EVALUATING FACTORS AFFECTING PELLET DURABILITY AND ENERGY CONSUMPTION IN A PILOT FEED MILL AND COMPARING METHODS FOR EVALUATING PELLET DURABILITY

by

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B.S., Kansas State University, 2005
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AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Grain Science and Industry
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Abstract

A series of experiments was conducted to compare methods used to evaluate the durability of animal feed pellets, as well as to investigate the potential for modeling the effects of formulation and processing factors on both pellet durability index (PDI) and pelleting energy consumption, measured in kilowatt hours per ton (kWh/ton). Seven different factors, including ground corn particle size, added fat level, inclusion of distillers dried grains with solubles (DDGS), feed rate, steam conditioning temperature, conditioner retention time, and pellet die thickness (L:D ratio) were examined. Each factor was evaluated at two levels, and treatments were developed in order that all factor to factor comparisons could be made. Pellet samples were analyzed according to the standard method as described in ASAE S269.4, a modification of this method, and by using the NHP100 pellet tester set to each of its four testing intervals (30, 60, 90, and 120 seconds). The standard method was found to provide the most consistent and repeatable determinations of pellet durability, and was found to correlate well with the modified method, as well as with the NHP100 results at 30 and 60 seconds. Physical attributes of feed pellets, such as pellet hardness, bulk density, and moisture content were found to have significant, but weak correlations with pellet quality. Pellet quality was found to be significantly influenced by all factors other than ground corn particle size and feed rate. Higher fat level, lower conditioning temperature, and the thinner pellet die most significantly lowered pellet quality, with increasing effect respectively. A regression model was developed that was able to predict pellet durability within an average of 1.1 PDI. Pelleting energy consumption was found to be significantly influenced by all seven factors, with the higher fat level, thinner pellet die, and higher conditioning temperature most improving efficiency, with increasing effect respectively. A regression model was developed that was able to predict energy consumption within an average of 0.3 kWh/ton. The successful creation of regression equations demonstrates that there is potential for modeling and optimizing pellet quality and energy consumption within a pelleting operation.

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Introduction

The pelleting of animal feed has long been described as being 'more art than science.' Over time this axiom has been supported by the wide variety of pelleting practices and theories, often with each being particular to a specific feed formulation, processing facility, or even the pellet mill operators themselves. Additionally, for many years pelleting was considered as a luxury reserved for commercial feeds or the most discriminating of production livestock feed producers. However, with rising ingredient and energy costs, and taking into consideration improvements in animal feed efficiency, pelleting has become more economically feasible and in many cases economically necessary. And with this change in perspective, there has also been a change in what is considered acceptable pellet quality as it relates to the amounts of pellets and fines delivered to the animal.

Commercial feed manufacturing companies have always put an emphasis on pellet quality, as this allows them to preserve profitable margins based on customers' willingness to pay a premium for pelleted feed. With increasing costs the margins are shrinking, and thus these companies must find ways to preserve high quality while lowering the cost of operation. Similarly, integrated companies are realizing that if dollars are to be spent pelleting feed, the resultant product should meet a high standard, as there is no sense in putting money into a process without realizing the maximum potential benefits in nutrition and feed efficiency. Currently, the 'art' of pelleting is no longer sufficient to support the needs of the industry, and anecdotal evidence of ways to improve pellet mill energy efficiency and pellet quality requires more substantive proof. The aim of this work is to revisit the science that does exist regarding pelleting, and to revive the process of adding to the academic knowledge base for efficient and effective pelleting in the future.

What must be considered first and foremost is the effect of pelleting and pellet quality on animal nutrition. Pelleting feeds is certainly useful for improving material handling and promoting feed safety, but it is the positive net effect on animal growth and efficiency that is most important. As is true for most things in the feed industry, if it does not improve animal performance, and thus the bottom line, it probably won't be considered worth doing. The second component to consider is what factors influence the cost of pelleting and pellet quality. Unfortunately, the majority of actions taken in the feed mill to improve pellet quality also decrease pelleting efficiency, i.e., they add to the overall cost of producing feed.

In the first chapter of this work the literature, both scientific and popular press, is reviewed as it relates to each of these components in order to provide a basis of understanding for the experiments outlined in the later sections. These experiments are designed with three goals in mind. The first is to compare both common and uncommon measurement techniques for evaluating pellet quality. This includes an empirical test that has been in use for half a century, a relatively new take on another empirical method, and the use of laboratory-grade equipment. The second goal is to relate a number of set independent and measured dependent variables to measured pellet quality. The hope is to provide some updated guidance on which controllable factors can affect pellet quality, and the proportional degree to which they have this effect. Lastly, the relationship between pellet quality and energy efficiency is analyzed, with the goal of determining which factors will most positively affect pellet quality while least negatively impacting the bottom line.

Objectives

The objectives of the research described in chapter two were: (1) to determine whether one method of pellet durability testing is superior in terms of providing repeatable results across a range of pellet qualities, and (2) to determine what relationships might exist between methods that would allow for predicting pellet quality results from one method from known results of the other.

The objectives of the research described chapter three were to determine whether a relationship exists between pellet durability and (1) pellet hardness, (2) pellet density, (3), pellet die retention time, and (4) initial and final moisture.

The objectives of the research described in chapter four were to determine how seven processing and ingredient parameters: (1) interact and affect PDI, (2) interact and affect energy consumption, and (3) might be used to create regression equations in order to predict PDI and energy consumption in a particular processing facility.

Chapter 1 - Literature Review

Influence of Pelleting and Pellet Quality on Animal Nutrition

In general terms, pelleting is important to animal nutrition because it affects growth and feed efficiency. Research done regarding the effects of pelleted feeds has typically focused on average daily gain (ADG), feed efficiency (defined as the ratio of gain to feed (G/F)), and average daily feed intake (ADFI). A factor is said to have had a positive influence on animal performance when the results showed higher ADG, ADFI, or an overall improvement in G/F. Feed research typically investigates the effects of feed and/or feed processing on growth performance in production species. Swine and poultry are the most prevalent of those species fed pelleted feed, thus most of the literature focuses on these animals.

Research on the effects of pelleted feed on swine performance is certainly not new. Jensen and Becker (1965) demonstrated that in young pigs, G/F was improved ($p<0.05$) by pelleting corn-soy diets, but ADG was unaffected. Hanke et al. (1972) also found an improvement ($p<0.05$) in G/F, and an increase ($p<0.01$) in ADG. Some differences may have been related to the age of the animal, as was demonstrated by Skoch et al. (1983), where the authors reported no differences ($p>0.05$) in weanling pig ADG, ADFI, or G/F when using pelleted diets. However, in the same study a second experiment was conducted with grow-finish pigs, and while there was no improvement in ADFI or ADG, there was an improvement ($p<0.05$) in G/F with pelleting.

More recent work has also shown pelleting to be effective in improving animal performance. Wondra et al. (1995) found that pelleting increased ADG ($p<0.01$) and G/F ($p<0.001$) by 5 and 7%, respectively. The study also concluded that apparent digestibility of DM and nitrogen (N) were increased by pelleting ($p<0.001$). These findings were substantiated by Traylor (1997), who found that pelleted diets yielded improved digestibility of DM and N

($p<0.001$), improved G/F ($p<0.04$) of 4% in nursery pigs, and improved ADFI ($p<0.02$) and G/F ($p<0.08$) in finishing pigs. In general, the literature supports the idea that pelleting positively influences swine growth performance, with the most consistent and across-the-board results being found in finishing situations. One reason for this positive effect is that pelleting reduces segregation and prevents an animal from sorting out palatable ingredients, thus improving the chance of feeding a uniform and balanced diet.

Providing a pelleted versus a mash feed is one part of the overall effect of pelleting on animal performance. Another factor is pellet quality, or the amount of pellets in relation to pellet fines presented to the animal. The effects of pellet quality on growth performance and feed efficiency were examined by Stark (1994). Two nursery experiments were conducted with treatments consisting of mash, pelleted, and pelleted with added fines diets. In the first experiment, no difference in ADG ($p>0.17$) was noted among treatments, though the addition of 25% fines did appear to reduce G/F ($p<0.07$). The second experiment noted no difference in ADG or G/F because of added fines. In both experiments, daily fines accumulation more than doubled when the diets containing fines were fed, which may point to increased feed wastage. In addition, experiment 2 showed improvements in ADG ($p<0.06$) and G/F ($p<0.01$) of 8 and 15%, respectively, along with greater DM and N digestibility ($p<0.01$) when feeding pellets versus mash diets. A finishing study was also conducted. There was no effect on animal performance by diet form, and digestibility of DM was improved ($p<0.01$) by pelleting while digestibility of N was not affected by diet form or percent fines. The presence of fines in the diets did tend to decrease G/F (linear effect, $p<0.09$). Generally, the data suggests that pelleting of swine diets has a beneficial effect on growth performance and feed efficiency. While pellet quality does not necessarily affect growth, there is evidence that high percentages of fines may decrease overall feed efficiency.

While swine feeds may often be fed as a mash diet, most poultry feeds are pelleted. Research generally agrees that pelleted feed yields positive effects on growth and efficiency (Kilburn and Edwards, 2001, Greenwood et al. 2004, McKinney and Teeter, 2004). A problem in the poultry feeding industry is that very often the pellets have low durability and the transportation and handling of the feed tends to generate additional fines. This has led to questions regarding the impact of pellet quality on poultry performance.

Greenwood et al. (2004) conducted an experiment to examine the effect of feed fines percent on the growth of broilers. Body weight gain (BWG) and average feed intake (AFI) decreased an average 7.9% and 5.8% respectively (both significant, $p<0.001$) as the level of fines increased from 20 to 60%. No significant effect was observed on feed efficiency. McKinney and Teeter (2004) conducted a study that observed the effects of pellet versus mash feeding as well as the effect of pellet quality on bird performance. In the experiment, birds were fed diets with 100, 80, 60, 40, and 20% pellets with the remainder of the rations being fines. A mash treatment was also fed to act as a negative control. Neither pelleting nor pellet quality had an effect on feed intake ($p=0.5$), though birds did selectively consume pellets over fines, with selectivity decreasing as the level of fines in the diet increased. Both pelleting and level of fines had an effect on BWG ($p<0.01$ and $p<0.001$, respectively) with pelleting improving BWG by 6% over mash. Improved feed efficiency was also observed as fines decreased ($p<0.01$), and pelleted diets yielded a 5% improvement in efficiency over the mash treatment. Data from this study also suggests that 40% pellet quality (60% fines) is the minimum necessary pellet quality to observe positive nutritional effects from pelleting, and that birds eat less frequently and rest more frequently as the proportion of pellets in the diet increases. This suggests that a lower energy requirement during feed consumption as well as decreased segregation and sorting by the animal leads to improvements in efficiency.

Scheideler (1995) also described the positive effect of pellet quality on broiler performance. More interestingly, the author described the possible positive economic impact of improved pellet quality relating to decreased feed consumption and improved feed to gain ratios. The discussion was that the decrease in required feed production could possibly offset the cost of pelleting, leading to increased profit margins, dependent on the increase in cost for pelleting. If producers were able to produce high quality pellets when feed ingredient prices are high, and if pelleting costs can be kept to a minimum, there is potential for pelleting to be a cost-saving measure.

Testing Pellet Quality

Forces affecting pellet quality have been characterized as impact, compression, and shear (Pfost et al., 1962). Feed pellets are degraded by two forces, fragmentation and abrasion (Thomas and Van der Poel, 1996). After pellets leave the pellet mill die, they are immediately exposed to these forces as they travel through a cooler, are handled by bucket elevators and drag conveyors, and are transferred to holding bins. From this point forward the pellets may be bagged for retail sale, or bulk shipped and exposed to additional handling by augers, drag chains, and feed lines on their way to the animal feeder. Once the feed reaches the animal, the amount of fines versus pellets can affect performance as noted in the previous section. Pellet durability, measured at the feed processing facility, is one way to predict pellet quality, or how much fines may be produced as a result of handling.

In Pfost et al. (1962), the authors described an experimental set-up that simulated pelleted feed handling in a model system. The fines produced by this model system were then compared to those produced by various testing devices to determine which best predicted fines production. These devices included tumbling cans and jars, two commercial hardness testers, and a locally constructed pneumatic hardness tester, similar in design to today's texture analyzer or Instron-type devices. The tumbling can method produced the highest correlation with the model system. The authors theorized that it was the best because it tested a large number of pellets and caused enough quantitative damage. Cooled pellets correlated more with the model system than did pellets that were tested directly after production.

The purpose of those experiments was to develop standard methods and equipment for testing pellet quality in order to compare feed types and production facilities. The authors chose to adopt a tumbling box with square dimensions, because it was assumed to be the easiest to construct to standard specifications. A range of sample sizes, tumbling times, and rotating speeds were investigated. A 500 gram sample size, tumbling time of ten minutes, and a rotating speed of 50 revolutions per minute (RPM) were found to provide the most consistent and accurate results. (Pfost et al, 1962). This collective work led to the development of the device and methods described in ASAE Standard S269.4: Cubes, Pellets, and Crumbles--Definitions and Methods for Determining Density, Durability, and Moisture Content (ASAE, 1997). This standard allows for the determination of the pellet durability index (PDI), which is defined as the percentage of whole pellets remaining after a sifted sample has been tumbled according to the method described.

In addition to prescribing the above equipment and method, the standard also suggests that pellets be tested directly after cooling. If testing cannot be done immediately, it is stated that subscripts are to be added to PDI values to denote, in hours, the amount of time between cooling and testing. However, no explanation is given as to what differences might occur, what the extent of variation might be, or what time ranges are acceptable. An experiment has recently been concluded that investigated the effect of time after cooling on pellet quality results (Lewis, 2010). The data demonstrated that the largest changes in PDI occurred within the first two hours, with PDI increasing by two percentage points. After this period, the PDI values remained generally constant for a period up to two weeks before beginning to gradually decrease. The immediate increase in PDI was theorized to be due to the curing of the pellets, where any liquid bridges, gelatinized starches, and denatured proteins become fully set.

The relationship between PDI and percentage fines has been noted in recent studies evaluating effects of pellet quality. Briggs et al. (1999) and Gilpin et al. (2002) each noted a negative correlation between PDI and fines production. Both found that high PDI pellets yielded lower fines production, with Briggs et al. showing an approximate 50% reduction in fines with a 40% improvement in PDI. In some experiments researchers added items to the tumble box compartments to simulate rougher handling characteristics and to more accurately reflect fines production in specific handling and production environments. The addition of such items may also affect the repeatability and sensitivity of the test. Cavalcanti and Behnke (2005b) added five ½ inch hex nuts and found that the modified PDI was more sensitive to high levels of fat than standard PDI. It is also worth noting that while higher PDI values generally mean lower fines production, it may not always be the case. In some cases fine particle size ingredients and pellet mill component wear may lead to high fines production when mash material can exit the pelleting chamber without passing through the pellet die.

Instead of the tumble box method described in ASAE S269.4, some processing facilities are using one of the TekPro (Norfolk, GBR) manufactured line of Holmen pellet testers (NHP 100, NHP 200, NHP 300) distributed by Borregaard LignoTech (Sarpsborg, NOR) in the United States. These devices are an update of the previous Holmen pellet tester, and like that model use pneumatic pressure to agitate a 100 gram sample for a fixed period of time. In the original model, the pellets were circulated in a tube, similar to how they might be pneumatically conveyed. The NHP 100 is the most commonly used of the new testers, and is referred to as the "portable" model. The NHP 100 agitates the pellets in a pyramid-shaped perforated chamber during testing. The fines exit the chamber, avoiding the need for a final sifting step, and the test can be run for 30, 60, 90, or 120 seconds. This test is faster and more portable than the tumble box, but little is known about how the results of each method compare. While the NHP 100 is manually operated, the NHP 200 and 300 models are automated. The NHP 300 can be placed directly in the process flow. The product website claims that the NHP 200 and 300 have a repeatability accuracy of ±0.1% PDI (www.holmenfeed.com/Products, accessed Oct. 24, 2011).

The only documented comparison of the tumble box and NHP testers was provided by Winowiski (1998), an employee of Borregaard LignoTech. He described the relationship of the NHP to the tumble box procedure as well as to an original Holmen pellet tester. He stated that the NHP was more destructive than either the standard or modified PDI test, but correlated well with both, while being very similar overall to the original Holmen tester. It also appears from the data presented that both the NHP device and the original Holmen tester are more sensitive to changes in pellet quality that may be a result of changing factors in formulation or production practices. More work is required to investigate the repeatability and accuracy of the tumble box and NHP across a variety of pellet qualities in order to determine how the tests compare in both scientific and industrial applications.

Methods such as the tumble box and NHP are empirical, meaning that they do not specifically measure a single attribute such as hardness or elasticity which, from a scientific standpoint, would be preferable. Pfost et al. (1962) stated that measuring pellet hardness as a method to determine pellet durability was relatively ineffective for correlating fines production in the model system. However, in these experiments hardness was measured using spring–type compression testers, which are not particularly precise, and whose accuracy is questionable due to the human error factor. Wood (1987) used a more modern manual compression tester manufactured by Kahl (Hamburg, GER). Hardness, as measured by compression of 10 pellets, was found to be related logarithmically to durability (r = 0.94), which was measured by an original Holmen tester with a one minute test cycle. The description of the method does lead to some questions however, as a laboratory-scale vertical shaft pellet mill was used rather than a production-scale ring-die pellet mill typically found in most feed production facilities. The equipment used for steam conditioning was also atypical, and may have led to abnormal pellet qualities.

Thomas and Van der Poel (1996) reported data demonstrating that pellet hardness, as measured by three compression and/or shear devices, increased with conditioning temperature and with die thickness. The data was collected by replicated study, but no statistics were reported. Durability, as measured by an original Holmen pellet tester and the tumble box, was also reported, and the same trends were evident. The durability testers were more consistent than the compression or shear devices, with lower coefficients of variation (CV) among the replications. The tumble box had lower CV values than the Holmen tester. In all cases, the CV increased as hardness/durability decreased. For these experiments, the pellets were made of pure barley, and were therefore of much higher quality than a typical broiler or swine corn-soy based ration. Salas-Bringas et al. (2007) conducted a similar experiment, but used a modern computer controlled texture analyzer. The authors found that texture analysis, i.e., measuring the tensile stress as a function of first-peak force, did not correlate well with pellet quality as determined by an original Holmen tester.

Thomas and Van der Poel (1996) stated that the best device for testing pellet quality would measure the effects of both abrasion and fragmentation. The Holmen tester seems to fit this description the best. However, they also stated that the best test will be one that most closely relates to the actual factors affecting pellet durability at the specific plant, and therefore the best test may vary by facility. The authors suggested that a ‘scientific’ method that is standardized and tests only for one inherent quality would be best. Unfortunately, so far none of the methods appear to be better than the empirical tests due to variation in pellet quality. In any case, the importance of the test is to give some idea of final fines amount as consumed by the animal, because it is fines consumption rather than pellet durability that negatively influences animal performance. Accordingly, whatever provides for the most consistent method is probably the best for determining and tracking the correlation.

Influence of Formulation and Processing Factors on Pellet Quality and Pelleting Cost

As explained in the previous section, pelleting plays an important role in animal performance. Pelleting is also important in materials handling because it improves product flow, increases bulk density, and prevents the segregation of ingredients that can cause dustiness, fines, and leaching of liquids. Therefore, it is important to determine which factors positively and negatively impact pelleting, both from a quality and a cost standpoint.

Five binding mechanisms have been described that lead to the durability of densified products such as feed pellets. These mechanisms are solid bridges, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces, and interfacial forces and capillary pressure (Thomas and Van der Poel, 1996; Kaliyan and Morey, 2006). Specific to pelleted animal feed, Thomas and Van der Poel (1996) stated that it seems unlikely that adhesion and cohesive forces such as Van der Waals or electrostatic forces are largely responsible for pellet quality in a significant way given the relatively large size of feed particles. They also suggested that particular formulation and processing parameters can have an impact on which forces are the most important for pellet stability.

One unfortunate truth about pelleting animal feeds is that “almost anything that is done to improve pellet quality (durability) will either increase the cost of the ration or reduce the capacity of the pelleting system, or both” (Behnke, 2006). For this reason, it is necessary for a feed manufacturer to understand the value of pellet quality in their specific market, the production costs in their facility, and the relationship of the two. It has been theorized that a modeling system could be constructed that would assist the producer in making decisions based on minimum criteria for pellet quality and production costs. Thomas et al. (1997) described a decision support system (DSS) that was developed for use in the Netherlands to optimize pellet quality, production rate, and energy efficiency. The system cataloged previous runs and used the data to develop regression relationships. From this a diet formulation could be optimized for pellet quality by manipulating processing variables. According to the authors, the DSS showed promise and was shown to improve throughput and reduce energy consumption while only slightly decreasing pellet durability. The authors maintained however that there was a large amount of information yet to be collected and that specific processing and ingredient relationships still needed to be established. To this end, the authors suggested that more process research was needed rather than research focusing solely on the finished product.

Pelleting Costs

There are fixed and variable costs associated with pelleting. Equipment and labor costs are relatively fixed, assuming that proper preventative maintenance procedures are followed. Operating costs associated with pelleting include the production of steam for conditioning and electrical energy to operate the pellet mill, feeders and conditioners, and pellet cooling system. These costs are variable, and depend on prices for natural gas and/or electricity. Of the variable costs, electrical energy is typically considered the most important to monitor. Steam production needs, while high (up to 72% of the energy required to pellet may be used for steam conditioning according to Skoch et al. (1983)), are relatively fixed considering the tons of feed produced, and are not likely to be adjusted as a cost-saving measure.

Electrical usage at the pellet mill is generally reported in the terms of units of energy per unit of throughput and/or time, such as kilowatt-hours per ton (kWh/ton), with lower values corresponding to less energy consumption per ton produced. Energy consumtion is minimized by operating at the maximum possible production rate based on diet characteristics, die volume, or motor load. When production rate is based on maximum motor load, less mechanical energy required at the die will lead to higher production rates. Factors within the diet may affect electrical energy consumption based on mechanical energy requirements by affecting friction within the die or because of compaction characteristics of the mash.

Payne (2004) shared data gathered from pelleting trials in commercial mills from 1975 to 2000. It appears that pellet quality improved and energy consumption decreased until sometime between the mid 1980's and early 1990's, and has remained fairly constant since that time. Payne suggested that producing high quality dairy, swine, and broiler pellets should require approximately 20, 15, and 10 kilowatt hours per metric ton, respectively. The author also suggested that for diets with low pellet quality attributes, changing factors leading to an increase in energy consumption can lead to an improvement in pellet quality. This might be done by slowing throughput, increasing die thickness relative to hole diameter (L:D ratio), or increasing the gap between the roll and die surface. The author stated that the relationships between pellet quality, energy consumption, and formulation should be examined, but that these relationships will likely be specific to the processes in a particular facility and therefore less useful in a global sense.

Factors Affecting Cost and Quality

Steam conditioning is likely the most important factor affecting pellet quality. The amount of research on the topic, along with articles published in the popular press and general industry expert opinion, would suggest that many believe the success or failure of pelleting under a variety of circumstances depends on the attention paid to this process. There are a several conditioner types found in the industry today. While conditioner design is not the focus of this work, the fact that so much effort has gone into improving the process gives credence to its importance in producing quality feeds.

