the model, damping ratio ($P < 0.022$), and not K_{dyn} ($P > 0.059$), proved to be significant. More importantly, it was found that the interaction between the 2 parameters showed the highest significance level ($P < 0.0007$). Dynamic shell stiffness was, therefore, kept in the model. Furthermore, it was proved that there was a significant influence of the logistic chain as well ($P < 0.0001$). Figure 1 shows the visualization of the model for the 4 logistic chains. As most breakage was found in the chain with battery cages, the graphic of this chain provides the model with the most adequate information. From this figure, it can be seen that damping ratio is of minor importance for eggs with low dynamic stiffness values. For eggs with high dynamical stiffness, on the other hand, the damping ratio value of the egg will largely influence the incidence of the egg breaking during handling.

To compare the probability for breakage in the different chains, Odd's ratios (**OR**) were calculated. Table 4 shows the different OR in the considered chains. This OR denotes the difference in occurring impacts in the different production chains. The higher impacts that occurred in the chain with the battery cages resulted in high OR values when this chain was compared with the other chains (namely 9.558, 13.313, and 29.974; Table 4). For example, the odds $(\pi/1 - \pi)(\pi/1 - \pi)$ of breakage, where π = the probability defined by the proportion of cracked eggs, were 13.313 times higher in the battery chain when compared with the chain with the aviary. These OR confirm the observations of total breakage from the critical points for breakage.

DISCUSSION

The relatively high breakage generated by laying in both cage systems (6.73% in battery cages and 10.72% in furnished cages) is in agreement with the findings of Van Niekerk and Reuvekamp (1995, 1999) and Leyendecker et al. (2001). A high percentage of breakage in furnished cages was also found by Abrahamsson et al. (1995) and Guesdon and Faure (2004). From the work of Wall and Tauson (2002), it was shown that devices like egg savers and long nest curtains are very effective in reducing cracks in furnished cages. However, even if such measures are taken, egg breakage in furnished cages is still highly dependent on the design of the cage and the nest. The extremely high breakage measured after collecting the eggs from the battery system is not representative of battery systems in general, but it does highlight the point that the acoustic technique can be used to pinpoint problems in any logistic chain for egg production.

The 3.83% breakage caused by collecting eggs from the furnished cages could be because the eggs had to be collected from different heights (cages with 3 levels) and, as a consequence, had to pass through a collection mill that brought them to the collecting level in the egg storage room. The low and comparable breakage after collecting in both the aviary and free-range system (1.94 vs. 1.99%) can be explained by the fact that both systems had the same laying nest material, and all nests were situated on the same level as the collecting platform.

Thompson and Hamilton (1986) stated that, from laying to final destination, most eggs are broken during transportation. This is in contrast with our findings, in which breakage due to transportation, which varied from 0.16 to 2.65%, was lower than breakage in the other operations (laying, collecting, and grading and packing). This con-

Table 3. Average values and SD for dynamic shell stiffness (K_{dyn}) and damping ratio in the different housing systems and per different feed

Housing (feed)	K_{dyn} (N/m)	Damping ratio (%)
Battery (A)	$13,474 \pm 1,779^{b}$	3.68 ± 0.94^{c}
Furnished cages (B)	$13,419 \pm 2,083^{b}$	3.99 ± 1.11^{b}
Aviary (B)	$14,140 \pm 1,915^{a}$	3.48 ± 0.94^{c}
Aviary (C)	$13,998 \pm 1,876^{a}$	3.60 ± 1.00^{c}
Free-range (D)	$11,404 \pm 1,765^{c}$	4.26 ± 1.07^{a}

a–c Mean values within a column lacking a common superscript differ ($P < 0.05$).