Pfost (1964) reported that the highest possible conditioning temperature improved ($p<0.01$) both pellet durability and reduced pellet mill energy consumption in no or low-fat diets, and improved pellet durability in high fat diets ($p<0.05$). The fact that no significant reduction in energy consumption was noted with increasing conditioning temperatures when pelleting a high-fat diet may be related to a change in moisture absorption by the feed particles, or because fat has a larger proportional effect on energy consumption. The experiment also examined the effect of die thickness on pellet durability. While the author noted no significant die thickness by temperature rise interaction, it was noted that conditioning temperatures may need to be lowered when using thicker dies to prevent roll-slippage and pellet mill plugging. This is supported by Smallman (1996), who described how a change in conditioner design led to higher moisture mash at equal conditioner discharge temperatures. This in turn led to roll slippage and pellet mill plugging, requiring a thinner pellet die. Energy consumption and pellet durability both reportedly improved with the thinner die, demonstrating that conditioning may have the greater effect.

Skoch et al. (1981) found that increased steam conditioning led to a decrease in mechanical friction during pelleting, as determined by lower temperature rise across the pellet die, decreased electrical energy consumption, and an improvement in pellet durability. Total observed energy requirements, which included steam and electrical, increased with temperature due to the higher steam requirement. However, the improvements in throughput and pellet durability may offset the overall cost increase depending on the scenario. The authors also noted a limited effect on starch damage as temperatures increased. This is important because it has long been believed that an increase in starch gelatinization causes the improvement in pellet durability. In this case, much more damage was noted during cold pelleting, suggesting that friction at the pellet die is more responsible for any starch modification. In agreement with these findings, Stevens (1987) found that the amount of starch gelatinization actually decreases as conditioning temperature increases, according to samples of entire pellets. Low conditioning temperature did lead to an increase in gelatinized starch in the exterior portion of the pellet. This was attributed to increased frictional heat through the die.

The overall conditioning temperature is only partially responsible for effects on pellet durability and energy consumption. As with any thermal process, both temperature and time must be considered. Gilpin et al. (2002) found that increasing retention time in two separate conditioners by slowing the rotation using a variable frequency drive significantly improved pellet durability. Briggs et al. (1999) found that changing the pitch of the conditioner paddles, and thus increasing residence time, also increased pellet durability. It is surmised that the increased retention time allows the moisture to more fully penetrate the particle, which in turn softens the particle and makes it more "adhesive."

Briggs et al. (1999) found that changing the pitch of the conditioner paddles also reduced pellet mill energy consumption ($p<0.05$). Gilpin et al. (2002) alternatively found that retention time influenced pellet durability but not energy consumption, but did determine that pellet durability had a significant negative correlation with energy consumption. This is a logical conclusion, as conditioning factors such as temperature and retention time that positively affect pellet quality also positively affect energy consumption.

Steam quality also has an effect. For example, Gilpin et al. (2002) found that pelleting was optimized in one experiment using 80% steam quality, suggesting that adding water in the liquid phase to the conditioner may be beneficial. The authors suggested that several strategies can be pursued to optimize the process. Unfortunately, many operations today use long runs of un-insulated steam piping to cool and condense the steam and increase the liquid water content, wasting the energy that was input and paid for in the boiler.

Steam pressure has also been investigated as a factor influencing pellet durability and energy consumption. It has been theorized that high pressure steam, which has a higher enthalpy, could be more beneficial in a thermodynamic sense. Cutlip et al. (2008) found that increasing the pressure of the steam used for conditioning improved pellet durability ($p<0.10$) as measured by the standard method, and also improved durability ($p<0.05$) when the pellets were measured using the modified method. However, the increases in PDI and modified PDI were only 0.5% and 1.5%, respectively. The authors noted that these improvements were much less than those noted when conditioning temperatures were increased during the same experiment. Stevens (1987) found no effect of steam pressure on pellet durability or production rate.

Thomas et al. (1997) stated that there was no clear relationship between steam pressure and pellet durability, even though one might be expected due to theoretical relationships between steam pressure, heat, and moisture content. The authors did suggest that the design and upkeep of the steam supply itself, which will vary from facility to facility as shown in Maier and Gardecki (1993), likely has a more definitive relationship with pellet quality. Briggs et al. (1999) recommended using a pressure somewhere between the low and high values previously studied. The authors felt that, since low pressure steam is more likely to contain condensate, there could be problems with excessive moisture in the conditioner, which could lead to pellet mill plugging. High pressure steam was described as being energy inefficient, and unnecessary for the purpose of conditioning feed materials. The overall consensus is that steam pressures between thirty and fifty pounds-per-square-inch are sufficient, and that these pressures have less to do with pellet durability than with balancing system requirements and steam production costs.

There are many characteristics of a pellet die that can affect pellet durability and energy consumption. They include metallurgy, which can affect friction and temperature buildup, hole design, which includes straight bore and relief, and hole pattern and number. However, the characteristic that has the largest effect is the thickness of the die in relation to the hole diameter, known as the die L:D ratio. A larger L:D ratio means that the die is thicker, which will typically increase pellet durability due to friction and possibly die retention time, but is negatively related to throughput and energy consumption.

Pfost (1964) showed that thinner dies decreased ($p<0.01$) pellet quality and reduced kWh/ton in low or non-fat diets. Increasing the L:D ratio did not have a significant effect on pellet durability in high fat diets, but there was some evidence that it may increase energy consumption. This may indicate that the fat content of the diet plays a more direct role in pellet quality than die selection. Traylor (1997) reported that as pellet size increased production rate increased and energy consumption decreased. Pellet die hole sizes of 2, 4, 8, and 12 mm were used, and while die thickness was not specified, knowledge of the pellet die selection at Kansas State leads allows for the assumption that as pellet diameter increased, die L:D ratio decreased. This leads to the conclusion that lower L:D ratios result in higher production rates and reduced energy consumption. Traylor (1997) also demonstrated a substantial decrease in pellet durability as L:D ratio decreased (again assuming that as pellet diameter increased, L:D ratio decreased), with reductions from 90.3 to 70.5 PDI in swine nursery diets and 93.4 to 81.9 PDI in swine finishing diets.

Particle size is one of the few pre-processing factors linked to pellet quality. In the United States it is typical for a single cereal grain, usually corn but occasionally sorghum, to make up a majority portion of a pelleted poultry or swine diet. In other regions of the world, such as Europe, a number of different cereals may be present in the diet, such as corn, wheat, barley, and oats. In either case, these ingredients are ground prior to pelleting. In the U.S. corn or sorghum is pre-ground (ground prior to mixing) and in Europe cereals and other ingredients are mixed together and then post-ground in order to address the complexities of mill flow when using multiple cereal ingredients. For facilities producing pelleted diets, grinding is most often done by a hammer mill. The resultant particle size can be measured in terms of both geometric mean and standard deviation (ASAE, 2008). It has long been debated how, and to what degree, particle size affects pellet quality.

Stevens (1987) examined the effects of particle size of ground corn on pelleting, and found no effect ($p>0.05$) on production rate or PDI. Corn in the diet was ground to 1023, 794, and 551 microns yielding PDI values of 89.9, 88.8, and 90.3, respectively. However, coarse ground corn (1023 microns) did lead to an increase energy consumption ($p<0.05$) in comparison with a medium ground corn (794 microns). Stark (1994) found that particle size of the overall diet significantly affected pellet durability ($p<0.01$). Corn/soy diets with particle sizes of 543 and 233 microns yielded PDI values of 97.3 and 98.5, respectively. However, while significant, this difference was only slightly more than that reported by Stevens, and may not have practical implications in a commercial process.

Reece et al. (1985) demonstrated that a larger particle size led to a higher pellet durability. As the geometric mean particle size increased from 670 microns to 1,289 microns, the PDI value increased ($p<0.05$) from 91.0 to 92.5 respectively. However, the work also stated that the PDI test was run with 2,000g of sample for a total of forty minutes. Both values were well outside the standard testing method. It is possible that one explanation for the increase in PDI is that, although the pellets may have fractured, the sample made using the larger particle size would have large pieces of unground corn that would remain after sieving. It is also possible that an increase in geometric standard deviation, from 2.22 to 2.48 could play a part in the improved durability.

The theory has always been that smaller particles lead to fewer fracture points within the pellet and thus increase durability. It has also been suggested that smaller particles can be more adequately conditioned and compressed. Robinson et al. (1962) reported that, while a finer grind produced a slightly more durable pellet, an increase in conditioning temperature improved pellet durability equally for both fine and coarse grinds. This implied that no interaction between conditioning and particle size exists. The authors also found that a finer grind yielded a lower motor load and fewer fines exiting the pellet mill. This means that less re-pelleting of fines would be required, which represents an overall cost savings. The authors closed the article by stating that the “best recommendation…is to grind as fine as is necessary to make a quality pellet.” This seems to fit the general attitude today that grinding, while important, is not one of the most important changes to make in order to affect pelleting. This is true also because, as Behnke (2006) stated, “The effects [of particle size] are not the same under all conditions or for all rations. The operators must conduct their own research under their own operating conditions and on the feeds that they produce.”

The effect of production rate on pellet durability and energy consumption has only recently begun to be considered in pelleting research. This is because it is a relatively recent phenomenon where facilities are operating above design capacity in order to satisfy throughput demands. Stark (2009) reported that an increase in pellet mill throughput (545 kg/h to 1646 kg/h) led to a linear increase in pellet mill efficiency (73.3 to 112.4 kg/hph) and linear reduction in pellet durability (55.4 to 30.2 PDI.) These findings suggest that pellet mill throughput is an important factor affecting pellet durability and energy consumption.

In many cases it makes little sense to sacrifice production rate for pellet quality. The exceptions are cases where pellet durability and low fines production are driving forces with respect to product value. Operating at the maximum production rate allows the pellet mill motor to operate at peak efficiency, where the highest proportion of energy used to material produced is found. It is generally true that as production rate increases, kWh/ton decreases. Higher production rates also improve margins across the facility as they lower the ratio of fixed costs per ton produced. Poor pellet durability may be caused by higher production rates because of greater fill in the conditioner, possibly to the point where the conditioner is filled above the design level. The overly full conditioner may not allow for uniform condensation of moisture throughout the mash resulting in a non-uniform moisture distribution and treatment effects. Higher production rates also mean less retention time in the die, and so pellets are exposed to frictional heating and pressure for a shorter duration.

The formulation of a pelleted diet is an important factor in final pellet durability. It is also highly influential in energy consumption as many ingredients are known to dramatically improve or diminish production capacity. This can be due to the presence, or lack thereof, of lubricating factors, the ability of ingredients to scour or "polish" the pellet die, or because the bulk density of an ingredient requires the mill to exert an excess amount of energy to compress the material before it can be extruded through the die (Behnke, 2006).

Because ingredients are considered so important to pellet durability, a good deal of work has gone into cataloguing the effects of individual ingredients on PDI. The result of one such effort wass the creation of "pelletability" factors for various ingredients, which can be found in "The Pelleting Handbook" (Payne et al., 2001). The idea was that each ingredient affects pellet quality to a certain degree, and by totaling the pellet quality factor based on ingredient inclusion rate, the "pelletability" can be determined for the overall diet. The suggestion is to include this factor in least cost formulation, in order that pellet quality might be given some consideration based on its own economic impact. For example, if least cost formulation leads to poor pellet durability, and production costs were to increase as a result of needing to re-pellet fines, along with an increase in costs associated with customer complaints and feed wastage, the overall cost savings might be negligible (Robinson et al., 1962).

Unfortunately, it is still rare today that pellet durability is taken into consideration in formulation though it is known to affect the economics of feed manufacturing. Consider the following statement, presented in an article in 1962: "A limited amount of work has been done on establishing [ingredient] factors and inserting them in the formula by companies using data computors [sp] to establish their formulas. It is understood results to date have been encouraging and that this may develop into one of the principal methods of varying durability" (Robinson et al., 1962). This statement shows that there was interest in pursuing this idea fifty years ago. The more recent strategies of formulating with ingredient pellet quality factors and development of systems such as the DSS, described earlier, demonstrates that the interest still exists. It seems that the pertinent question is twofold. First, is there enough of an economic interest to influence a change? And if so, has modeling of pellet durability based on ingredient factors not been done because of a lack of data, or because it is an idea too overly complex to realize?

Cavalcanti and Behnke (2005a) conducted an experiment that utilized response surface designs to investigate the effects of starch, protein, fat, and fiber on pellet quality. Fifteen separate diets were created using milled corn fractions to target levels of each nutrient. The authors found that PDI had a quadratic relationship with starch inclusion, with the maximum PDI values being produced when starch values were approximately 65%. Increased protein level had a singularly negative effect on pellet durability, but in the presence of high starch did lead to improved PDI values, demonstrating an interaction. The inclusion of fat in the diet led to lower PDI values, and appeared independent of any other variable.

A similar, subsequent experiment by Cavalcanti and Behnke (2005b) looked at the effects of nutrients on pellet durability, but instead used corn, soybean meal, and soybean oil to create the thirteen treatments investigated. Again, the highest PDI values were found when fat inclusion was at the lowest levels. In this case protein had a positive influence on pellet durability. This result appeared to be correlated more with the addition of soybean meal protein than with overall protein, which included the corn fraction. The influence of starch on pellet durability appeared to be largely dependent on other ingredients. Overall, the authors were able to effectively model the use of corn, soybean meal, and soy oil, but surmised that the models would likely not be feasible as other ingredients were included into the formulation.

Wood (1987) described a set of experiments that determined that the functional properties of protein and starch had a greater influence on pellet durability than did the conditioning method. In this case, raw protein and pre-gelatinized starch led to the best pellets, while the combination of denatured protein and native starch led to the lowest overall pellet durability. Protein inclusion had the larger improvement effect on pellet durability, while energy consumption decreased and throughput increased with higher pre-gelatinized starch inclusion. While the basic results of this experiment are worthy of consideration, the process and equipment design had significant differences in comparison to a full scale feed production facility. For example, instead of a typical, ring-die pellet mill, a small-scale vertical shaft pellet mill was used, which is known to have different energy consumption behavior. Also, steam conditioning was done "in a small horizontal mixer fitted with steam jets," instead of a dedicated steam conditioner, which may explain the lesser conditioning effect.

Protein and starch, and the functional properties of each, are typically included at levels determined by nutritional requirements of the target species. Therefore, changing the levels at the production facility for the sake of energy consumption or pellet durability is not likely. Another factor that is generally fixed by the formulation, due to the ingredients called for, is the overall moisture content of the diet. Research has been done to determine how altering this initial moisture content can affect pelleting.

In the experiments done by Gilpin et al. (2002), effect of mash moisture on pellet durability and energy consumption was examined. Increasing mash moisture improved PDI and energy consumption. Also, there was a moisture by retention time interaction effect on energy consumption, with higher mash moisture yielding lower energy consumption and shorter retention time showing a more dramatic effect than longer retention time. Moritz et al. (2002) found that adding five percentage points of moisture at the mixer to a broiler diet improved ($p<0.05$) pellet quality, and suggested that adding moisture at the mixer may offer a solution to pellet durability problems with formulations containing a high amount of fat.

The addition of fat to a pelleted diet can be very influential on pellet durability. It is assumed that fats coat the feed particles, making it more difficult for steam to penetrate and thus add moisture or transfer heat during the conditioning process. Fat also adds lubrication, both inherently as well as by keeping moisture at the surface of the particle. This leads to decreased friction, and thus compaction, in the pellet die. Fat, or oil content, has been shown to decrease pellet durability (Stark, 1994; Briggs et al., 1999). Stark (1994) reported that an addition of 1.5% and 3% fat decreased pellet quality by 2% and 5%, respectively. The addition of fat to the diet can reduce energy consumption due to the lubrication effect. However, the addition of fat or oils will not always affect pellet energy consumption (Briggs et al., 1999). This may be a result of an interaction with other processing variables or due to physical properties of the fat source used.

Distillers dried grains with solubles (DDGS) are a co-product of the fermentation of cereal grains. Most commonly these are corn-based, though sorghum-based DDGS can be sourced, and are a co-product of the fuel ethanol industry. The concentrating of protein in DDGS, approximately three times the amount of the raw cereal grain, and the relatively low cost, makes DDGS a very attractive ingredient in least-cost formulation. Unfortunately, the inclusion of DDGS in feed rations has caused problems in feed production facilities as processors have had to learn how to deal with a new, relatively high inclusion rate ingredient with different physical and processing properties.

Data gathered at Kansas State University showed that adding DDGS to the diet at 10% and 20% decreased pellet durability from 90.3 PDI for the control to 88.3 and 86.8 PDI, respectively (Fahrenholz, 2008). While the difference between the control and 20% DDGS treatment was statistically significant ($p<0.05$), the practical difference is likely negligible. Stender et al. (2008) pelleted diets that contained 0 and 20% DDGS. Pellet durability was found to decrease as the level of DDGS increased with durabilities of 78.9 PDI and 66.8 PDI for the levels of 0 and 20%, respectively. Feoli (2008) found an increase in pellet durability when adding 30% DDGS to pelleted diets, with PDI increasing from 88.5 PDI for the corn-soy control diet to 93.0 PDI with 30% DDGS. These differences in effects of DDGS on pellet durability lead to the conclusion that DDGS can have a major effect on pellet durability, but sometimes do not. Thus, there may be possible interactions unaccounted for in processing differences not described in these experiments.

Wang et al. (2007a) found that the quality of pellets decreased from a visual standpoint as DDGS were added to the diet at levels of 0, 15, and 30%, with diets containing 30% DDGS pelleting “extremely poorly” with many fines. However, pellet quality was not measured by any method other than visual observation, which leaves questions about overall pellet quality and durability. Min et al. (2008) found that an increased level of fines was produced as DDGS were added to swine diets in the starter, grower, and finisher phases, again at levels of 0, 15, and 30%. Starter diets were pelleted using a 2.38 mm (3/32”) die while grower and finisher diets were pelleted using a 4.76 mm (3/16”) die; no mention of die thickness is made. In this case, percentage fines was measured by sifting pellets over a 2 mm screen for 30 seconds. Fines increased from 1.0 to 12.0% in starter diets, 10.5 to 26.9% in grower diets, and 12.8 to 42.6% in finisher diets. However, as in Wang et al. (2007a), the amount of fat added to the diet as DDGS percentage increased rose significantly in order to retain isocaloric diets. This increase in fat could certainly explain a large amount of the increase in fines. In diets where fat level was kept constant, less variation was seen in the percentage of fines as DDGS level increased (Wang et al., 2008).

Chapter 2 - Examining Methods for Testing Pellet Quality

Pellet quality, the final ratio of pellets to fines consumed by the animal, is predicted by pellet durability, which tests the ability of pellets to be handled without generating excessive fines. In the United States durability is often measured in accordance with ASAE S269.4: Cubes, Pellets, and Crumbles--Definitions and Methods for Determining Density, Durability, and Moisture Content. This standard allows for the determination of a value known as the pellet durability index (PDI), which is the percentage of whole pellets remaining after a sifted sample has been tumbled according to the method described. The portion of ASAE S269.4 dealing with the determination of PDI has its basis in work presented in the proceedings of the 1962 Feed Production School sponsored by the Midwest Feed Manufacturers Association (Pfost et al., 1962). The method and equipment described have allowed feed manufacturers to analyze and compare pellet quality on a relatively consistent basis for five decades.

Instead of the tumble box method described in ASAE S269.4, some processing facilities are using one of the TekPro (Norfolk, GBR) manufactured line of Holmen pellet testers (NHP 100, NHP 200, NHP 300) distributed by Borregaard LignoTech (Sarpsborg, NOR) in the United States. These devices are an update of the previous Holmen pellet tester, and like that model use pneumatic pressure to agitate a 100 gram sample for a fixed period of time. The NHP 100 is the most commonly used of the new testers, and is referred to as the “portable” model. The NHP 100 agitates the pellets in a pyramid-shaped perforated chamber during testing. The fines exit the chamber, avoiding the need for a final sifting step, and the test can be run for 30, 60, 90, or 120 seconds. This test is faster and more portable than the tumble box, but little is known about how the results of each method compare.

The only documented comparison of the tumble box and NHP testers was provided by Winowiski (1998), an employee of Borregaard LignoTech. He described the relationship of the NHP to the tumble box procedure as well as to an original Holmen pellet tester. He stated that the NHP was more destructive than either the standard or modified PDI test, but correlated well with both, while being very similar overall to the original Holmen tester. It also appears from the data presented that both the NHP device and the original Holmen tester were more sensitive to changes in pellet quality that may be a result of changing factors in formulation or production practices.

The tumble box has been the pellet quality testing method of choice in the U.S., and is the only method defined by a science-based standard method. However, the portability and shorter time for each test has made the NHP an attractive option. If significant correlations existed between the results of the tumble box and the NHP, the results of one test could then be used to predict the results of the other. Thus, pellet durability could be compared between two facilities using different testing methods and equipment. In the best case scenario, one time interval on the NHP 100 would correspond with the results from the tumble box. It may also be found that the different devices are better suited for different ranges of pellet quality, e.g. the use of the NHP-100 for very high quality pellets and the tumble box method for medium to low quality pellets.

The objectives of the research described in this chapter were: (1) to determine whether one method of pellet durability testing is superior to the other in terms of providing repeatable results across a range of pellet qualities, and (2) to determine what relationships might exist between the two methods that would allow for predicting pellet quality results from one method from known results of the other. The hypotheses were: (1) that the tumble box method would be superior because of a larger sample size and less aggressive pellet movement, and (2) that only weak correlations might exist between the results of the tumble box and Holmen testers.

Materials and Methods

The samples analyzed in pursuit of the experimental objectives consisted of representative durabilities manufactured in order to satisfy the experimental objectives presented in Chapter 4. These samples were manufactured using combinations of seven dependent variables in order to determine the effect each variable had on pellet durability. This research was conducted first in order to determine the superiority of one method over the other, and to use that method in subsequent data analyses.

The manufacture of twenty nine treatment batches was replicated four times across a two-week period, with each week used as a block containing two replications of each treatment. The pellet samples representing the two replications were collected at separate points within a single batch-run of feed in order to reduce experimental error in PDI values. The treatments were manufactured randomly throughout the week, and all ingredients were procured from a single source or lot. Two of the dependent variables were distillers' dried grains with solubles (DDGS) and fat, with each being included at two different rates. There were a total of four formulations (Table 2.1), with each being formulated to supply similar protein, energy, and mineral values, in accordance with basic nutritional requirements for broilers according to the National Research Council (NRC, 1994). The diets were formulated based on the addition of three percent fat, with the assumption that the diets with one percent fat would have the remainder post-pellet coated prior to feeding. Pellets were manufactured on a CPM Master Model 1000 HD pellet mill (Crawfordsville, IN).

Pellets were collected immediately upon discharge from the pellet mill and placed into cooling trays at a depth of approximately 3.8 cm (1 ½ inches). Pellets were then cooled with ambient air in a locally constructed batch cooler. When pellets reached a temperature within 2.8°C (5°F) of the ambient temperature, as measured by an infrared temperature gun (Fisher Scientific, 15-077-968), they were removed from the cooler and immediately tested. These steps were in accordance with the ASAE Standard S269.4 (ASAE, 1997) specifying that pellets be tested directly after cooling. If testing cannot be done immediately, the standard requires that subscripts are added to PDI values to denote, in hours, the amount of time between cooling and testing.

Each sample was split into six subsamples and then tested with the KSU tumble box (standard and modified) and the Holmen NHP 100 (TekPro; Norfolk, GBR). The standard tumble box method used a device locally constructed and operated in accordance with the requirements of ASAE Standard S269.4 (ASAE, 1997). A variation, hereafter referred to as "modified PDI", included five 1.3 cm (½ inch) hex nuts in the compartment. Two sub-samples were sifted over a U.S. #6 sieve to remove all fines, and then 500 grams (±0.5g) of each was placed into one of the tumbling can compartments. For the modified method the hex nuts were then added to the compartment. The sub-samples were tumbled at 50 RPM for a period of ten minutes in accordance with S269.4. Each sub-sample was then sifted over the same screen to remove fines and then re-weighed. The final weight of pellets was then divided by the initial weight of pellets to determine PDI, and reported as a percentage. The tumbling box compartments were cleaned out by hand after testing each sample in order to remove any fines build-up in the corners.

The remaining other four sub-samples were tested in the NHP 100 at each of the four selectable run times of 30, 60, 90, and 120 seconds. Sub-samples were sifted over a U.S. #6 screen to remove all fines, and then 100 grams of a sub-sample was placed into the testing chamber. The filter tissue placed over the chamber was used for a full sample run (each of the four run times) and then discarded. The run times were checked twice daily against a stopwatch. As pellets were emptied from the testing chamber, each side was tapped and brushed by hand to remove any pieces lodged within the perforations. These were counted in the final weight as they did not exit the chamber along with the fines. Fines were removed from the waste chamber after the four sub-samples were tested. The final weight of pellets was then divided by the initial weight of pellets to determine PDI, and reported as a percentage.

Statistical analysis was completed using the general linear model in SAS (v. 9.1.3). The range between the two PDI values obtained for each treatment and within each block was determined and used as a value for evaluating repeatability for each testing method. The average range between values for each testing method was compared using Tukey's studentized range for pairwise analysis. Testing methods were compared to determine whether any correlations existed between them. Where significant correlations existed, statistical models for determining PDI were identified.

Results and Discussion

The pairwise analysis of the range averages (Table 2.2) showed that the tumble box provided for the most consistent results. The standard method provided lower ranges ($p<0.05$) than the NHP 30, 60, 90, and 120 second tests, while the modified method was only lower ($p<0.05$) than the NHP 60, 90, and 120 second tests. There was no significant difference in range between the NHP 30 and 60 second tests, or between the NHP 60, 90, and 120 second tests. Because the samples used to calculate the ranges were taken from the same batch-run, it was assumed that any differences in PDI were due the test itself, rather than variability within the samples.

The importance of the narrower ranges can be viewed in terms of both experimental and practical significance. From an experimental standpoint, the narrower range indicates that the results can be used to more precisely evaluate, model, and predict the effects on pellet durability because of the smaller experimental error. In practical terms, the narrower range is important because it reduces the amount of "noise", and allows for a more consistent tracking of pellet durability, and a greater ability to determine when a product is outside the normal specifications.

As seen in Figures 2.1 through 2.5, PDI values determined by each testing method decreased in the following order: standard PDI, modified PDI, NHP 30, NHP 60, NHP 90, and NHP 120. This was consistent with the order of increasing destructiveness. Greater destruction also supports the trend seen in Table 2.2, with more destructive tests leading to larger differences in PDI within samples assumed to be equal. It should be noted that there are points in each figure representing the lowest PDI results that appear to be possible outliers. For the analyses presented in Chapter 4, this was indeed found to be the case, likely because of a feed mixing error. However, these points do represent samples that were collected and analyzed correctly for PDI. Therefore, while they are much lower than the other samples analyzed, they do represent valid points for PDI comparison among the methods, and are not considered outliers in this chapter.

One question that arises is whether any of the methods may be more suited to consistently determine PDI when pellet durabilities are known to be high or low. In order to examine this question, the methods were evaluated to determine whether any significant correlations existed between the ranges and the average of the PDI values used to determine the ranges. Plots of these relationships are shown in Figures 2.6 through 2.11. The only test for which a significant correlation was found was the Standard PDI method (linear, $p<0.02$); however, the R^2 value was very low at 0.10, and thus the model is not considered to impart any useful information. Overall, the lack of significant correlation is important because it showed that no one test is more consistent than the others at different PDI levels.

During the course of the experiment, a possible problem with the NHP tests came into evidence. The tumble box results would not have been affected by how many times or how often tests were run because there are no changing variables within the testing chambers. However, it may be that short interval testing had an effect on the NHP, as running the tests in short order "warms-up" the device, leading to higher air temperatures and changes in the operating pressure. In the present experiment, it is possible that the first samples analyzed were either more or less repeatable than samples run at the end of the day. A short post-trial experiment was conducted to examine this possibility. A single sample of pellets that was manufactured one week earlier was collected, mixed, and split. The split sample was then analyzed using each of the four time periods, run sequentially. This process was repeated four times, allowing only enough time for reloading between each run and clean-out after each four-run set. The results of this experiment are shown in Table 2.3. It appears that short interval testing may indeed increase both the pressure and temperature of the forced air. The results also suggest that even a single split sample may yield a range of PDI values, as the range increased with test time. These observations support the conclusion that the NHP may not be suitable to run frequent or sequential analyses.

Each method was compared to each other method by modeling the PDI results of less destructive test versus the PDI results of more destructive test (e.g. Standard PDI versus Modified PDI.) The plots of Standard PDI versus each of the other methods are shown in Figures 2.1 through 2.5. Each comparison was examined for a statistically significant linear, quadratic, and logarithmic relationship. The R^2 value was determined when a significant relationship existed. Significant relationships with R^2 values greater than or equal to 0.90 are reported in Table 2.4. Where both conditions were met by different relationship types (linear or logarithmic), the relationship with the highest R^2 value was reported.

The results of the post-trial NHP experiment reported in Table 2.3 were useful in evaluating some of the correlations described above. As this subsequent experiment was independent, it provided a good opportunity to validate the predictive equations shown in Table 2.4. Taking into consideration only the NHP methods, five relationships were found to exhibit R^2 values greater than 0.90. The corresponding equations for these five relationships were used to predict PDI values for NHP methods based on the known results from the post-trial experiment. These predicted values were then compared to the known values for the respective NHP methods. The average residuals and percentage variation were then determined and are shown in Table 2.5. The results demonstrate that the regression models were able to accurately predict PDI values for an independently collected series of samples.

Conclusions

In regards to the first objective, based on the results of this research the tumble box provides for the most consistent and repeatable evaluations of pellet durability. Therefore, it remains the superior method compared to the Holmen line of pellet testers. This is likely due to the following factors: (1) the larger sample size (500g vs. 100g) provides for a more representative sample that will less likely contain disproportionally high or low durability pellets, and (2) the tumble box equipment is also simpler in design and easier to operate. Thus, there are fewer sources of error causing variation in measured PDI. The tumble box is also superior because tests can be run often and sequentially without concern of equipment variation.

Of the methods evaluated, four were found to correlate well with each other (PDI, Modified PDI, NHP 30, and NHP 60). This satisfies the second objective and demonstrates that it may be possible for facilities to compare pellet durability while using different testing methods. The regression models that were developed allowed for the creation of the equations shown in Table 2.4. These equations can be used to predict the PDI that might be reported for one test based on the known results of another. The logarithmic relationships that exist when making comparisons using the more destructive NHP tester demonstrate that it may not be the best choice when evaluating low durability pellets. It is apparent that with low pellet quality, the PDI variation between samples would be artificially low simply because the results are approaching zero. The same situation would exist with high durability pellets and the less destructive tumble box tester, with less reported variation at Standard PDI values above 90%. However, the samples analyzed in this experiment were not of high enough quality to verify this hypothesis.

More information must be gathered to definitively state that these correlations would remain accurate across multiple diet types and large variations in feed quality. Each method likely has its place in evaluating pellet durability, dependent on feed type and quality, necessity of portability and quickness of test, and overall repeatability. While the NHP may be a good choice for industrial applications, it does appear the standardized tumble box method (ASAE S269.4) remains the best choice for specific analytical and experimental situations.

Table 2.1: Ingredient Composition of Feed Rations Manufactured for Pellet Durability Analysis.

	% Inclusion			
Ingredient	**Diet 1**	**Diet 2**	**Diet 3**	**Diet 4**
Corn	64.60	64.60	59.70	59.70
Soybean Meal, 48%	29.65	29.65	24.75	24.75
DDGS	-	-	10.00	10.00
Soybean Oil	3.00	1.00	3.00	1.00
Monocalcium Phosphate, 21%	0.60	0.60	0.30	0.30
Calcium Carbonate	1.90	1.90	2.04	2.04
Salt	0.25	0.25	0.21	0.21
Total	**100.00**	**98.00***	**100.00**	**98.00***

* Diets 2 and 4 are equal to diets 1 and 3, respectively, except for the removal of 2% soybean oil. This was done to represent a complete diet where the soybean oil would be added via a post-pellet liquid application system rather than in the batch mixer prior to pelleting.

Table 2.2: Average Ranges of Replicated PDI Values within a Block

Tumble Box		**NHP**			
Standard	Modified	30 Sec	60 Sec	90 Sec	120 Sec
0.68^{A}	$1.01^{A,B}$	$1.61^{B,C}$	$2.08^{C,D}$	2.85^{D}	2.62^{D}

$^{A, B, C, D}$ Means within a row with different superscripts are significantly different ($p<0.05$)

Table 2.3: Effect of Sequential NHP Tests on PDI, Air Pressure, and Air Exhaust Temperature

	NHP Time (seconds)	Replication Sequence 1	2	3	4
PDI (%)	**30**	84.77	85.34	84.50	83.68
	60	70.01	66.85	67.67	67.19
	90	55.71	52.04	55.42	48.25
	120	41.16	41.94	47.50	35.05
Air Pressure (millibar)	**30**	70	71	72	72
	60	70	71	72	72
	90	70	71	71	71
	120	70	71	72	72
Air Temperature (°F)	**30**	70.4	84.1	87.0	87.0
	60	78.6	87.6	88.9	89.7
	90	85.6	89.4	90.2	90.3
	120	88.8	90.7	91.2	91.5

Table 2.4: R^2 Values and Predictive Equations Determined by Correlating Six Methods for PDI Analysis

Model y	x	Relationship	R^2	Equation
PDI	Modified PDI	Linear	0.99	y = 24.67 + 0.75x
PDI	NHP 30	Linear	0.93	y = 34.36 + 0.62x
PDI	NHP 60	Logarithmic	0.90	y = 11.04 + 17.71 ln(x)
Modified PDI	NHP 30	Linear	0.94	y = 13.34 + 0.83x
Modified PDI	NHP 60	Logarithmic	0.92	y = -18.34 + 23.71 ln(x)
NHP 30	NHP 60	Logarithmic	0.98	y = -37.89 + 28.53 ln(x)
NHP 30	NHP 90	Logarithmic	0.93	y = 3.81 + 19.74 ln(x)
NHP 60	NHP 90	Logarithmic	0.96	y = -50.82 + 29.82 ln(x)
NHP 60	NHP 120	Logarithmic	0.97	y = -20.40 + 23.73 ln(x)
NHP 90	NHP 120	Linear	0.96	y = 12.03 + 0.96x

Table 2.5: Average Residuals and Percentage Variation when Comparing Observed PDI Values in Table 2.3 to Predicted Values Determined Using Equations Shown in Table 2.4

Known NHP Method	Predicted NHP Method	Average Residual[1] (PDI)	Average Variation[2] (%)
60	**30**	2.1	2.5
90	**30**	2.5	2.9
	60	1.3	1.9
120	**60**	2.7	3.9
	90	2.3	4.3

[1] Calculated as the absolute difference between the predicted and observed value

[2] Calculated as 1 – (predicted value / observed value)

Figure 2.1 Standard PDI vs. Modified PDI with Plotted Regression Equation

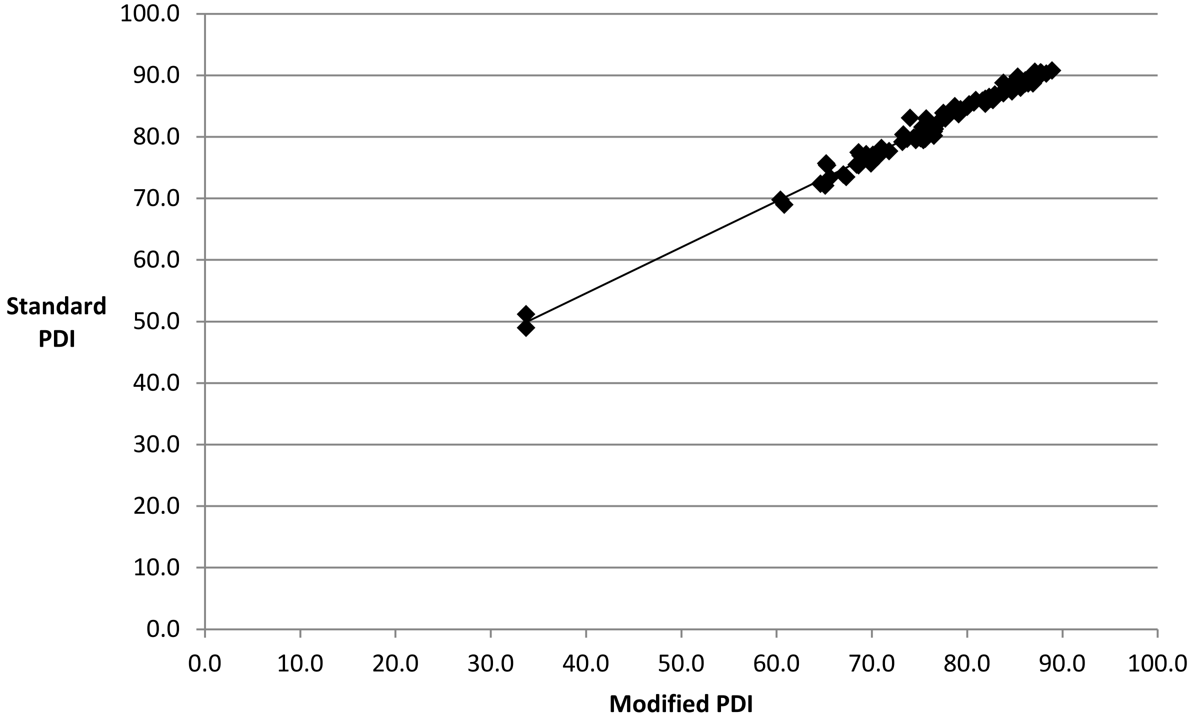


Figure 2.2 Standard PDI vs. NHP 30 with Plotted Regression Equation

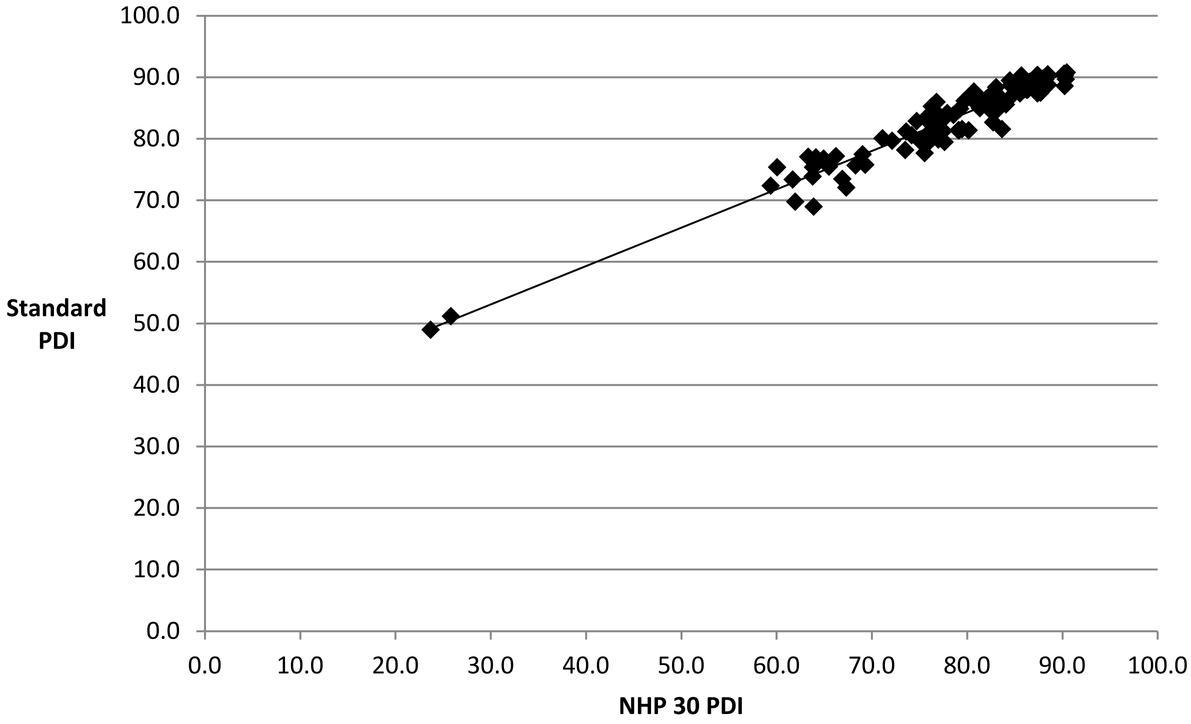


Figure 2.3 Standard PDI vs. NHP 60 with Plotted Regression Equation

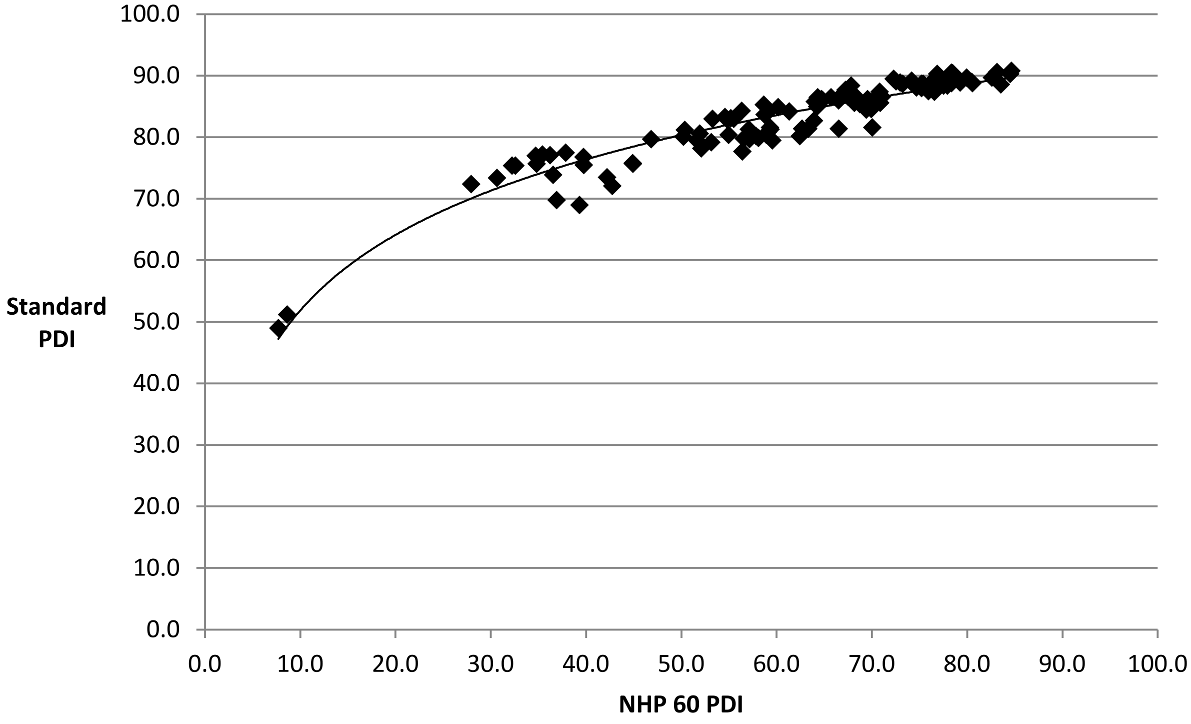


Figure 2.4 Standard PDI vs. NHP 90

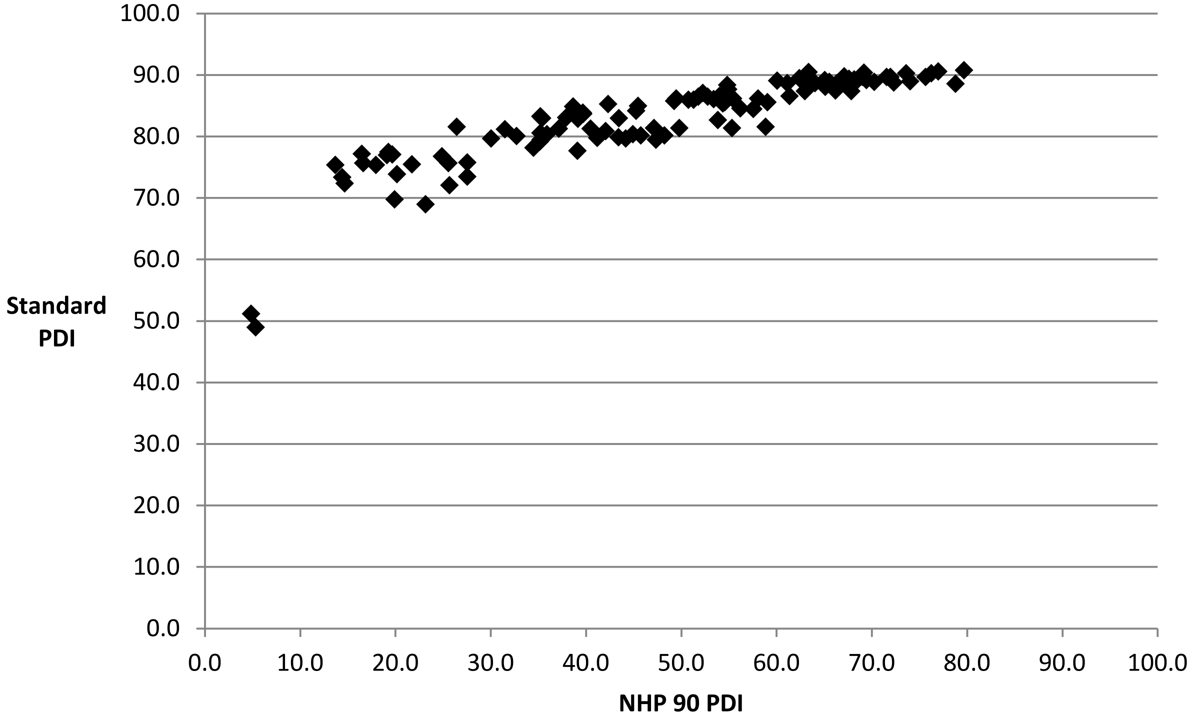


Figure 2.5 Standard PDI vs. NHP 120

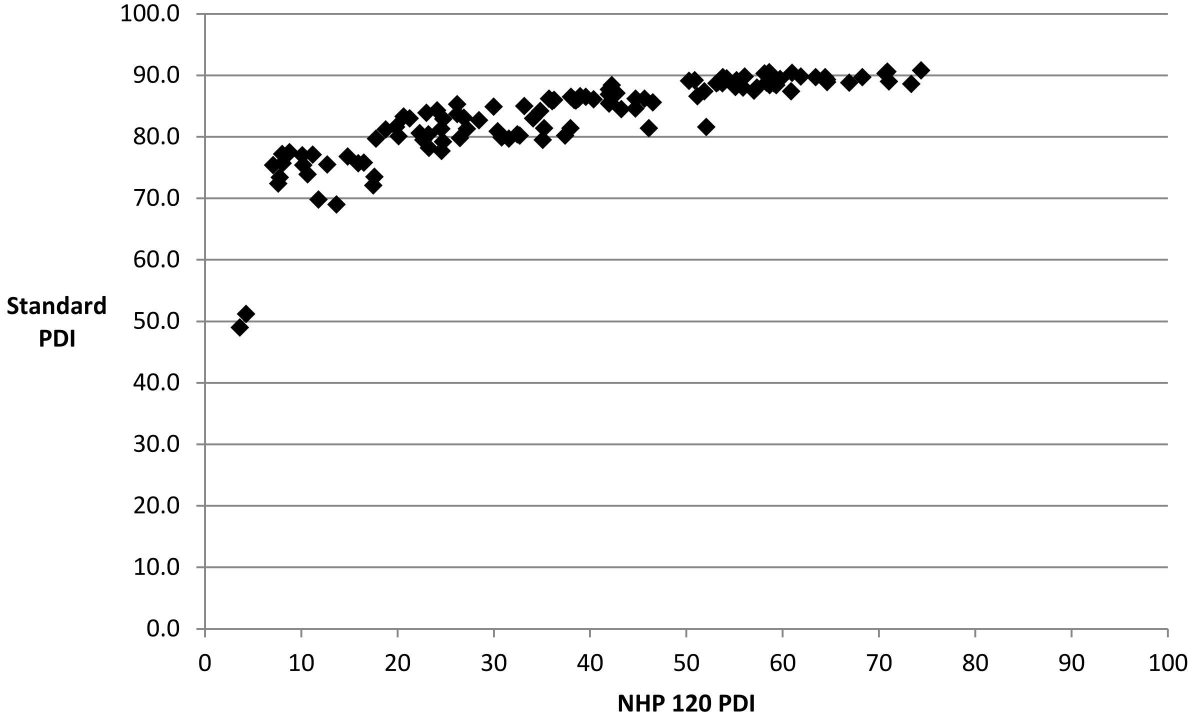


Figure 2.6 Range of Replicated Standard PDI Values within a Block vs. Standard PDI