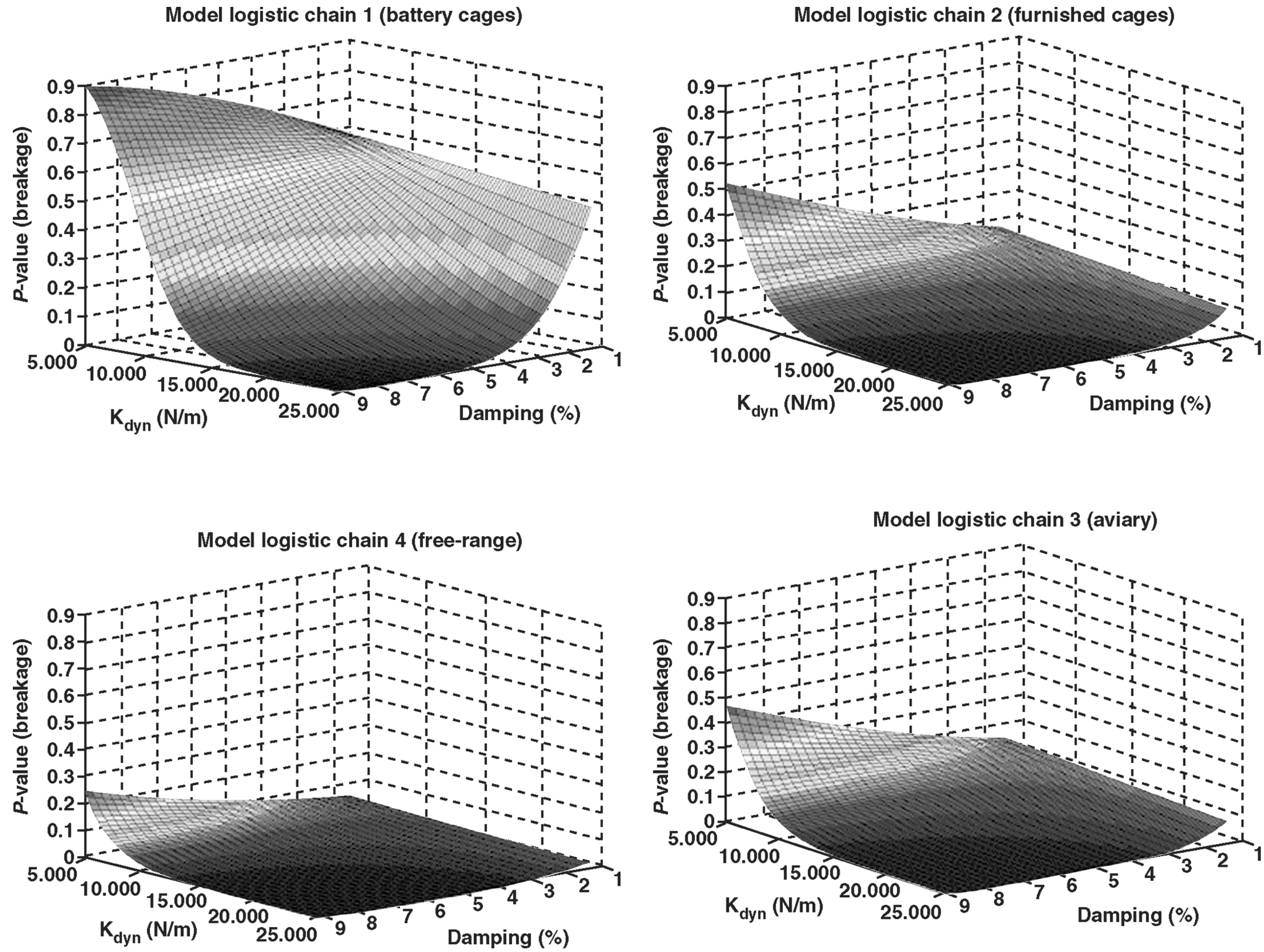

Figure 1. Graphical representation of the 4 logistic models for the different logistic chains. The interaction between both dynamic shell stiffness (K_{dyn}) and damping ratio showed the highest predictive capacity for the likelihood of breakage ($P < 0.0007$).

trast is probably because they performed their research in an egg grading station, and, as a result, the samples of eggs they investigated also included eggs that were already broken directly after laying or during collecting but were not detected and sorted out by the farmer. In our research, all broken eggs and eggs with haircracks, were sorted out in each operation of the logistic chain. Besides packing material, several factors influence transportation damage: truck suspension, traffic density, road conditions, location of the egg package on the truck, and atmospheric conditions (Nethercote et al., 1974), but driver attitude in both driving and handling of the egg packages should also be considered. The difference in breakage between transportation to the packing station (1.37%) and transport to the retail store (0.21%) observed in our study, however, was most likely caused by a difference in packaging material. For transport to the packing station, the eggs were packed in trays of 30 eggs and stacked up in rolling containers that contained 144 trays at most; for the transport to the retail store, the eggs were packed in cardboard boxes of 4 to 12 eggs and then put into boxes of 120 to 180 eggs in total. In other words, more material (cardboard) was available around the egg for the absorption of vibrations generated during transportation.