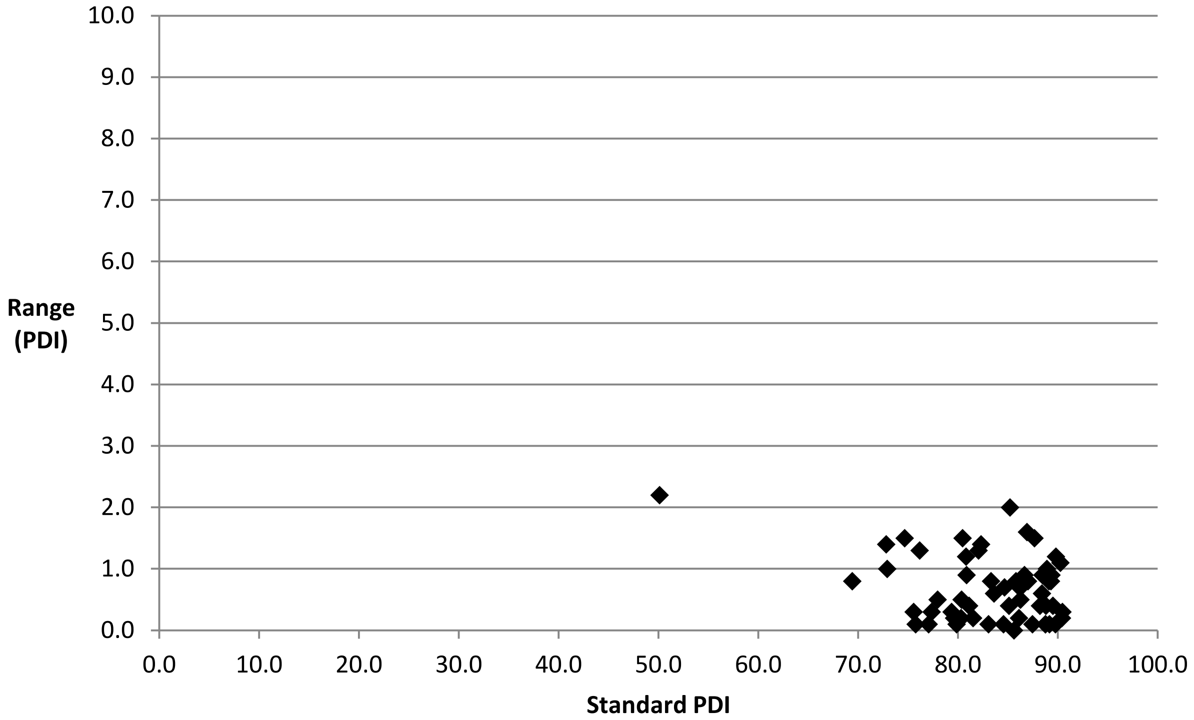


Figure 2.7 Range of Replicated Modified PDI Values within a Block vs. Modified PDI

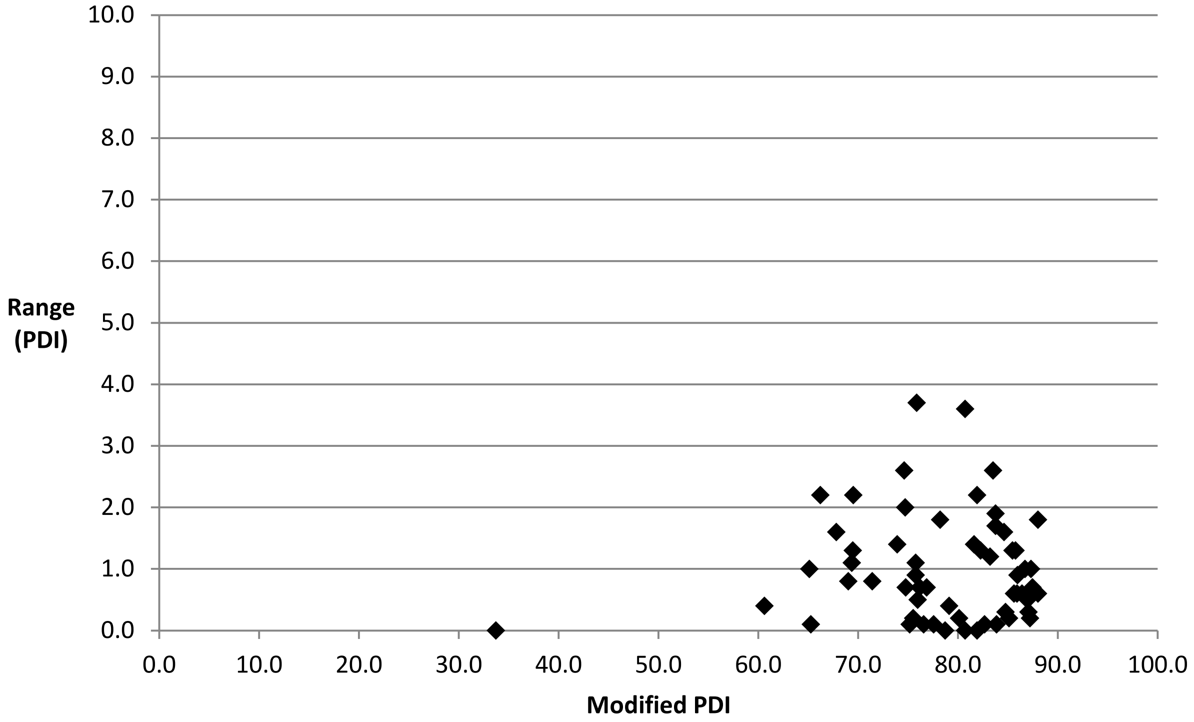


Figure 2.8 Range of Replicated NHP 30 PDI Values within a Block vs. NHP 30 PDI

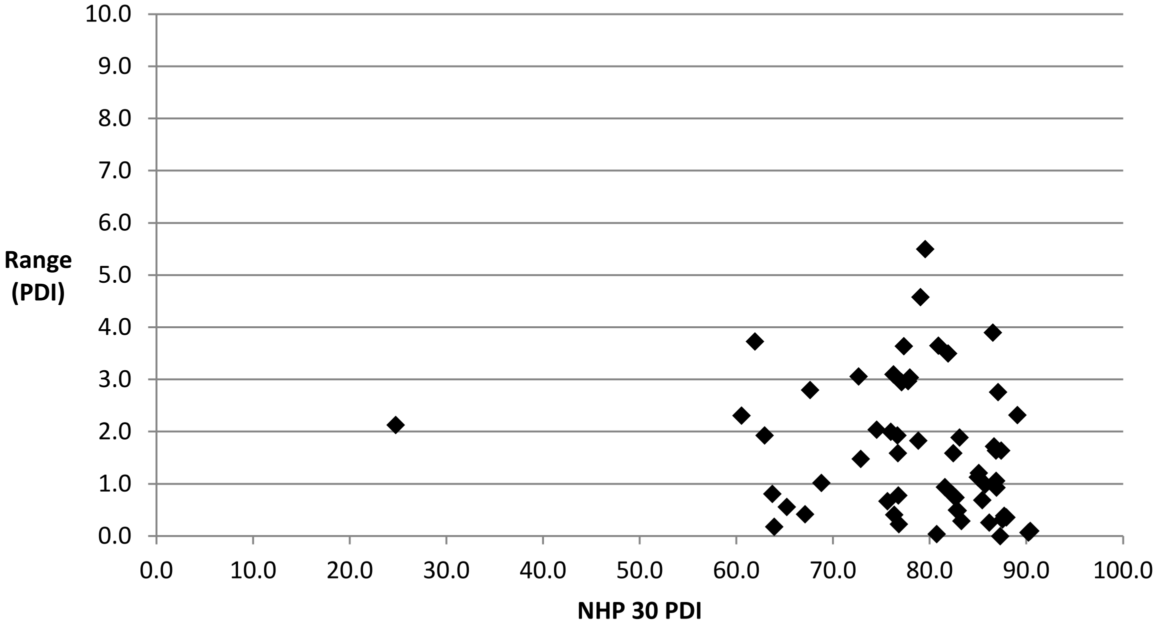


Figure 2.9 Range of Replicated NHP 60 PDI Values within a Block vs. NHP 60 PDI

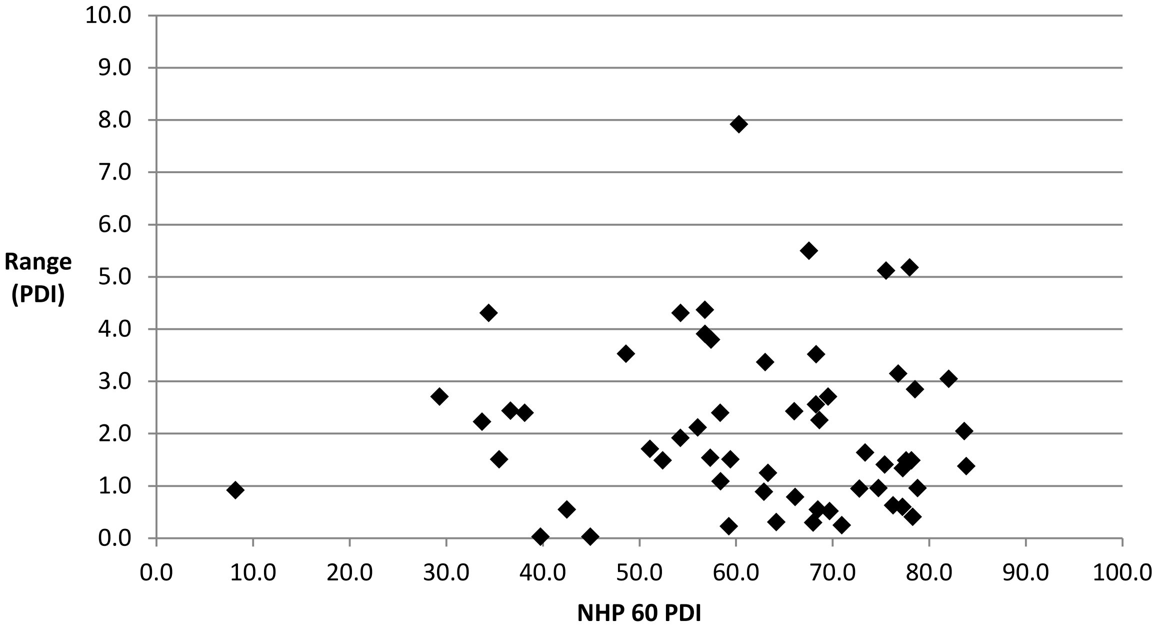


Figure 2.10 Range of Replicated NHP 90 PDI Values within a Block vs. NHP 90 PDI

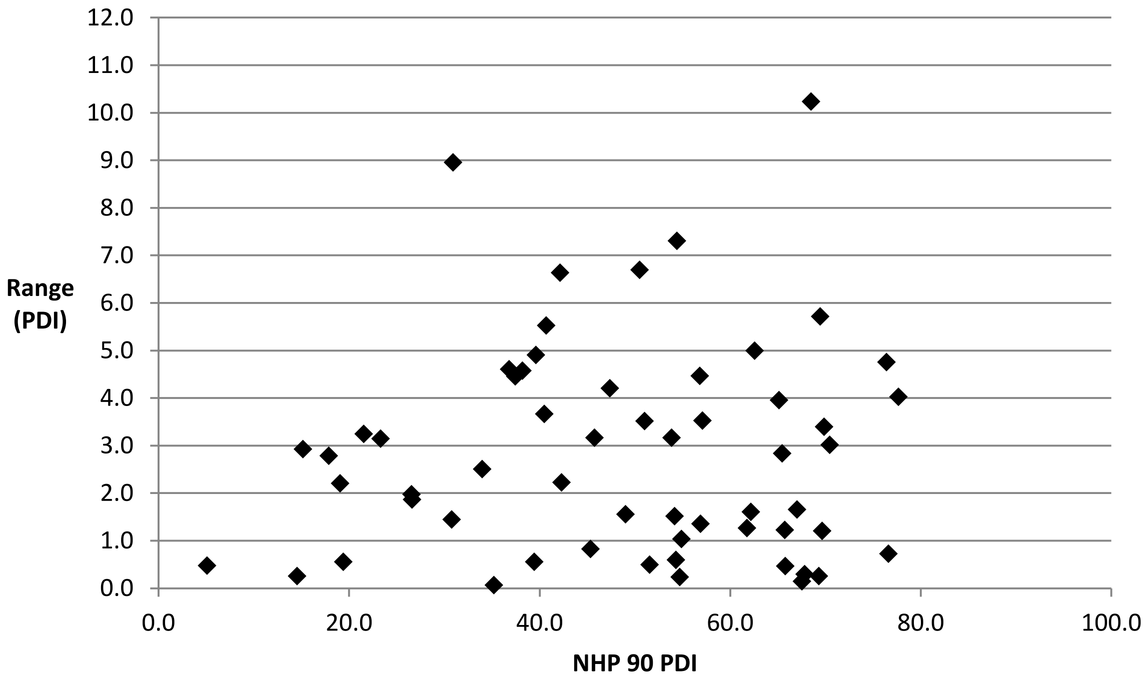
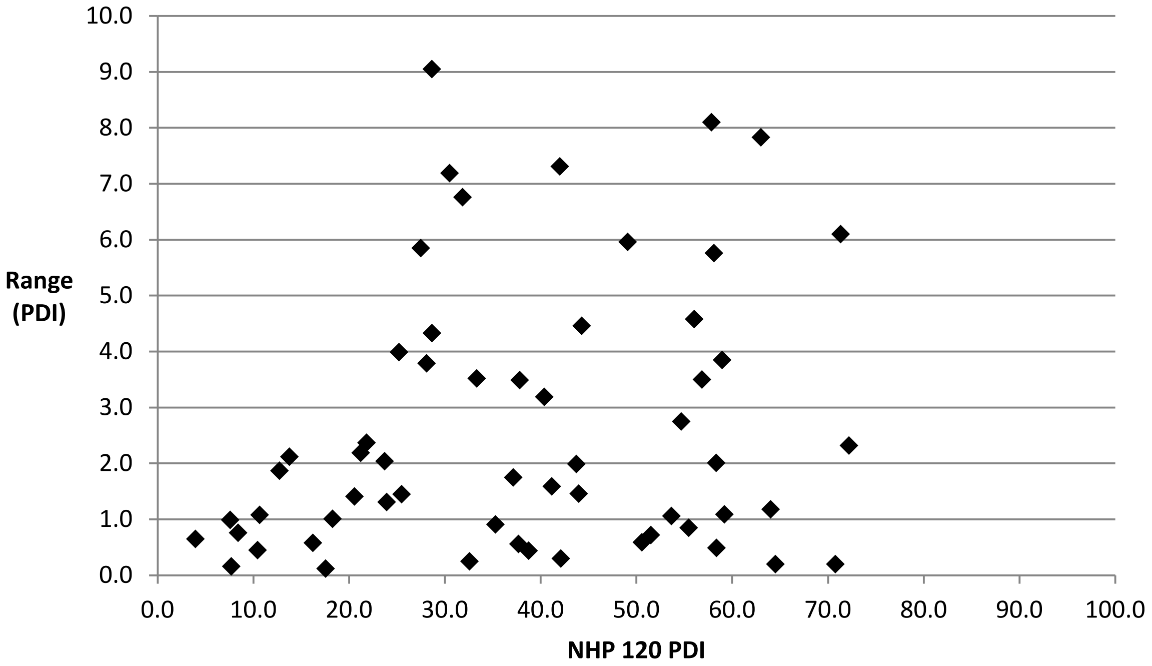


Figure 2.11 Range of Replicated NHP 120 PDI Values within a Block vs. NHP 120 PDI



Chapter 3 - Effects of Physical Properties of Feed Pellets and Dependent Processing Variables on Pellet Durability

Methods such as the tumble box and NHP are empirical, meaning that they do not specifically measure a single attribute such as hardness or elasticity, which from a scientific standpoint would be preferable. Pfost et al. (1962) stated that measuring pellet hardness as a method to determine pellet durability was relatively ineffective for correlating fines production in a model system. However, in those experiments hardness was measured using spring–type compression testers, which are not particularly precise, and whose accuracy is questionable due to the human error factor.

Thomas and Van der Poel (1996) compared pellet hardness as measured by three compression and/or shear devices to PDI results provided by an original Holmen pellet tester and the tumble box method. The durability testers appear to be more consistent than the compression or shear devices, with lower coefficients of variation (CV) among the replications. The tumble box had lower CV values than the Holmen tester. In all cases, the CV increased as hardness/durability decreased. For these experiments, the pellets were made of pure barley, and were therefore of much higher quality than a typical broiler or swine corn-soy based ration. Salas-Bringas et al. (2007) conducted a similar experiment, but used a modern computer controlled texture analyzer. The authors found that texture analysis, i.e., measuring the tensile stress as a function of first-peak force, did not correlate well with pellet durability as determined by an original Holmen tester.

In addition to pellet hardness, there are other factors that might also have an effect on pellet durability. Some of these are related to formulation components and processing variables. The density of feed pellets is related to the initial bulk density of the material and is affected by the compression occurring within the pellet die. It has been assumed that higher densities would describe more compact pellets, and lead to greater pellet durability. Retention time within the pellet die might also affect pellet durability. Retention time is a variable dependent on density, production rate, and die L:D ratio. Thus, it is related to the amount of friction and compaction generated during processing. A prolonged exposure to the heat imparted by the pellet die, which acts somewhat as a heat sink, has been suggested to have some relationship to pellet durability because of an increased "cook," as suggested by Stevens (1987), who suggested that it is movement through the pellet die that has an impact on starch gelatinization.

The moisture level throughout processing can also have an effect on pellet durability. Starting mash moisture is determined by the moisture content of the ingredients in the formulation. In experiments conducted by Gilpin et al. (2002), the researchers examined the effect of mash moisture on pellet durability and energy consumption. They found that increasing the mash moisture positively influenced both factors. Moritz et al. (2002) found that adding five percent moisture in the mixer to a broiler diet ($p<0.05$) improved pellet durability. Feed moisture is also dependent on the amount of steam added during conditioning, and on the amount of evaporation when exposed to the high temperatures inside the pellet die. Final pellet moisture is also certainly dependent on cooling and drying, and while these factors were not examined in these experiments, it is prudent at this point to examine what relationships might exist between the final moisture level and determined pellet durability.

The objectives of the research described in this chapter were to determine whether a relationship exists between pellet durability and (1) pellet hardness, (2) pellet density, (3), pellet die retention time, and (4) initial and final moisture.

Materials and Methods

For comparisons between pellet durability and pellet hardness, hardness was measured by determining the force of first fracture of individual pellets using a Texture Analyzer (Model TA-XT2i, Stable Micro Systems, Surrey, United Kingdom), and Texture Exponent 32 analysis software (Stable Micro Systems, Surrey, United Kingdom). The force (kg) required to crush a pellet was determined by evaluating the peak amount of force applied before the first fracture occurred. Fifteen pellets were analyzed from each of the 116 separate pellet samples. Pellets were chosen that were between 10mm and 12mm in length, in order to minimize the effect of surface area on results. Pellets were crushed perpendicular to their longitudinal axis. It was determined that it was impractical to attempt crushing also in a vertical direction, with no appropriate way to stabilize the pellets in a vertical orientation.

Before comparing hardness to pellet quality, the texture analysis results were normalized according to the pellet length and resulting contact surface area to determine if a force value of kg/cm^2 was more appropriate for final analysis. However, since no significant differences were found between the simple and normalized results, the former values were used, where force of first fracture is described in kilograms. An average force of first fracture was determined for each of the 116 samples and was then used to compare to the relative PDI values for each experimental unit. The maximum and minimum forces of first fracture were also determined and compared to PDI in the expectation that they might relate more closely than the average.

Individual pellet density was calculated as pellets were chosen for hardness testing. The fifteen pellets selected were measured using digital calipers to the nearest 0.01mm, and weighed to the nearest 0.0001g. Final values were expressed as g/cm^3. Similar to pellet hardness, the fifteen determined densities for each sample were averaged and the minimum and maximum values were determined. Pellet bulk density was determined using an 80mL cylindrical container. The small sample size was used in order to limit the effect of compression on the results. Pellets were sifted to remove any fines, poured into the cylinder, and leveled by striking off the overflow using the edge of a ruler. The mass was then recorded and density determined. Three replications were conducted for each of the 116 pellet samples, and average, minimum, and maximum values were recorded.

Die retention time was calculated using the individual pellet densities and the determined production rate for each run. The total number of die holes was counted for both the 8:1 (5/32” x 1 ¼”) and 5.6:1 (5/32” x 7/8”) pellet dies, and thus total holding volume could be determined. The 8:1 die was determined to have a holding capacity of 37.15 in^3 while the 5.6:1 die had a holding capacity of 24.83 in^3. Knowing the pellet density for each specific experimental unit, the total mass held within the pellet die was then calculated. This value was then divided by the determined production rate to estimate an average retention time, expressed in seconds.

Moistures were determined for the mash, conditioned mash, hot pellets, and cooled pellets via AACC International Method 44-19.0, Air Oven Drying at 135°C. Duplicate samples were collected at the mixer, and mash and pellet samples were taken during and after processing for each experimental unit. Samples were immediately frozen, and were kept in the freezer until moisture analysis was conducted.

Statistical analysis was completed using the general linear model in SAS (v. 9.1.3). Each individual factor was initially analyzed to determine if significant differences existed between treatments. Where significance was found, a regression model was created using the respective factor and PDI to determine if a significant relationship existed. If a significant relationship was found, the values were plotted for visual comparison.

Results and Discussion

For every variable examined, there were significant differences in values across treatments. While these results did not determine that the variables were related to pellet durability, it did show that the variables were affected by the factors examined throughout the experiment, and were thus worthy of investigation. Most variables exhibited some significant relationship to pellet durability, though the relationships were far from predictive. The plots of those variables that had a significant relationship with PDI can be found in Figures 4.1 through 4.11. The variable that did not have any significant relationship with pellet durability was individual pellet density. This was attributed to the low individual masses, and the difficulty in determining the exact volumes of pellets as they were not perfectly cylindrical. A more accurate method for determining the exact volume needs to be developed in order to further investigate whether individual density has a significant relationship with PDI.

Before proceeding further, it should be noted that there are points in each figure representing the lowest PDI results that appear to be possible outliers. For the analyses presented in Chapter 4, this was indeed found to be the case, likely because of a feed mixing error.

However, these points do represent samples that were collected and analyzed correctly for PDI and the variables discussed in this chapter. Therefore, while they are much lower than the other samples analyzed, they do represent valid points for comparison among the methods, and are not considered outliers here.

Pellet bulk density was found to have a significant relationship with pellet durability when comparing PDI to average density ($p<0.0001$), maximum density ($p<0.0001$), and minimum density ($p<0.0001$). Figures 4.1 through 4.3 illustrate the plotted relationship of PDI vs. bulk density. A trend is visible in all three figures, with higher bulk density correlating weakly ($R^2 <0.2$ in all cases) with higher pellet quality. This suggests that more compact pellets will exhibit higher pellet quality, which is a logical conclusion. Additionally, the fact that pellet bulk density had a significant relationship, while individual density did not, suggests that the larger sample size was more appropriate in making determinations on pellet durability attributes.

Fracture force had a significant relationship with pellet durability when comparing PDI to average fracture force ($p<0.001$), maximum fracture force ($p<0.002$), and minimum fracture force ($p<0.0002$). Figures 4.4 through 4.6 show the plotted relationship of PDI vs. fracture force. There is a weak correlation between fracture force and PDI, with the minimum fracture force having the highest correlation coefficient ($R^2 = 0.12$). It appears that the highest fracture forces correspond with high PDI values, while lower fracture forces may be found for pellets exhibiting both high and low PDI values.

Die retention time was found to have a significant ($p<0.0005$) relationship with pellet durability, with longer retention time tending to correlate with higher PDI values, as can be seen in Figure 4.7. However, the correlation is weak ($R^2 = 0.10$) and thus retention time alone is not a major factor influencing pellet quality. This is in some agreement with the three factors that are used to calculate die retention. The inconclusive data concerning individual pellet density, as well as the lack of an effect on PDI by feed rate and the large effect on PDI by die L:D ratio as discussed in the previous chapter, all help to explain the existing but weak relationship seen here. The positive relationship is driven primarily by die thickness leading to increased retention, while the feed rate and pellet density only add noise to the model.

Moisture content related significantly to PDI when evaluating mash moisture ($p<0.04$), hot pellet moisture ($p<0.01$), and cooled pellet moisture ($p<0.0003$), while conditioned mash moisture was found to have no significant relationship (Figures 4.8 through 4.11). However, there is a very weak correlation in each comparison, with only a slight trend exhibited where higher moisture content leads to improved pellet quality, in agreement with the literature. A lack of a major relationship was to be expected, as the ranges in moistures were not large, and were only due to formulation and conditioning variation, where other experiments have added significant amount of moisture in the form of free water at the mixer or steam conditioner.

However, there are some interesting observations to be made concerning moisture to PDI relationship. The lack of a significant relationship between conditioned mash moisture and PDI suggests that moisture content alone is not responsible for the improvement seen in pellet durability when conditioning at increased temperatures. There is a possibility that the high temperature itself plays an important role, and that as moisture level increases beyond a certain threshold it will no longer lead to an improvement in pellet durability. Another observation is that, when comparing the conditioned mash moisture and hot pellet moisture, there is no substantial moisture loss across the pellet die. Finally, there is a trend that higher cooled pellet moisture leads to higher observed PDI values. More importantly, the cooled pellet moistures are relatively high, and are higher on average than the original mash moisture. This demonstrates that cooling to ambient temperature may not adequately dry pellets in all situations.

Conclusions

The physical variables of pellet density, hardness, and moisture content, along with the processing variable of die retention were found to have significant relationships with pellet durability. Unfortunately, each of these is a dependent variable, and can only be measured or observed rather than fixed during processing. This relates to the relatively weak associations with PDI, and makes it difficult to use these variables to predict pellet durability. However, understanding the underlying relationships is certainly valuable, and can be used to make some determinations and decisions on processing effectiveness.

The pellet density and hardness observations suggest that pellet durability is best tested by methods using a large quantity of sample and that closely represent actual handling practices. For example, fracture force is significantly related to pellet durability, but the test uses individual pellets and is time consuming. Therefore, it is only practical to test a relatively small number of pellets (15 in these experiments). This small sample size is not enough to achieve a useful explanatory model. Additionally, high PDI pellets were found to have both high and low fracture force, which led to a weak correlation. These conclusions suggest that fracture force is not a complete predictor of pellet durability as evaluated by the tumble box method. However, the data does demonstrate that hard pellets do make for durable pellets, and so making an effort to produce such pellets is worthwhile.

The data suggested that high final pellet moisture leads to high PDI values. This data supports an effect of cooling on final pellet quality and also raises questions as to whether the standard method for testing pellets adequately addresses moisture content. Under ASAE Standard S269.4, pellets are tested when they reach ambient temperature, without mention of moisture content relative to the starting mash moisture. Examining this relationship is a possible focus for future research.