Table 4. Survey of the odds ratios (OR) of the breakage occurring in 2 investigated production chains[1]

	Production chain A			
Production chain B	Battery cages	Furnished cages	Aviary	Free-range
Battery cages	1	0.105	0.075	0.033
Furnished cages	9.558	1	0.718	0.383
Aviary	13.313	1.393	1	0.533
Free-range	29.974	2.613	1.876	1

[1]Odds $_{(\text{breakage chain A})}$/odds $_{(\text{breakage chain B})}$ denotes the difference in probability of an egg breaking in 1 chain compared with the other.

Breakage during grading and packaging, which varied from 1.50 to 3.44%, is influenced by, among other factors, packing speed, filler flats speed, and packing material (Britton, 1978). These effects, however, were not taken into account or evaluated in the current study. Differences in shell strength (Table 3) from eggs originating from the different housing systems cannot be separated from possible dietary effects with 1 exception: There was a significant difference in K_{dyn} and damping ratio between eggs from furnished cages and from the part of the aviary that were in the same house, which were also given the same feed (13 419 N/m vs. 14 140 N/m and 3.99 vs. 3.48%). One possible explanation for this is that the birds in the aviary system consumed more feed than those in furnished cages, and, as a result, their Ca intake was higher (Abrahamsson et al., 1995; Leyendecker et al., 2001). Comparing the K_{dyn} for both aviary divisions fed on different diets (feed B vs. C), it can be noted that adding corn cob mix to the ration causes no differences in K_{dyn}.

Concerning the relationship between eggshell strength and the incidence for breakage, Charles and Strong (1988) found the specific gravity and the percentage of shell to be of possible use to estimate the shell quality, whereas Britton (1978) presented the shell deformation as a measure. In the work presented, it was shown that eggshell strength, defined by both K_{dyn} and damping ratio, and, more specifically, the interaction between these 2 parameters, shows a good predictive capacity for breakage in the field. This result is comparable to the work of Bain et al. (2006), who found that K_{dyn} could predict the likelihood of an egg cracking during routine handling. Significant effects of visit, egg weight, and the eggs' position in the house were all found to improve the model developed by these authors, but, interestingly, the damping ratio was not found to be a significant effect in their study. Further experiments are, therefore, necessary to clarify the situation and develop a model which can be universally applied.

Furthermore, whereas previous studies have all attempted to find a relationship between different measurements of shell quality and field observations based on correlations, the presented work tried to predict breakage in practice by a direct measurement. When logistic regression was applied to these data, it became possible to develop a model that denoted the effect of a change in eggshell strength in terms of a change in breakage probability. In other words, using the acoustic test, it was possible to predict the minimum strength an egg needs to have not to break in a given chain with certain occurring impacts under normal practical circumstances. From the model developed in this research, it was shown that the damping ratio is of bigger importance for strong eggs (high K_{dyn}) than it is for weaker eggs. In other words, strong eggs (thick shell) with high damping ratios are able to absorb the impact energy, whereas strong eggs with low damping ratio aren't, and they become brittle.

In conclusion, the eggshell strength, determined by the acoustic resonance technique and characterized by the K_{dyn} and the damping ratio, proves to be an acceptable measure for eggshell quality. Based on logistic regression analysis, the interaction between these 2 parameters shows a good predictive capacity for the likelihood of breakage during handling.

Analysis of 4 logistic chains and housing systems pointed to an effect of the housing system by itself on eggshell strength. Although differences in likelihood of breakage of eggs originating from different housing systems were found, it is stressed at this point that these results reflect the situation of 1 time point only, and no prematurely generalizing conclusions concerning the comparison of housing systems should be drawn. Nevertheless, it does provide certain indications on which future research could be based. Moreover, it shows and confirms different application possibilities for the acoustic resonance technique. In particular, it shows that the acoustic resonance technique is very suitable for highlighting critical control points for shell breakage in a logistic chain.

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