Figure 3.1 PDI vs. Average Pellet Bulk Density

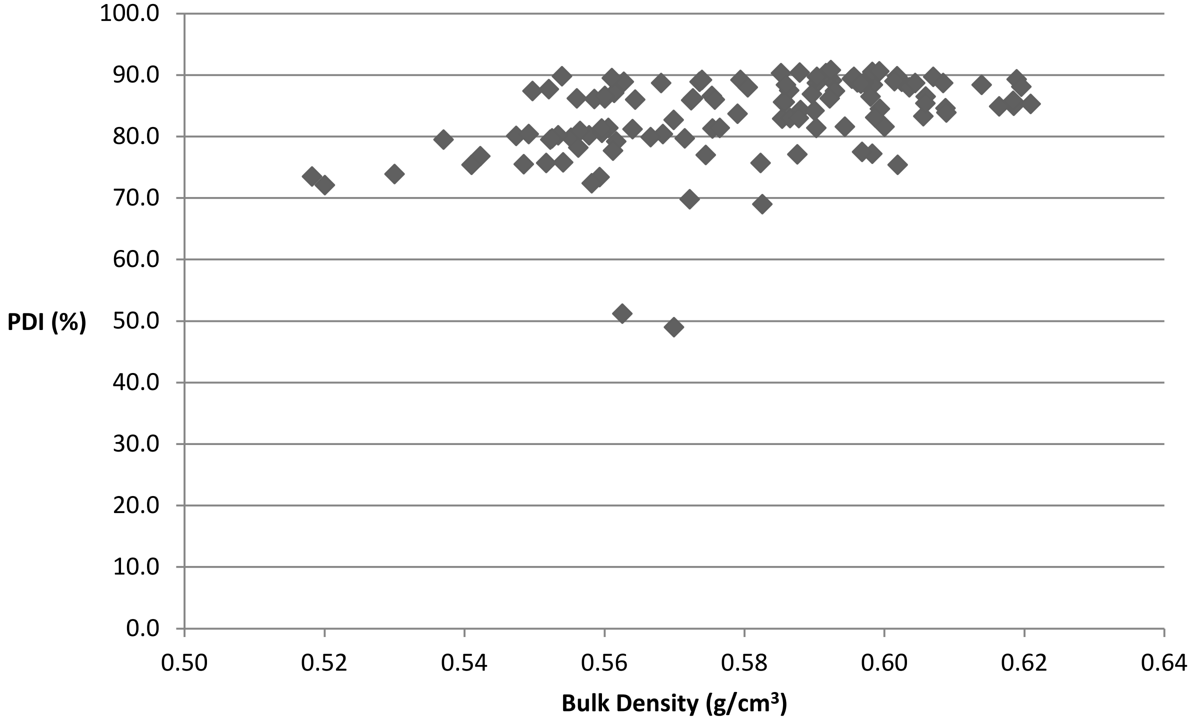


Figure 3.2 PDI vs. Maximum Pellet Bulk Density

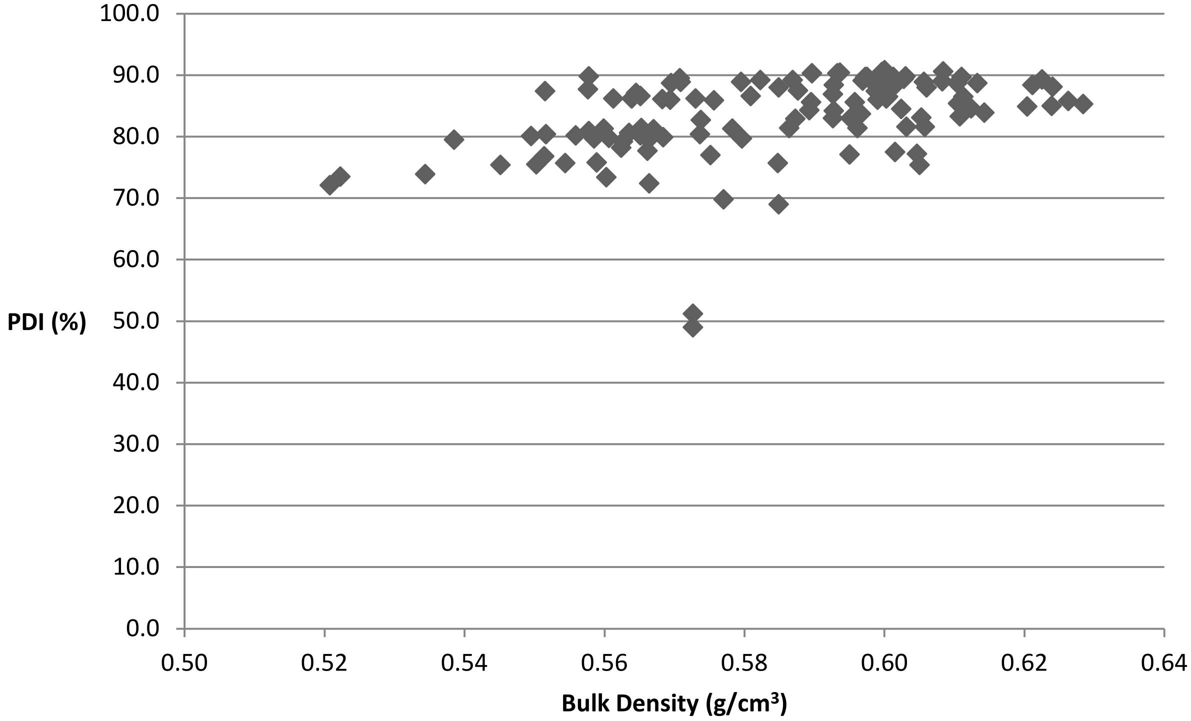


Figure 3.3 PDI vs. Minimum Pellet Bulk Density

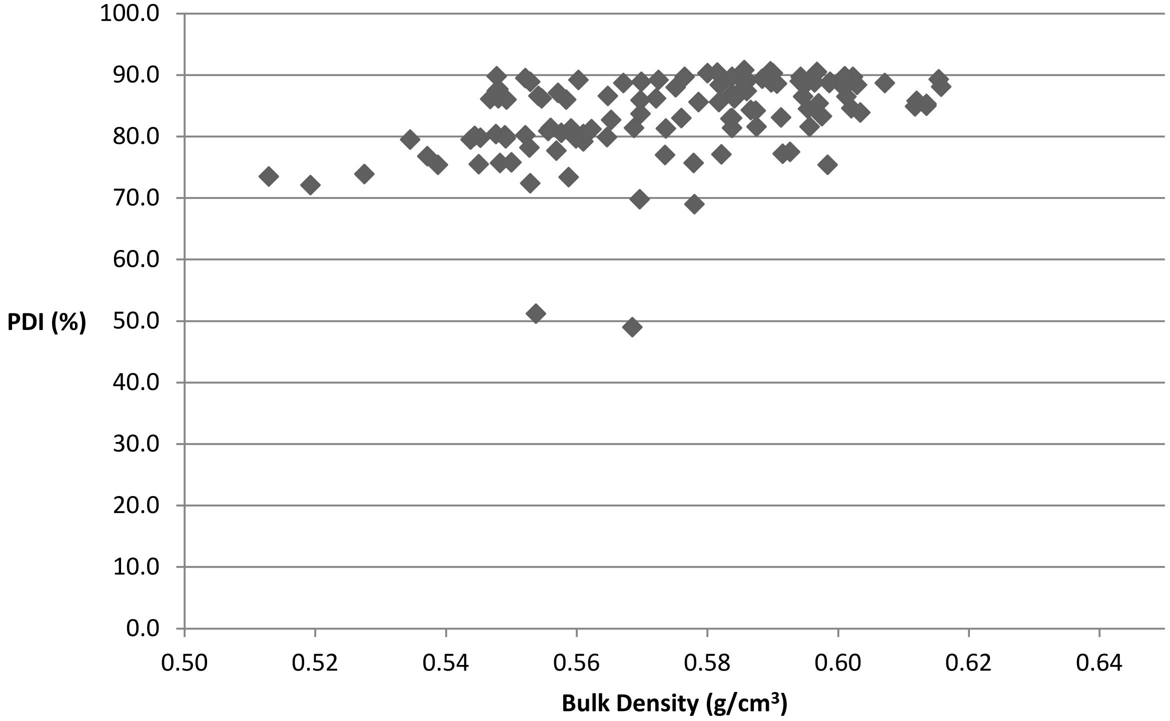


Figure 3.4 PDI vs. Average Fracture Force

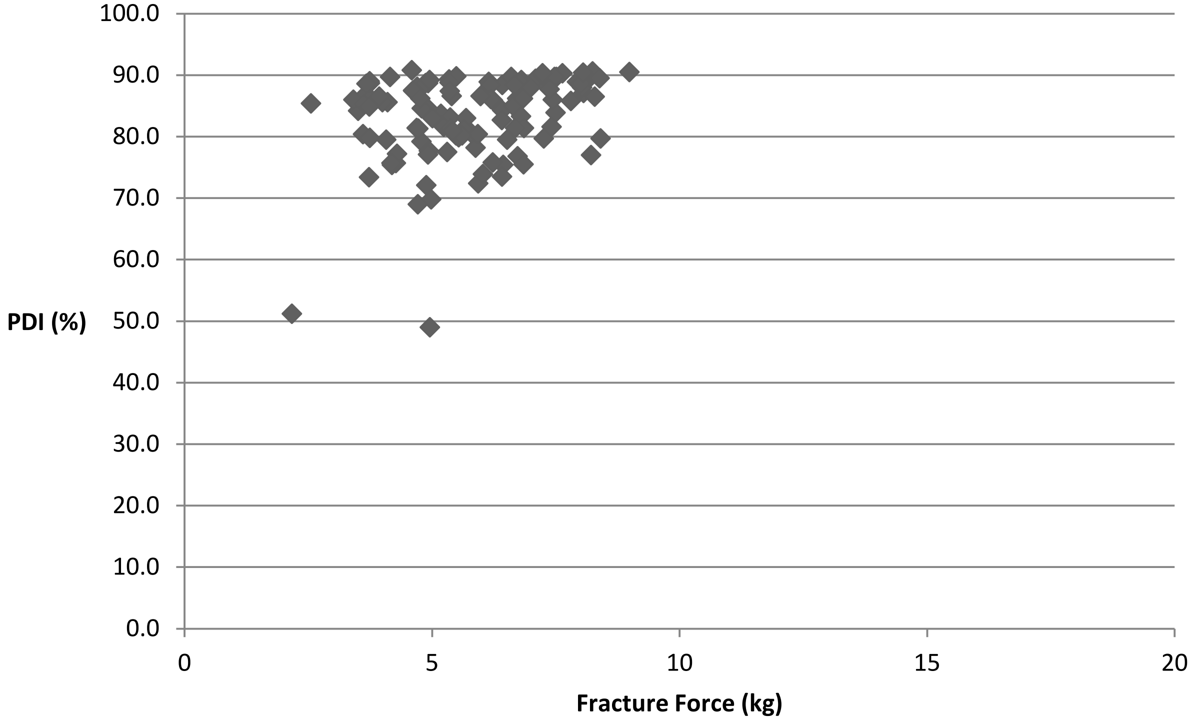


Figure 3.5 PDI vs. Maximum Fracture Force

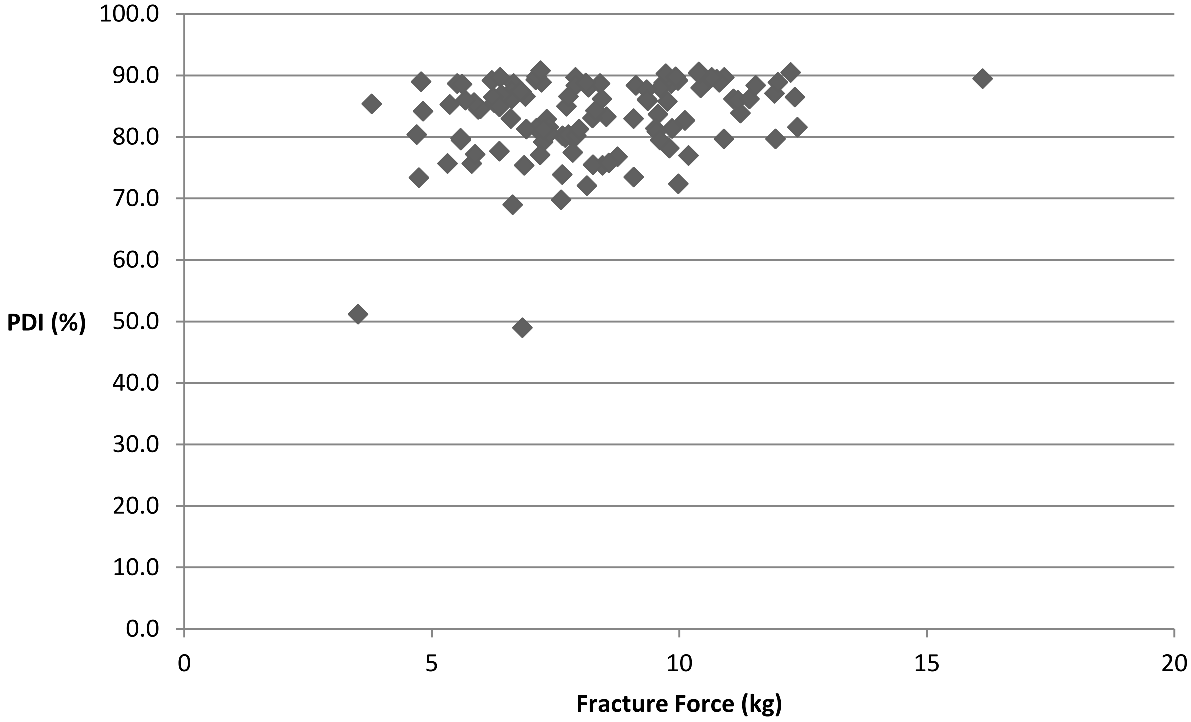


Figure 3.6 PDI vs. Minimum Fracture Force

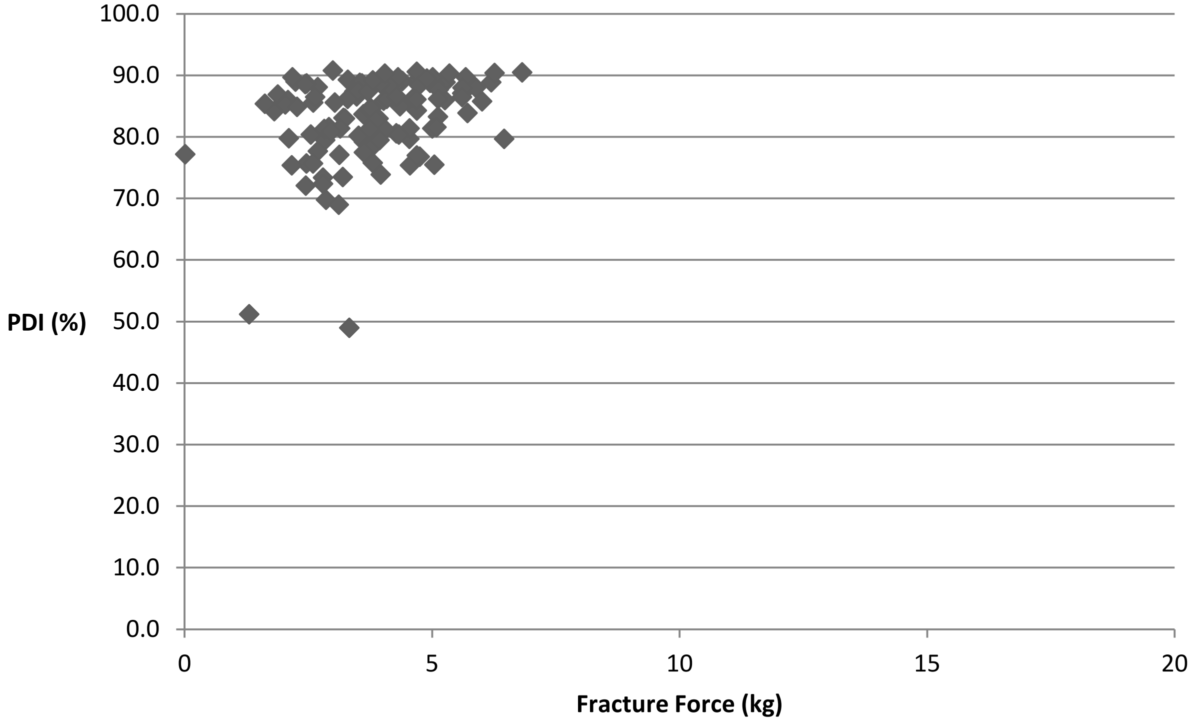


Figure 3.7 PDI vs. Die Retention Time

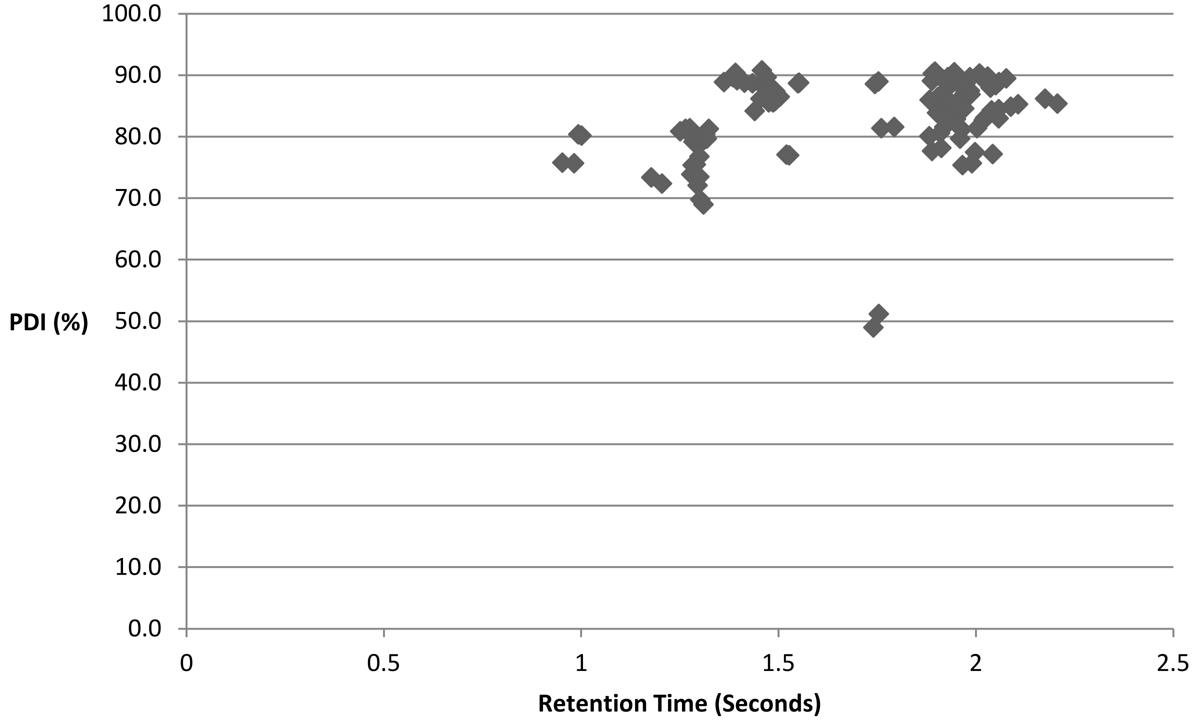


Figure 3.8 PDI vs. Mash Moisture

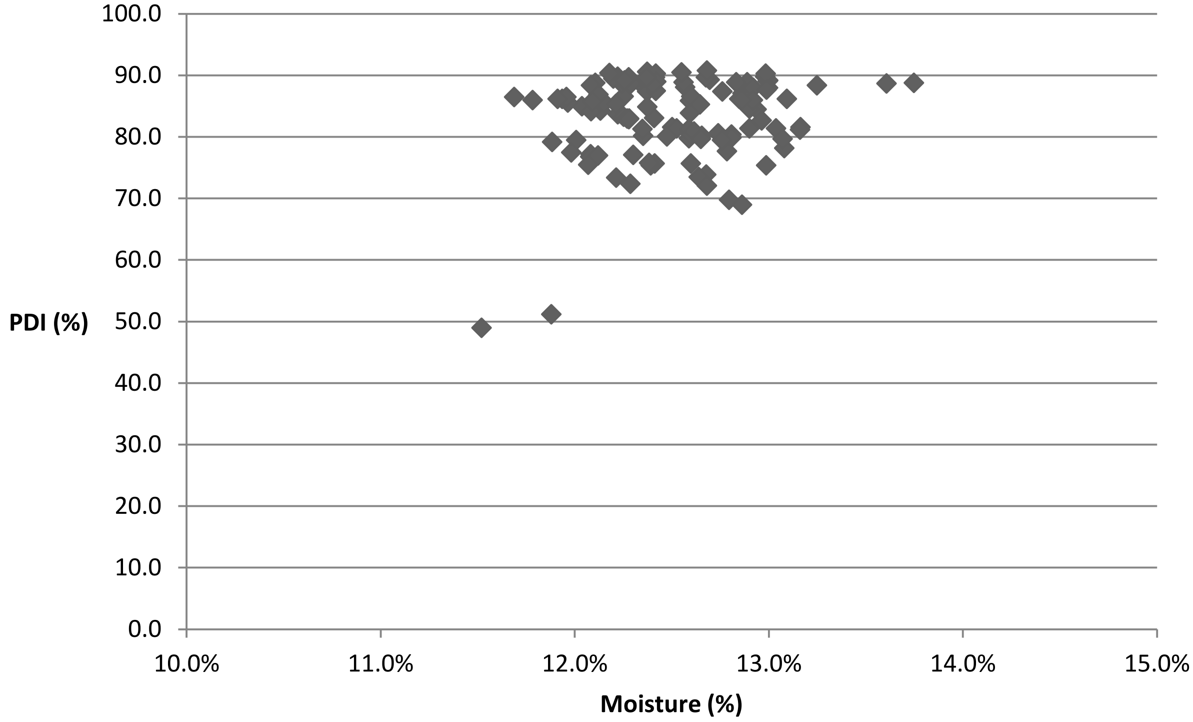


Figure 3.9 PDI vs. Conditioned Mash Moisture

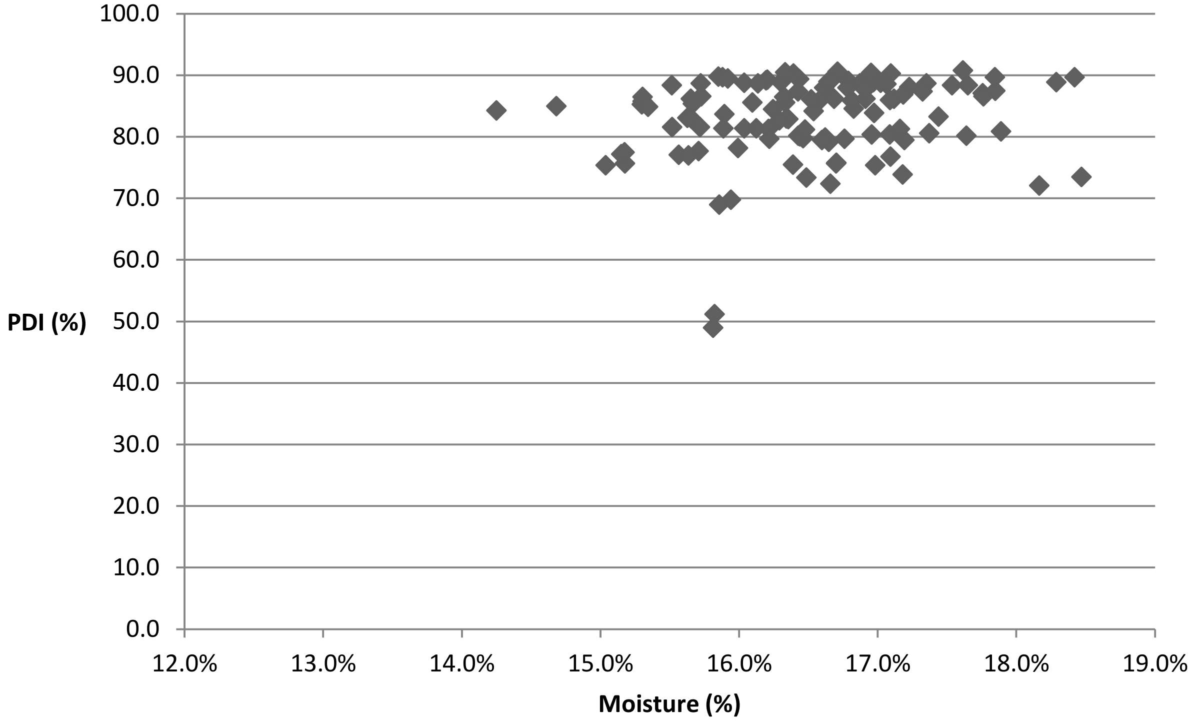


Figure 3.10 PDI vs. Hot Pellet Moisture

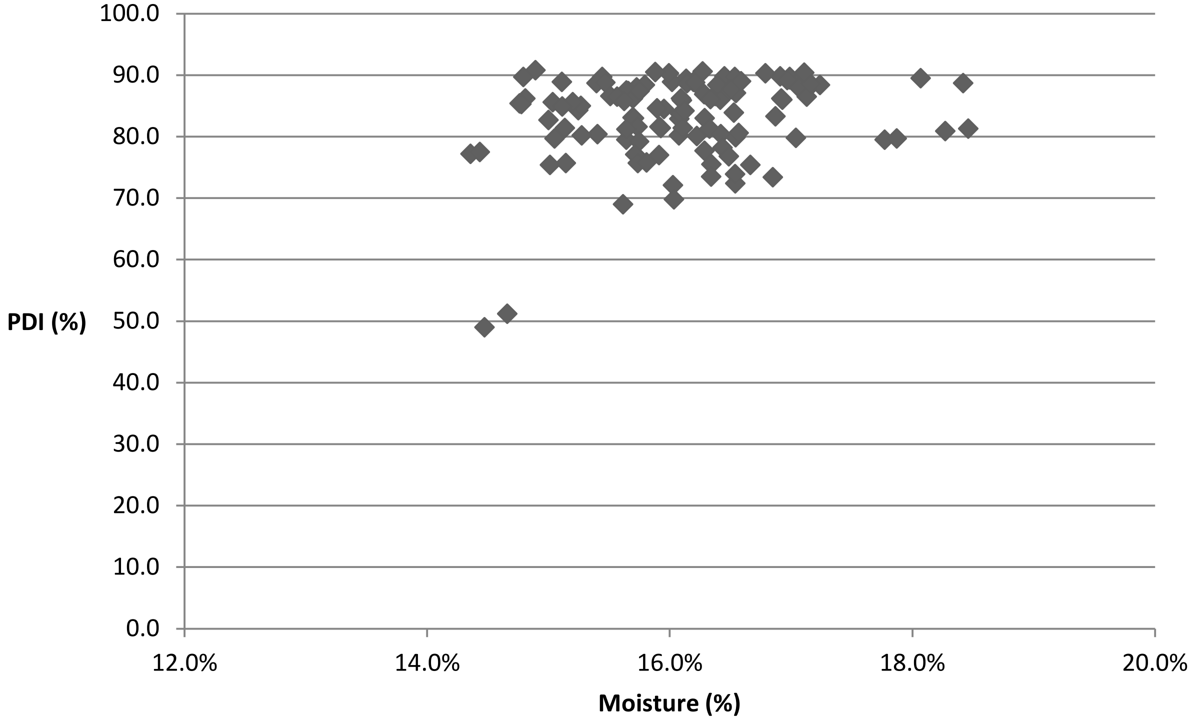
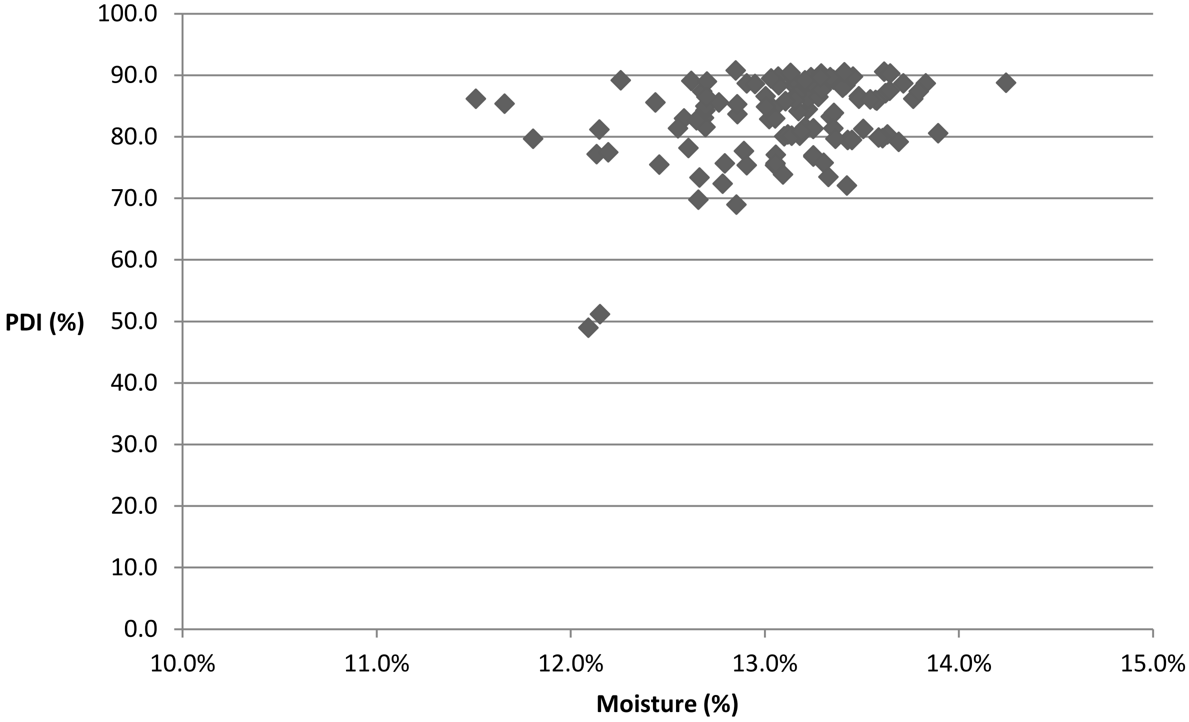


Figure 3.11 PDI vs. Cooled Pellet Moisture



Chapter 4 - Formulation and Processing Factors Affecting Pellet Quality and Energy Consumption

Pelleting of animal feeds can lead to improvements in many different areas, including animal performance and material handling. Therefore, it is important to determine what factors positively and negatively impact pellet durability so that feed producers may make predictions about how changes in formulation or processing parameters will affect overall feed quality. Five binding mechanisms have been described that lead to the strength and durability of feed pellets. These mechanisms are solid bridges, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces, and interfacial forces and capillary pressure (Thomas and Van der Poel, 1996; Kaliyan and Morey, 2006).

There are fixed and variable costs associated with pelleting. Equipment and labor costs are relatively fixed, assuming that proper preventative maintenance procedures are followed. Operating costs associated with pelleting include the production of steam for conditioning and electrical energy to operate the pellet mill, feeders and conditioners, and pellet cooling system. These costs are variable, and depend on prices for natural gas and/or electricity. Of the variable costs, electrical energy is typically considered the most important to observe. Steam production needs, while high (up to 72% of the energy required to pellet may be used for steam conditioning according to Skoch et al. (1983)), are relatively fixed considering the tons of feed produced, and are not likely to be adjusted as a cost-saving measure.

Electrical usage at the pellet mill is generally reported in the terms of units of energy consumption per unit of throughput, such as kilowatt-hours per ton (kWh/ton), with lower values corresponding to less energy consumption per ton produced. Energy consumption is minimized by operating at the maximum possible production rate based on diet characteristics, die volume, or motor load. When production rate is based on maximum motor load, less mechanical energy required at the die will lead to higher production rates. One unfortunate truth about pelleting animal feeds is that "almost anything that is done to improve pellet quality (durability) will either increase the cost of the ration or reduce the capacity of the pelleting system, or both." (Behnke, 2006)

Steam conditioning is an important factor affecting pellet durability, and also plays a significant role in energy consumption. Pfost (1964) reported that the highest possible conditioning temperature improved ($p<0.01$) pellet durability and lowered pellet mill energy consumption in no or low-fat diets, and improved ($p<0.05$) pellet durability in high fat diets. Skoch et al. (1981) found that increased steam conditioning led to a decrease in mechanical friction during pelleting, as determined by lower temperature rise across the pellet die, decreased electrical energy consumption, and improved pellet durability.

The overall conditioning temperature is only partially responsible for effects on pellet durability and energy consumption. As with any thermal process, both temperature and time must be considered. Gilpin et al. (2002) found that increasing retention time in two separate conditioners by slowing shaft rotation using a variable frequency drive significantly improved pellet durability. Briggs et al. (1999) found that changing the pitch of the conditioner paddles, and thus increasing residence time, also increased pellet durability. It is surmised that the increased retention time allows the moisture to more fully penetrate the particle, which in turn softens the particle and makes it more "adhesive."

Briggs et al. (1999) found that changing the pitch of the conditioner paddles also reduced ($p<0.05$) energy consumption. Gilpin et al. (2002) alternatively found that retention time influenced pellet durability but not energy consumption, but did determine that pellet durability had a significant correlation with energy consumption. This is a logical conclusion, as conditioning factors such as temperature and retention time that improve pellet durability also reduce energy consumption.

There are many characteristics of a pellet die that can affect pellet durability and pelleting energy consumption. They include metallurgy, which can affect friction and temperature buildup, hole design, which includes straight bore and relief, and hole pattern and number. However, the characteristic that has the largest effect is the thickness of the die in relation to the hole diameter, known as the die L:D ratio. A higher L:D ratio means that the die is thicker, which will typically increase pellet durability due to friction and possibly die retention time, but decreases throughput and increases energy consumption. Pfost (1964) showed that thinner dies decreased ($p<0.01$) pellet durability and reduced pellet mill energy consumption in low or non-fat diets. Increasing the L:D ratio did not have a significant effect on pellet durability in high fat diets, but there was some evidence that it may increase energy consumption. Traylor (1997) reported that as pellet size increased production rate increased and energy consumption decreased.

Particle size is one of the few pre-processing factors linked to pellet durability. In the United States it is typical for a single cereal grain, usually corn but occasionally sorghum, to make up a majority portion of a pelleted poultry or swine diet. The corn or sorghum is pre-ground (ground prior to mixing), and for facilities producing pelleted diets, grinding is most often done by a hammermill. The resultant particle size can be measured in terms of both geometric mean and standard deviation (ASAE, 2008). Stevens (1987) examined the effects of particle size of ground corn on pelleting, and found no effect ($p>0.05$) on production rate or PDI. Corn in the diet was ground to 1023, 794, and 551 microns yielding PDI values of 89.9, 88.8, and 90.3 PDI, respectively. However, coarse ground corn (1023 microns) did increase energy consumption ($p<0.05$) in comparison with a medium ground corn (794 microns). Stark (1994) found that particle size of the overall diet significantly affected pellet durability ($p<0.01$). Corn/soy diets with particle sizes of 543 and 233 microns yielded PDI values of 97.3 and 98.5 PDI, respectively. However, while significant, this difference was only slightly more than that reported by Stevens, and may not have practical implications in a commercial process.

The predominant theory has always been that smaller particles lead to fewer fracture points within the pellet and thus increase durability. It has also been suggested that smaller particles can be more adequately conditioned and compressed. Robinson et al. (1962) reported that, while a finer grind produced a slightly more durable pellet, an increase in conditioning temperature improved pellet quality equally for both fine and coarse grinds. This implied that no interaction between conditioning and particle size exists. The authors also found that a finer grind yielded a lower motor load and fewer fines exiting the pellet mill. This means that less re-pelleting of fines would be required, which represents an overall cost savings. The authors closed the article by stating that the “best recommendation…is to grind as fine as is necessary to make a quality pellet.”

It is now typical for large-scale integrated facilities to operate above design capacity in order to satisfy throughput demands. Often, production rate is sacrificed for pellet durability only in the cases where final pellet quality is a superior driving force with respect to product value. Operating at the maximum production rate allows the pellet mill motor to operate at peak efficiency, where the highest proportion of energy used to material produced is found. It is generally true that as production rate increases, energy consumption decreases. Stark (2009) reported that an increase in pellet mill throughput (545 kg/h to 1646 kg/h) led to a linear increase in pellet mill efficiency (73.3 to 112.4 kg/hph) and linear reduction in pellet durability (55.4 to 30.2 PDI.)

The formulation of a pelleted diet has always been considered to be one of the most important factors that influence pellet durability. It is also highly influential in energy consumption as many ingredients are known to dramatically improve or diminish production capacity. This can be due to the presence, or lack thereof, of lubricating factors, the ability of ingredients to scour or “polish” the pellet die, or because the bulk density of an ingredient requires the mill to exert an excess amount of energy to compress the material before it can be extruded through the die (Behnke, 2006).

An experiment by Cavalcanti and Behnke (2005b) evaluated the effects of nutrients on pellet durability, using corn, soybean meal, and soybean oil to create thirteen treatments investigated. The highest PDI values were found when fat inclusion was at the lowest levels. Also, protein had a positive influence on pellet durability. This result appeared to be correlated more with the addition of soybean meal protein than with overall protein of the diet, which included the corn fraction. The influence of starch on pellet durability appeared to be largely dependent on other ingredients. Overall, the authors were able to effectively model the use of corn, soybean meal, and soy oil, but surmised that the models would likely not be feasible as other ingredients were included into the formulation.

The addition of fat to a pelleted diet can be very influential on pellet durability. It is assumed that fats coat the feed particles, making it more difficult for steam to penetrate and thus add moisture or transfer heat during the conditioning process. Fat also adds lubrication, both inherently as well as by keeping moisture at the surface of the particle. This leads to decreased friction, and thus compaction, in the pellet die. Fat, or oil content, has been shown to decrease pellet durability (Stark, 1994; Briggs et al., 1999). Stark (1994) showed an addition of 1.5% and 3% fat decreased pellet quality by 2.0 and 5.0 PDI, respectively. The addition of fat to the diet can also reduce energy consumption due to the lubrication effect.

Distillers' dried grains with solubles (DDGS) are a co-product of the fermentation of cereal grains. Most commonly these are corn-based, though sorghum-based DDGS can be sourced, and are a co-product of the fuel ethanol industry. The concentrating of protein in DDGS, approximately three times the amount of the raw cereal grain, and the relatively low cost, makes DDGS a very attractive ingredient in least-cost formulation. Unfortunately, the inclusion of DDGS in feed rations has caused problems in feed manufacturing facilities as processors have had to learn how to deal with a new, relatively high inclusion rate ingredient with different physical and processing properties.

Data gathered at Kansas State University has shown that adding DDGS to the diet at 10% and 20% decreased pellet durability from 90.3 PDI for the control to 88.3 and 86.8 PDI, respectively (Fahrenholz, 2008). While the difference between the control and 20% DDGS treatment was statistically significant, the practical difference is likely negligible. Stender et al. (2008) produced pelleted diets that contained 0 and 20% DDGS. Pellet durability was found to decrease as the level of DDGS increased with durabilities of 78.9 and 66.8 PDI for the levels of 0 and 20%, respectively. Feoli (2008) found an increase in pellet durability when adding 30% DDGS to pelleted diets, with PDI increasing from 88.5 for the corn-soy control diet to 93.0 PDI with 30% DDGS. These differences in effects of DDGS on pellet durability lead to the conclusion that DDGS can have a major effect on pellet durability, but sometimes do not. Thus, there may be possible interactions unaccounted for in processing differences not described in these experiments.

In addition to understanding how different ingredients or processing parameters singularly affect pellet durability, it would be beneficial to understand any interactions between the factors, and the proportional effects of each. This knowledge would allow feed processors to make decisions on what factors to change based on which have the most or least effect on pellet durability. A chart (Figure 4.1) of proportional effects of various factors on pellet quality has been referenced by many different authors and presenters over the past thirty years. However, there is no consistent citation associated with the chart, and therefore it cannot be attributed to any particular source. It is assumed that the proportions are based off of educated assumptions rather than actual data. While this chart was likely never intended to be a true decision making tool, its consistent use has given it a degree of factual presence.

The objectives of the research described in this chapter were to determine how seven processing and ingredient parameters: (1) interact and affect PDI, (2) interact and affect energy consumption, and (3) might be used to create regression equations in order to predict PDI and energy consumption in a particular processing facility. The hypotheses were: (1) that fat level, production rate, die L:D ratio, and conditioning temperature would have significant effects on pellet durability and energy consumption, and (2) that the processing would be consistent enough to produce regression equations with R^2 values of at least 0.75.

Materials and Methods

A total of twenty nine treatments with four replications per treatment were manufactured across a two-week period in order to reduce any error that might be attributed to environmental changes. Each week was used as a block containing two replications of each treatment. The treatments were manufactured randomly throughout the week, and all ingredients were procured from a single source or lot. Batches were mixed in a Forberg model F-500 twin shaft paddle mixer (Ontario, CAN) according to the standard operating procedures on file at Kansas State University. Feed was steam conditioned in a custom-built Bliss conditioner (Ponca City, OK), and pellets were manufactured on a CPM Master Model 1000 HD pellet mill (Crawfordsville, IN). Pellet samples were cooled in a custom built batch cooler until they were within 2.8°C (5°F) of the ambient temperature. Pellet quality was determined according to ASAE S269.4, which was found to be the most consistent testing method as discussed in Chapter 2.

The twenty nine treatments were also analyzed to determine what effects, both simple and interaction, each factor had on energy consumption, as measured by kWh/ton. Energy consumption was determined using an Amprobe (Everett, WA) DMII Pro Data Logger Recorder. The recorder was set to take readings of amperage, voltage, power factor, and total energy, measured in Watts, every five seconds during the production runs. The recorded data was then uploaded and analyzed using the Amprobe Download Suite software (v. 3.0.0.03). The start, stop, and sample collection times were noted during production. The determined production rate was then used along with the average energy consumption during the sampling period to determine kWh/ton.

The experiment was designed in order to compare each of seven different factors (corn particle size, percent fat, percent DDGS, production rate, conditioning temperature, conditioning retention time, die L:D ratio) to every other factor in a two by two factorial arrangement. Due to the constraints of time and raw ingredient storage capability (the need to run pellet durability analysis directly after feed production and the need to use ingredients from a single lot or source) an experimental design was established to keep total number of batches and overall feed production to a minimum. Each factor was examined at two levels, a base level and an experimental level, where the base level was considered the most typical for achieving high pellet durability. For treatments where a factor was not a part of the relationship being examined, it was kept at the base level, reducing the number of necessary runs. The treatments are summarized in Figure 4.2.

Each individual factorial design had a base level by base level treatment, and this treatment was the same across all designs. Similarly, each factorial had two base-level by experimental level treatments, which corresponded to all other base level by experimental level treatments for the factor held at the experimental level. With seven factors, there were seven of these treatments. Thus, the only treatments that were not shared between multiple experiments were the experimental level by experimental level treatments, of which there were twenty one. This experimental design allowed for every factor by factor relationship to be examined, and therefore evaluate proportional effects and interactions, while minimizing total production requirements. This design also provided for a large data set for the creation of the regression models.

For treatments used to investigate the effect of ground corn particle size on pellet quality, grinding was done using a Jacobson Model P240D Pulverator full-circle “tear-drop” hammer mill (Minneapolis, MN). The base level was the coarse grind, which was achieved using a #12 ((0.48cm or 3/16 inch) hammer mill screen, while the experimental level was the fine grind, achieved using a #4 (0.16cm or 1/16 inch) screen. The fine grind was chosen as the experimental level because feed processing facilities must consider if the added expense and lower throughput is worthwhile. Samples of the ground corn were taken from the mixer prior to the addition of the other ingredients, and were analyzed to determine the geometric mean particle size (d_{gw}) and geometric standard deviation (s_{gw}) as described in ASAE S319.4 - Method of Determining and Expressing Fineness of Feed Materials by Sieving (ASAE, 2009). The equipment used was a Tyler Ro-Tap Model B sieve shaker (Mentor, OH) with thirteen screens and sieving aids. The test was run for fifteen minutes, and a fumed-silica product was used as a dispersion agent, added at a level of 0.5%, or 0.5 grams added to the 100 gram sample. The fumed-silica was added to the sample and was then shaken to fully mix the dispersion agent with the sample. The coarse ground corn was found to have an average d_{gw} of 462 microns (μ) and an average s_{gw} of 3.34. The finely ground sample was found to have an average d_{gw} of 298 μ and an average s_{gw} of 2.90.

Distillers’ dried grains with solubles (DDGS) and fat were each included at two different levels, for a total of four separate formulations (Table 2.1). Each was formulated to supply similar protein, energy, and mineral values, in accordance with basic nutritional requirements for poultry according to the National Research Council (NRC, 1994). The diets were formulated based on the addition of three percent fat, with the assumption that the diets with one percent fat would have the remainder post-coated prior to feeding.

Both dry feed rate and retention time were set through the control of variable frequency drives. The speed of the drives was determined during a preliminary set of runs, in which each of the four formulations, with both coarse and finely ground corn, were dry-run through the system and the rate and retention time measured. Feed rate was measured and set by collecting material in a known-weight container for a period of three minutes. Retention time was measured and set using the "hold-up" method as described by Salim (2008), where the amount of material held in the conditioner is measured and then divided by the feed rate to determine an average retention time in seconds. After drive settings were determined to provide for feed rates and retention times of 1,360 and 1,814 kilograms per hour (3,000 and 4,000 pounds per hour) and 30 and 60 seconds, each formulation was dry run an additional three times at each of the four settings for verification. The base levels for feed rate and retention time were 1,360 kilograms per hour (3,000 pounds per hour) and 30 seconds, respectively.

For these experiments dry feed input rate was set, while total production rate was recorded. This was done because feed rate can be set and used as an independent variable, while final production rate is dependent on steam addition and small variances in material flow. However, it was desired to use production rate as the rate variable in the final regression analyses. Therefore, total run times for each batch were recorded during processing and the actual production rate in tons per hour was determined. These values were used to verify that feed rate was correctly set, and also as the values in the final regression analyses.

Conditioning temperature was set to 65°C or 85°C, measured at the exit of the conditioner, by controlling the steam input rate via a manual valve, with 85°C being the base level. For each treatment, time at temperature was recorded, and pellet samples were taken at consistent intervals based on this start time. Two pellet dies were used in the experiment, a 4mm x 3.2cm (5/32" x 1 ¼") straight bore die (L:D ratio of 8:1) and a 4mm x 2.2cm (5/32" x 7/8") straight bore die (L:D of 5.6:1). The 8:1 pellet die is representative of a typical industry die L:D ratio, and was used as the base level. The 5.6:1 die is substantially thinner than the typical die used in the feed industry, and represents an extreme. The treatments requiring the 5.6:1 die were all run on a single, randomly chosen day within each week. In all cases, a warm-up run was conducted prior to the first treatment of the day in order to heat the die to a steady-state temperature, and then all runs were completed in close sequence in order to keep the die at a consistent starting temperature.

Statistical analysis was completed using the general linear model in SAS (v. 9.1.3). PDI and kWh/ton values for each treatment were collected as two replications within each of two blocks, for a total of four replications. Each of the seven factors was compared in a two by two factorial design, and the significance of the main effects of each factor, their interaction, and the blocking were examined. Where pairwise analysis was required, Tukey's Studentized Range was used. Where statistical significance was found for both factors within a two factor design, variance terms for each factor were calculated based on the reported mean square values, and then compared to the overall variance within the model in order to estimate which factor had the greatest proportional effect.

Predictive regression models were also constructed using the individually collected samples and the values associated with their production. The full models with all main and interaction effects were pared down by use of the Akaike Information Criterion (AIC) to create the most significant models with the minimum amount of significant predictive terms. The purpose of this was to determine what, if any, potential such models might have in predicting and evaluating pellet quality and energy consumption.

The models for predicting PDI and energy consumption were then used to demonstrate what application they might have in production-cost analyses. This required determining values for both ingredient and pelleting costs. Ingredient costs were set according to ingredient prices at the Kansas State Feed Processing and Research Center on November 1, 2011, with the diet containing no DDGS priced at $326.45/ton and the diet containing 10% DDGS priced at $315.36/ton. Pelleting costs were determined by adding the costs for labor, energy, steam, and preventative maintenance. Assumed values and calculations related to these costs can be found in Appendix 1. For each of the 29 treatments, the estimated ingredient and pelleting costs were added together to obtain a total feed cost. This was then divided by the respective PDI value for each treatment to obtain $/PDI.

As a further demonstration of possible applications, the models were applied to estimate the impact of PDI and kWh/ton on broiler growth performance and production cost. McKinney and Teeter (2004) published data that reported the effects of pellet quality on growth performance. This data was used as a basis for estimating a total production cost based on body weight gain (BWG). A number of assumptions were made based on the reported data. They included a feed consumption of 0.4lbs/bird/day and a linear relationship between feed conversion (feed:gain) and feed quality (% pellets) between 60% and 100% pellets. Other assumptions included the feeding of 5,000 birds per day, thus requiring 1 ton of feed per day, and that predicted PDI would be representative of the final pellet quality (% pellets) in the feeder. For each of the 29 treatments, the feed conversion and total BWG were predicted from PDI. The total feed cost was then divided by the respective BWG to obtain $/lb of gain.

Results and Discussion

The average PDI values for each treatment and factorial design can be found in Figure 4.3. The average kWh/ton values for each treatment and factorial design can be found in Figure 4.4.

Blocking was a significant factor in the majority of cases when analyzing the treatments for energy consumption. Ambient conditions were recorded throughout the experiment, and there were no distinct differences in temperature or relative humidity between each of the two production periods that would lead to a conclusion that blocking was significant due to environmental changes. It is possible that blocking was significant due to the settings of the roll-to-die gap, as they could have been slightly different from week to week as the dies were changed during the course of the experiment. A review of the base-line motor load showed a small difference in no-load power consumption, and thus may support this conclusion.

As discussed in the previous chapters, there were two outliers evident in the data set. These outliers represented the two replications within the first block for treatment 28. This treatment utilized the 65°C conditioning temperature and the 5.6:1 die L:D ratio. The PDI and kWh/ton values for these data points did not exhibit the same behavior as the data points from the second block. Additionally, analysis of the data showed that these points also had calculated production rates substantially lower than the set feed rate because the run time was much longer than the other treatments, though the feeder speeds were constant. It was theorized that the batch size was actually much larger than desired, leading to the longer run time. It is possible that an ingredient such as corn or DDGS was mistakenly added to the batch, leading to poor pellet quality and high energy consumption. The decision was made to remove these data points from the analysis in this chapter. This led to an unbalanced factorial design for the conditioning temperature to die L:D ratio comparison, and a lack of data points for treatment 28 in the regression analysis for the first block.

Particle Size

Particle size was found to have an effect ($p = 0.0175$) on pellet durability only when compared with conditioning temperature, which was also significant ($p < 0.0001$), likely because a significant interaction was also present ($p = 0.0255$). At the 65°C conditioning temperature, the treatment with the more finely ground corn (298µ) had a significantly lower PDI than the treatment with coarsely ground corn (462µ). No significant difference due to particle size was observed at the 85°C level. Significant differences existed between the temperature levels at both particle sizes. Because particle size was found to be significant only in this one case, these findings appear to agree with Stevens (1987), who found no effect of particle size on durability. Additionally, while in this case the smaller particle size led to a slightly lower durability, in disagreement with Stark (1994), in both cases the difference in PDI was slight, and possibly insignificant from a practical perspective. Also, the PDI values found by Stark (1994) were eight to ten points higher, suggesting other factors may have played a part in the differences. This interaction is in disagreement with Robinson et al. (1962), who found no interaction between conditioning temperature and particle size.

Particle size was found to have an effect ($p<0.02$) on energy consumption in four of the six comparisons. A smaller corn particle size resulted in reduced kWh/ton. No significant interaction was found between particle size and any other factor at the α = 0.05 level, though particle size and conditioning temperature were nearly significant (p = 0.06). These findings are in agreement with the trend observed by Stevens (1987), though differences were found here with much finer particle sizes, and a lesser range between levels examined. The findings suggest that smaller particles may be easier to compact and form than larger particles, requiring less energy at the roll-to-die nip.

Fat

An increase in fat level from one percent to three percent lowered pellet durability in every comparison (p<0.0001). This is in agreement with Stark (1994), Briggs et al. (1999), and Cavalcanti and Behnke (2005b) who all demonstrated that fat, or oil content, had an effect on pellet quality, with higher levels leading to lower durability. Statistically significant interactions were found between fat and DDGS (p = 0.0078), feed rate (p = 0.0455), conditioning temperature (p = 0.0023) and retention time (p = 0.017). Pfost (1964) described a possible interaction between fat and die L:D ratio, as pellet durability was affected by die L:D in low fat diets, but was not affected by die L:D in high fat diets. No such interaction was found in this experiment, as differences in PDI related to changes in fat or die L:D were constant across the levels of the other factor. Analysis of the variance terms showed fat to have a greater proportional effect on PDI than all of the other factors except conditioning temperature.

The inclusion of fat reduced (p<0.0001) energy consumption in every comparison, with the higher fat level leading to a reduction in energy consumption. There were no significant interactions between fat and the other factors examined. Fat level was one of the more influential variables affecting energy consumption, with only conditioning temperature and die L:D ratio leading to a higher proportion of the variance terms when compared directly. These findings are in agreement with Stark (1994).

DDGS

The inclusion 10% DDGS was not found to have a significant effect on PDI in the comparison with particle size. In the other five comparisons DDGS was found to lower ($p<0.03$) pellet durability when included in the ration. This is in agreement with Fahrenholz (2008) and Stender et al. (2008), as well as generally accepted industry findings. Significant interaction was found between DDGS and fat ($p = 0.0078$) and die L:D ratio ($p = 0.0008$). Analysis of the variance terms showed that the only case in which DDGS accounted for a higher proportion of variation was in comparison with retention time.

DDGS level, the other formulation factor in addition to fat level, was found to have an effect ($p<0.004$) on energy consumption when compared with fat, production rate, and conditioning temperature. In most cases, the addition of DDGS slightly reduced energy consumption, which is in conflict with the assumptions and reports of the feed industry.

The differences in kWh/ton values are small and in some agreement with the lack of an effect as seen by Fahrenholz (2008). Because that experiment was conducted in the same facility, it is possible that the pilot processing equipment used is responsible for differences in observed influences of DDGS. Interactions involving DDGS were observed in two comparisons. The interaction ($p<0.03$) between DDGS level and conditioning temperature was due to the addition of DDGS causing a relatively large drop in energy consumption at the lower conditioning temperature, which might be due to inconsistent and unstable pelleting under those conditions. The more interesting interaction ($p<0.0001$) was between DDGS and feed rate, where the addition of DDGS led to a reduction in energy consumption at 3,000 lbs/hr, but an increase in kWh/ton at 4,000 lbs/hr. The lower bulk density of the DDGS makes the mash feed more difficult to compact, which could be especially problematic when pelleting above rated capacity.

Feed Rate

Feed rate was found to have a weak effect (p = 0.0455) on pellet durability only in the comparison with fat, where an interaction was also present (p = 0.0455). In this instance, the higher production rate led to a slightly higher PDI when the ration contained three percent fat. That a higher production rate would lead to a higher PDI was unexpected. In fact, it was expected that production rate would have more impact on pellet durability overall. In this experiment, the lower feed rate (3,000 lbs/hr) was set at the designed maximum throughput, while the higher feed rate (4,000 lbs/hr) was well above, in representation of current industry practice of operating beyond the designed capacity. This may relate to the overall small effect on pellet durability. Feed rate might have greater effect when comparing high rates to rates that fall within the designed operating parameters of the equipment, such as was the case in the findings reported by Stark (2009.)

Closer evaluation shows that while there is no difference in PDI due to feed rate when all other factors are held at the base level, in one case PDI decreased approximately one percent (DDGS) and in two cases decreased two percent (conditioning temperature and die L:D) with the higher feed rate. There are other factors for which a difference of this amount was found to be statistically significant, suggesting that the amount of difference itself may be relevant, but that variation in replications led to a lack of statistical significance. This could be explained by the fact that feed rate was set by a preliminary trial, as described in the materials and methods section, and may not have been as precisely controlled as the other factors in this experiment.

Feed rate was found to have a large effect ($p<0.02$) on energy consumption in all comparisons, with the higher feed rate leading to reduced energy consumption. As noted previously, this is due to distributing the base-line energy requirements across a greater material production. Feed rate was found to be the more significant factor when examining proportional effect on variance in the comparisons with particle size, DDGS level, and retention time. Feed rate was found to have a significant interaction only with DDGS, as described in the previous paragraph.

Conditioning Temperature

As expected, steam conditioning temperature was found to be a major factor in pellet durability, and was found to have an effect ($p<0.0004$) in each comparison, with the higher conditioning temperature leading to improved pellet durability. These findings are in agreement with Pfost (1964), who reported that the highest possible conditioning temperature improved pellet durability, and Skoch et al. (1981), who found that increased steam conditioning led to an improvement in pellet durability. Interactions were found to be significant between temperature and particle size ($p = 0.0255$), fat ($p = 0.0023$), and die L:D ratio ($p <0.0001$). In cases where both factors in a comparison were significant, analysis of the variance terms showed that temperature had a higher proportional effect on pellet durability in every case except in the comparison with die L:D ratio, and had only a slightly higher proportional effect than fat level.

Conditioning temperature was found to have an effect ($p<0.0001$) and explain a higher proportion of the total variance in every comparison. This high degree of effect on kWh/ton is in agreement with Pfost (1964) and Skoch et al. (1981). Interaction was present between conditioning temperature and DDGS ($p<0.023$), discussed previously, and retention time ($p<0.01$), which is examined in the following paragraph. There was no interaction between conditioning temperature and fat level such as was noted by Pfost (1964), who found no significant improvement in pelleting efficiency with increasing conditioning temperatures when pelleting a high-fat diet. In these experiments it was found that while fat level was a significant factor, a 20°C change in conditioning temperature was much more influential.

Retention Time

Retention time was generally found to weakly influence pellet quality, though in some cases its effect was important in an interaction with another factor. Retention time was found to have an effect ($p<0.04$) on pellet durability in four of the six comparisons, where an increase in retention time led to an improvement in PDI. This agrees with Gilpin et al. (2002) and Briggs et al. (1999), who both found that increasing retention time significantly improved pellet durability.

The two comparisons in which it was not significant were with particle size and die L:D ratio. No significance was found in comparison with particle size as the PDI values for the 30 and 60 second periods were the same when using the finely ground corn. No significance was found in the comparison with die L:D because any possible improvement from retention time was unable to counteract the decrease in PDI resulting from the lower L:D ratio. The approximately 1% improvement in PDI from increasing retention time at the base level of all other factors was not found to be significant in any pairwise analysis.

According to the analysis of variance model, retention time was found to be weakly significant in comparisons with DDGS level and feed rate. The increase in retention time netted an approximate one percent improvement in PDI at both levels of the other factors; however, pairwise analysis actually found no significant differences between treatments due to retention time in either case. There does appear to be a slight, although non-significant interaction between retention time and conditioning temperature, with the higher retention time providing for a greater improvement in pellet quality at the lower conditioning temperature. There was an interaction ($p<0.02$) between retention time and fat, where the higher retention time led to a 3% improvement in PDI at the higher fat level. Taken together, the data suggests that retention time may not be a major factor when all other factors are at levels promoting good pellet durability, but might be an effective tool in improving PDI when another factor is present at a level known to lead to a poor PDI. Supporting this conclusion, retention time was not found in any case to account for a higher proportion of the model variance.

Retention time was only found to have an effect ($p<0.02$) on energy consumption when compared to conditioning temperature, likely because of the significant interaction between the two. Retention time had no effect on efficiency at the higher temperature, but decreased efficiency at the lower temperature. A possible explanation is that the higher retention time allowed the moisture to further penetrate the particles, lessening surface moisture and increasing friction at the die. Perhaps this is a greater concern at the lower temperature, where less steam is used in the conditioning process, and thus less moisture is available.

Die L:D Ratio

Decreasing die L:D ratio from 8:1 to 5.6:1 had a dramatic effect on pellet durability. In all comparisons the L:D ratio was found to lower ($p<0.0001$) pellet durability. At the base level of all other factors, decreasing the L:D ratio was found to lower PDI by approximately nine percent, the largest difference among all factors. Significant interaction occurred between die L:D and DDGS level ($p=0.0008$) and conditioning temperature ($p <0.0001$). In the comparison with DDGS, the pellet durability decreased by one percent when using the 8:1 die, but decreased by a little over six percent when using the 5.6:1 die, suggesting that when adding DDGS to the diet, using a higher L:D ratio is highly advisable from a pellet durability standpoint.

Comparison of die L:D with conditioning temperature was found to have a significant interaction, where the average PDI decreased by 5.2% when temperature was lowered using the 8:1 die, but dropped by 10.7% when using the 5.6:1 die (the difference in PDI between die ratios at 65^{o}C was 14.5%). This was the largest effect on pellet durability observed during the experiment, and suggests that, if forced to condition at a lower temperature, a thicker die should be considered. Indeed, as noted by Pfost (1964), conditioning temperatures may need to be lowered in some cases when using thicker dies to prevent roll-slippage and pellet mill plugging due to increased moisture. Similarly, if using a thinner die, conditioning temperature must be maintained. This is in line with the findings of Smallman (1996), who reported that pellet durability improved with a thinner die and better conditioning. Smallman's findings may also be interpreted as demonstrating that conditioning may have a greater effect on pellet durability, as it compensated for the effect of the thinner die. This was not substantiated in the current experiment, as the die L:D was found to have the greatest proportional effect on variance in all comparisons where both factors were significant.

In five of the six comparisons die L:D ratio was found to have an effect ($p<0.0001$) and was the most responsible factor for variation in energy consumption. In the comparison with conditioning temperature, die L:D ratio was also found to be significant ($p<0.0001$), but did not exhibit a greater proportional effect on kWh/ton. No significant interactions were found between die thickness and the other factors investigated. In all cases, a thinner die led to a reduction in energy consumption, in agreement with Pfost (1964), Smallman (1996), and Traylor (1997). The fact that the die had less of an effect than conditioning temperature agrees with the findings of Smallman (1996), who found that energy consumption decreased with a higher conditioning temperature and thinner die, suggesting that conditioning has the greater effect.

Regression Models

There were a total of 116 pellet quality samples, each representing a combination of base and experimental levels of the seven factors. After removing the two outliers discussed previously, the total samples available for regression analysis became 114. As a means of validation, the first step was to create a predictive regression model for PDI based on the results found in the first block (first week of production.) The estimated regression equation is below, and is denoted as Equation 4.1. Variables were assigned to each factor as follows: a = particle size, b = fat, c = DDGS, d = production rate, e = conditioning temperature, f = retention time, g = die L:D ratio.

$$PDI = 165.08 - 0.05a - 7.11b - 0.82c - 76.43d - 0.47e - 0.03f - 2.63g - 0.01ab - 0.001ac + 0.02ad + 0.005ag + 1.91bd + 0.04be + 0.06bf + 0.004cf + 0.10cg + 0.50de + 3.02dg \quad \textbf{4.1}$$

The equation has 19 terms and an R^2 value of 0.99. The large number of terms and high correlation exists because the data set is relatively small and thus a very accurate model results. This equation was used to predict PDI values for the 29 treatments evaluated. These predicted values were then compared to the values found during the production of the second block (second week of production.) The average residual PDI value, the difference between the predicted and actual values, was 1.8. This translated into an approximate 2% variation between the model predictions and observed values.

The replicated values for kWh/ton within the first block were very similar among treatments. This was because, within the block, no changes were made to the equipment parameters, ambient conditions were relatively constant, and the power recording was conducted over entire runs, canceling out any small variations. This resulted in a very low error term. The regression model that was generated was therefore somewhat artificial, using all of the terms and having an R^2 value of nearly 1.0. In order to get a measure of consistency, it was decided that the observed values from the first block would be compared to the observed values from the second block. The average difference between the two observed values was 0.59 kWh/ton. This translated into an approximate 7% variation between the two observed values. This supported further regression modeling.

The total 114 experimental units were then used to create regression models representing the entire data set of both blocks. The estimated regression equations are below. Again, variables were assigned to each factor as follows: a = particle size, b = fat, c = DDGS, d = production rate, e = conditioning temperature, f = retention time, g = die L:D ratio.

4.2

$$PDI = 53.90 - 0.04a - 6.98b - 1.12c - 1.82d + 0.27e + 0.04f + 1.78g + 0.006ag - 0.23bc + 0.06be + 0.15cg$$

Equation 4.2 has 12 terms, and an R^2 value of 0.92. The average residual PDI value, the difference between the predicted and actual values, was 1.1. This translated into an approximate 1% variation between the model predictions and observed values.

4.3

$$\frac{kWh}{ton} = 55.93 - 0.01a + 1.88b - 0.05c - 30.90d - 0.41e + 0.17f - 1.20g + 0.02ad - 0.0001ae - 1.41bd - 0.01bf - 0.21cd + 0.004ce + 0.22de - 0.11df + 1.21dg$$

Equation 4.3 has 17 terms, and an R^2 value of 0.95. The average residual kWh/ton value, the difference between the predicted and actual values, was 0.3. This translated into an approximate 3% variation between the model predictions and observed values.

Application

Energy consumption does not necessarily have a predictive relationship with PDI values, as is shown in Figure 4.5. This is because some factors (high fat, low L:D ratio) lessen energy consumption but negatively impact pellet durability, while others (conditioning temperature) lessen energy consumption and improve pellet durability. Therefore, the relationship between the two values can be taken into account to allow for the production of high durability pellets while also addressing energy consumption concerns. With this in mind, the models for predicting PDI and kWh/ton were used to demonstrate how they might be applied in production-cost analyses.

An initial analysis was conducted with the objective of determining which treatment yielded the lowest feed cost per percentage PDI ($/PDI). The values for each treatment are shown in Table 4.1. Subsequently, the PDI and feed cost values were applied to make predictions on feed conversion, BWG, and overall $/lb of gain based on data reported by McKinney and Teeter (2004) concerning the effect of feed quality on broiler growth performance. The values for each treatment are shown in Table 4.2.

Treatment 11 (462µ, 1% Fat, 0% DDGS, 1.5 tons/hr, 85°C, 60 seconds, 8:1) was predicted to have the greatest PDI (90.7), and subsequently the best feed conversion and BWG. This was expected, as treatment 11 exhibited the greatest PDI during the course of the experiment (90.1). Feed conversion (1.872) and BWG (1068.3 lbs) followed PDI as they were directly tied within the analyses. A mid-range energy consumption value (8.8 kWh/ton) supports the assertion that high PDI is not necessarily linked to high energy consumption.

Treatment 19 (462µ, 3% Fat, 0% DDGS, 1.5 tons/hr, 85°C, 30 seconds, 5.6:1) represented the lowest energy consumption (6.4 kWh/ton). This was expected, as treatment 19 exhibited the lowest energy consumption during the course of the experiment (6.3 kWh/ton). This supports previous discussion, demonstrating that increasing fat level and decreasing die L:D ratio are the largest factors leading to a decrease in energy consumption when processing at a consistent conditioning temperature. Treatment 19 was predicted to have a relatively low PDI value (74.7.) This is a good example of how, in pursuit of low energy consumption, pellet durability can suffer when other factors are not taken under consideration.

Treatment 26 (462µ, 1% Fat, 0% DDGS, 2.0 tons/hr, 85°C, 30 seconds, 5.6:1) was predicted to have the lowest pelleting cost ($8.93/ton). Though treatment 19 exhibited a lower energy consumption (6.4 kWh/ton vs. 6.7 kWh/ton), the distribution of labor costs over a greater tonnage made treatment 26 more cost effective. This also demonstrates that reducing labor and energy costs is more influential than decreasing steam generation costs (as would have been the case if conditioning at 65°C) given the assumptions made. As fuel and electrical prices vary, these relationships could potentially change.

Treatment 20 (462µ, 1% Fat, 10% DDGS, 2.0 tons/hr, 85°C, 30 seconds, 8:1) was predicted to have the lowest overall feed cost ($324.41). Treatment 20 had both a mid-range energy consumption (8.3 kWh/ton) and pelleting cost ($9.05/ton). The main drivers in this case were the inclusion of DDGS, which substantially lowered ingredient costs, and the higher production rate, which allowed for the lowest pelleting cost among treatments containing DDGS.

Treatment 22 (462µ, 1% Fat, 10% DDGS, 1.5 tons/hr, 85°C, 60 seconds, 8:1) was predicted to have the best ratio of total cost to PDI ($3.66/PDI). The total feed cost of this treatment was predicted to be $325.76, while the PDI was predicted to be 89.0. The inclusion of DDGS kept the diet cost relatively low, while the combination of a 60 second retention time and 8:1 die L:D ratio helped to mitigate the negative effects of DDGS on PDI.

Finally, treatment 20, described earlier as the treatment predicted to have the lowest overall feed cost, was also the treatment predicted to have the best ratio of total cost per pound of BWG per day ($0.304/lb BWG/day). The low cost, as discussed above, related to the inclusion of DDGS and a high production rate. Additionally, this treatment was predicted to have a relatively good PDI (86.9) leading to a good conversion ratio (187.7) and BWG (1065.5) values. This example demonstrates the potential usefulness of effective predictive models. By taking into consideration as many factors as possible it may be possible to obtain the best overall return by finding the middle ground between producing high durability pellets and operating at the lowest possible energy consumption.

Conclusions

Considering the experimental design, there were seven two-level comparisons for each factor. These were made up by one comparison where the base and experimental levels of the specific factor were tested while all other factors were at their base level, and six comparisons where the base and experimental levels were tested while the other six factors were at experimental levels. Figures 4.6 (PDI) and 4.7 (kWh/ton) provide the average absolute difference of the seven comparisons for each factor, which are akin to the “main effects” of each. These are also displayed in a pie chart to provide a sense of proportion.

Die L:D ratio was found to be the most influential factor affecting PDI, with decreasing the die thickness and going from an 8:1 ratio to a 5.6:1 ratio leading to an average decrease in PDI of 10.9. Increasing conditioning temperature (average increase of 7.0 PDI) and decreasing fat level (average increase of 5.4 PDI) were also found to have a substantial influence. Particle size (0.5 PDI) and feed rate (0.6 PDI) were found to have little overall effect on pellet durability.

Increasing the conditioning temperature from 65°C to 85°C had the greatest impact on lowering energy consumption (2.7 kWh/ton). This was more than double the impact of next most influential factor, a thinner die L:D ratio (average decrease of 1.3 kWh/ton.) No other factor exhibited an influence on energy consumption greater-than or equal-to 1.0 kWh/ton. An increase in retention from 30 seconds to 60 seconds had nearly no impact on energy consumption (<0.1 kWh/ton.)

The presence of interactions further demonstrated the importance of understanding factor effects on pellet durability and energy consumption. While two factors may each negatively impact PDI or kWh/ton, the combination of the two can have a negative impact beyond the additive effects. This leads to the conclusion that if any one factor must be set to a level that does not promote good pellet durability or energy consumption, it is important, where possible, to mitigate the effect through control of the other factors..

The pelleting process was found to be consistent enough for potential regression modeling of both pellet durability and energy consumption. A comparison of predicted PDI values based on the results of the first week of trials was found to be within an average 1.8 PDI of the actual values determined during the second week. This represented a difference in PDI of only 2%. Incorporating all of the data from both weeks, a regression equation was developed having an R^2 value of 0.92. The average residual PDI improved to 1.1, translating into an approximate 1% variation between the model predictions and observed values. The difference in the observed energy consumption values between the first and second weeks of production was 0.59 kWh/ton, an approximate 7% variation between the two observed values. The regression model with all of the data had an R^2 value of 0.95. The average residual kWh/ton value improved to a difference of only 0.3 kWh/ton, or an approximate 3% variation between the model predictions and observed values. In addition to predicting the impact of each factor on pellet durability and energy consumption, these models may be useful when some factors (e.g. production rate and ingredient inclusion) cannot be varied due to demand or supply constraints. In these cases certain factors could be fixed and the remaining factors could be varied to give the best possible solution within those constraints.

It is evident that energy efficiency and pellet durability are not mutually exclusive. With the proper information at hand it is possible to manipulate factors in such a way as to preserve pellet durability while maintaining the lowest possible energy consumption. Following the assumptions described in the materials and methods section, the best (lowest) predicted overall feed cost ($324.41) had both a mid-range energy consumption (8.3 kWh/ton) and pelleting cost ($9.05/ton). Incorporating assumptions based on the work by McKinney and Teeter (2004), this was also predicted to have the best ratio of total cost per pound of BWG per day ($0.304/lb BWG/day). This example demonstrates how an understanding of the factors affecting finished feed quality, energy consumption, and animal performance could allow for the best return on investment.

With increasing ingredient and energy costs, knowing which factors within a facility affect production efficiency and feed quality should be considered a necessity. By taking into consideration current pricing, factor effects, and animal feed efficiency, a feed mill could be viewed not as a cost center, but as a tool for maximizing feed value. The practices suggested and presented in this work are offered as a basis for this purpose.

Table 4.1 Predicted PDI, kWh/ton, and Associated Costs for Experimental Treatments

TRT	PDI	kWh/ton	Pelleting Cost	Diet Cost	Total Cost	$/PDI
1	89.5	8.7	$ 10.42	$ 326.45	$ 336.87	$ 3.76
2	88.8	8.5	$ 10.40	$ 326.45	$ 336.85	$ 3.79
3	85.3	7.9	$ 10.35	$ 326.45	$ 336.80	$ 3.95
4	84.6	7.6	$ 10.33	$ 326.45	$ 336.78	$ 3.98
5	87.8	8.5	$ 10.40	$ 315.36	$ 325.76	$ 3.71
6	87.1	8.2	$ 10.38	$ 315.36	$ 325.74	$ 3.74
7	88.6	9.6	$ 9.15	$ 326.45	$ 335.60	$ 3.79
8	87.9	7.8	$ 9.01	$ 326.45	$ 335.46	$ 3.82
9	82.9	11.6	$ 10.41	$ 326.45	$ 336.86	$ 4.06
10	82.2	10.8	$ 10.35	$ 326.45	$ 336.80	$ 4.10
11	*90.7	8.8	$ 10.42	$ 326.45	$ 336.87	$ 3.72
12	90.0	8.5	$ 10.40	$ 326.45	$ 336.85	$ 3.74
13	78.9	7.3	$ 10.31	$ 326.45	$ 336.76	$ 4.27
14	80.4	7.0	$ 10.29	$ 326.45	$ 336.74	$ 4.19
15	79.1	7.6	$ 10.33	$ 315.36	$ 325.69	$ 4.12
16	84.4	7.3	$ 8.98	$ 326.45	$ 335.43	$ 3.98
17	76.4	10.7	$ 10.34	$ 326.45	$ 336.79	$ 4.41
18	86.4	7.4	$ 10.32	$ 326.45	$ 336.77	$ 3.90
19	74.7	*6.4	$ 10.24	$ 326.45	$ 336.69	$ 4.51
20	86.9	8.3	$ 9.05	$ 315.36	$ *324.41	$ 3.73
21	81.3	10.5	$ 10.33	$ 315.36	$ 325.69	$ 4.01
22	89.0	8.5	$ 10.40	$ 315.36	$ 325.76	$ *3.66
23	73.7	7.0	$ 10.29	$ 315.36	$ 325.65	$ 4.42
24	82.0	10.2	$ 8.97	$ 326.45	$ 335.42	$ 4.09
25	89.8	8.0	$ 9.03	$ 326.45	$ 335.48	$ 3.74
26	78.0	6.7	$ * 8.93	$ 326.45	$ 335.38	$ 4.30
27	84.1	11.6	$ 10.41	$ 326.45	$ 336.86	$ 4.01
28	72.3	10.1	$ 10.30	$ 326.45	$ 336.75	$ 4.66
29	80.1	7.3	$ 10.31	$ 326.45	$ 336.76	$ 4.21

*Highlighted values represent the best among treatments. (PDI: highest value, all others: lowest value)

Table 4.2 Predicted PDI, Feed Conversion, BWG, and Associated Costs for Experimental Treatments

				Assuming 5,000 Broilers Consuming 0.4 lbs/day†	
TRT	**PDI**	**Total Cost**	**Feed:Gain**	**BWG (lbs) / Day**	**$/lb BWG / Day**
1	89.5	$ 336.87	1.874	1067.4	$ 0.316
2	88.8	$ 336.85	1.875	1066.9	$ 0.316
3	85.3	$ 336.80	1.879	1064.3	$ 0.316
4	84.6	$ 336.78	1.880	1063.8	$ 0.317
5	87.8	$ 325.76	1.876	1066.2	$ 0.306
6	87.1	$ 325.74	1.877	1065.7	$ 0.306
7	88.6	$ 335.60	1.875	1066.8	$ 0.315
8	87.9	$ 335.46	1.876	1066.2	$ 0.315
9	82.9	$ 336.86	1.882	1062.6	$ 0.317
10	82.2	$ 336.80	1.883	1062.1	$ 0.317
11	*90.7	$ 336.87	*1.872	*1068.3	$ 0.315
12	90.0	$ 336.85	1.873	1067.8	$ 0.315
13	78.9	$ 336.76	1.887	1059.6	$ 0.318
14	80.4	$ 336.74	1.885	1060.8	$ 0.317
15	79.1	$ 325.69	1.887	1059.8	$ 0.307
16	84.4	$ 335.43	1.880	1063.6	$ 0.315
17	76.4	$ 336.79	1.891	1057.8	$ 0.318
18	86.4	$ 336.77	1.878	1065.2	$ 0.316
19	74.7	$ 336.69	1.893	1056.6	$ 0.319
20	86.9	$ *324.41	1.877	1065.5	$ *0.304
21	81.3	$ 325.69	1.884	1061.4	$ 0.307
22	89.0	$ 325.76	1.874	1067.1	$ 0.305
23	73.7	$ 325.65	1.894	1055.8	$ 0.308
24	82.0	$ 335.42	1.883	1061.9	$ 0.316
25	89.8	$ 335.48	1.873	1067.6	$ 0.314
26	78.0	$ 335.38	1.889	1059.0	$ 0.317
27	84.1	$ 336.86	1.881	1063.5	$ 0.317
28	72.3	$ 336.75	1.896	1054.9	$ 0.319
29	80.1	$ 336.76	1.886	1060.5	$ 0.318

*Highlighted values represent the best among treatments. (PDI and BWG: highest value, all others: lowest value)

† Assumptions based on data from McKinney and Teeter (2004) for 38-day-old broilers

Figure 4.1 Historically Accepted Proportional Effects of Factors on Pellet Quality

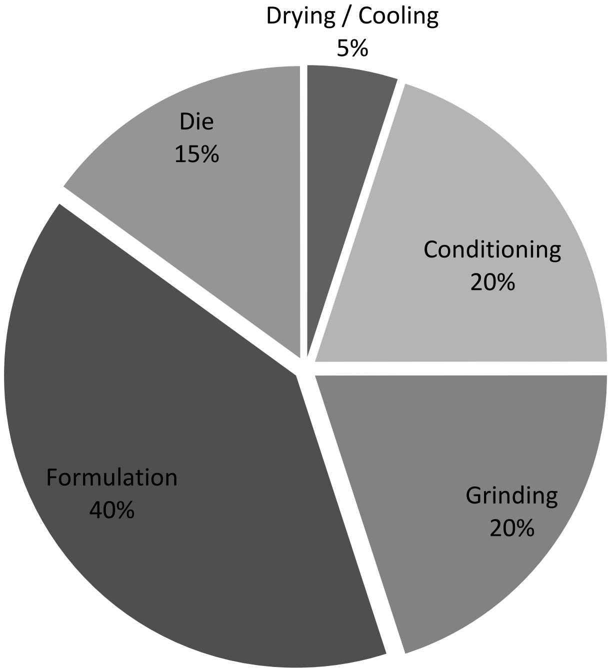


Figure 4.2 Experimental Treatments

Corn P. Size vs. Fat

	Coarse	Fine
1%	1	2
3%	3	4

Corn P. Size vs. DDGS

	Coarse	Fine
No DDGS	1	2
10% DDGS	5	6

Corn P. Size vs. Prod. Rate

	Coarse	Fine
3000 lbs/hr	1	2
4000 lbs/hr	7	8

Corn P. Size vs. Temp.

	Coarse	Fine
85 C	1	2
65 C	9	10

Corn P. Size vs. Ret. Time

	Coarse	Fine
30 sec	1	2
60 sec	11	12

Corn P. Size vs. Die L:D

	Coarse	Fine
8:1	1	2
5.6:1	13	14

Fat vs. DDGS

	1%	3%
No DDGS	1	3
10% DDGS	5	15

Fat vs. Prod Rate

	1%	3%
3000 lbs/hr	1	3
4000 lbs/hr	7	16

Fat vs. Temp.

	1%	3%
85 C	1	3
65 C	9	17

Fat vs. Ret. Time

	1%	3%
30 sec	1	3
60 sec	11	18

Fat vs. Die L:D

	1%	3%
8:1	1	3
5.6:1	13	19

DDGS vs. Prod Rate

	No DDGS	10% DDGS
3000 lbs/hr	1	5
4000 lbs/hr	7	20

DDGS vs. Temp.

	No DDGS	10% DDGS
85 C	1	5
65 C	9	21

DDGS vs. Ret. Time

	No DDGS	10% DDGS
30 sec	1	5
60 sec	11	22

DDGS vs. Die L:D

	No DDGS	10% DDGS
8:1	1	5
5.6:1	13	23

Prod. Rate vs. Temp

	3000 lbs/hr	4000 lbs/hr
85 C	1	7
65 C	9	24

Prod. Rate vs. Ret. Time

	3000 lbs/hr	4000 lbs/hr
30 sec	1	7
60 sec	11	25

Production Rate vs. Die L:D

	3000 lbs/hr	4000 lbs/hr
8:1	1	7
5.6:1	13	26

Temp. vs. Ret. Time

	85 C	65 C
30 sec	1	9
60 sec	11	27

Temp. vs. Die L:D

	85 C	65 C
8:1	1	9
5.6:1	13	28

Ret. Time vs. Die L:D

	30 sec	60 sec
8:1	1	11
5.6:1	13	29

Figure 4.3 Average PDI Values

Corn P. Size vs. Fat

	Coarse	Fine
1%	89.0^{A}	89.0^{A}
3%	83.9^{B}	84.9^{B}

Corn P. Size vs. DDGS

	Coarse	Fine
No DDGS	89.0^{A}	89.0^{A}
10% DDGS	88.0^{A}	87.2^{A}

Corn P. Size vs. Prod. Rate

	Coarse	Fine
3000 lbs/hr	89.0^{A}	89.0^{A}
4000 lbs/hr	89.0^{A}	88.5^{A}

Corn P. Size vs. Temp.

	Coarse	Fine
85 C	89.0^{A}	89.0^{A}
65 C	83.9^{B}	81.9^{C}

Corn P. Size vs. Ret. Time

	Coarse	Fine
30 sec	89.0^{A}	89.0^{A}
60 sec	90.1^{A}	89.0^{A}

Corn P. Size vs. Die L:D

	Coarse	Fine
8:1	89.0^{A}	89.0^{A}
5.6:1	80.1^{B}	80.4^{B}

Fat vs. DDGS

	1%	3%
No DDGS	89.0^{A}	83.9^{B}
10% DDGS	88.0^{A}	79.2^{C}

Fat vs. Prod Rate

	1%	3%
3000 lbs/hr	89.0^{A}	83.9^{C}
4000 lbs/hr	89.0^{A}	85.4^{B}

Fat vs. Temp.

	1%	3%
85 C	89.0^{A}	83.9^{B}
65 C	83.9^{B}	76.5^{C}

Fat vs. Ret. Time

	1%	3%
30 sec	89.0^{A}	83.9^{C}
60 sec	90.1^{A}	87.0^{B}

Fat vs. Die L:D

	1%	3%
8:1	89.0^{A}	83.9^{B}
5.6:1	80.1^{C}	74.5^{D}

DDGS vs. Prod Rate

	No DDGS	10% DDGS
3000 lbs/hr	89.0^{A}	88.0^{AB}
4000 lbs/hr	89.0^{A}	87.0^{B}

DDGS vs. Temp.

	No DDGS	10% DDGS
85 C	89.0^{A}	88.0^{A}
65 C	83.9^{B}	81.3^{C}

DDGS vs. Ret. Time

	No DDGS	10% DDGS
30 sec	89.0^{AB}	88.0^{B}
60 sec	90.1^{A}	89.0^{AB}

DDGS vs. Die L:D

	No DDGS	10% DDGS
8:1	89.0^{A}	88.0^{A}
5.6:1	80.1^{B}	73.7^{C}

Prod. Rate vs. Temp

	3000 lbs/hr	4000 lbs/hr
85 C	89.0^{A}	89.0^{A}
65 C	83.9^{AB}	81.6^{B}

Prod. Rate vs. Ret. Time

	3000 lbs/hr	4000 lbs/hr
30 sec	89.0^{A}	89.0^{A}
60 sec	90.1^{A}	90.0^{A}

Production Rate vs. Die L:D

	3000 lbs/hr	4000 lbs/hr
8:1	89.0^{A}	89.0^{A}
5.6:1	80.1^{B}	78.0^{B}

Temp. vs. Ret. Time

	85 C	65 C
30 sec	89.0^{A}	83.9^{C}
60 sec	90.1^{A}	85.5^{B}

Temp. vs. Die L:D

	85C	65C
8:1	89.0^{A}	83.9^{B}
5.6:1	80.1^{C}	69.4^{D}

Ret. Time vs. Die L:D

	30 sec	60 sec
8:1	89.0^{A}	90.1^{A}
5.6:1	80.1^{B}	80.4^{B}

$^{A, B, C, D}$ Within each design, means with differing superscripts are significantly different ($p<0.05$) according to Tukey's Studentized Range

Figure 4.4 Average kWh/ton Values

Corn P. Size vs. Fat

	Coarse	Fine
1%	8.8^{A}	8.4^{B}
3%	7.9^{C}	7.5^{D}

Corn P. Size vs. DDGS

	Coarse	Fine
No DDGS	8.8	8.4
10% DDGS	8.7	8.7

Corn P. Size vs. Prod. Rate

	Coarse	Fine
3000 lbs/hr	8.8^{A}	8.4^{B}
4000 lbs/hr	8.2^{B}	8.1^{B}

Corn P. Size vs. Temp.

	Coarse	Fine
85 C	8.8^{A}	8.4^{A}
65 C	11.5^{B}	10.1^{C}

Corn P. Size vs. Ret. Time

	Coarse	Fine
30 sec	8.8	8.4
60 sec	8.8	8.6

Corn P. Size vs. Die L:D

	Coarse	Fine
8:1	8.8^{A}	8.4^{B}
5.6:1	7.3^{C}	7.1^{C}

Fat vs. DDGS

	1%	3%
No DDGS	8.8^{A}	7.9^{B}
10% DDGS	8.7^{A}	7.7^{B}

Fat vs. Prod Rate

	1%	3%
3000 lbs/hr	8.8^{A}	7.9^{B}
4000 lbs/hr	8.2^{C}	7.5^{D}

Fat vs. Temp.

	1%	3%
85 C	8.8^{A}	7.9^{B}
65 C	11.5^{C}	10.8^{D}

Fat vs. Ret. Time

	1%	3%
30 sec	8.8^{A}	7.9^{B}
60 sec	8.8^{A}	7.6^{B}

Fat vs. Die L:D

	1%	3%
8:1	8.8^{A}	7.9^{B}
5.6:1	7.3^{C}	6.3^{D}

DDGS vs. Prod Rate

	No DDGS	10% DDGS
3000 lbs/hr	8.8^{A}	8.7^{B}
4000 lbs/hr	8.2^{C}	8.5^{D}

DDGS vs. Temp.

	No DDGS	10% DDGS
85 C	8.8^{A}	8.7^{A}
65 C	11.5^{B}	10.7^{C}

DDGS vs. Ret. Time

	No DDGS	10% DDGS
30 sec	8.8	8.7
60 sec	8.8	8.5

DDGS vs. Die L:D

	No DDGS	10% DDGS
8:1	8.8^{A}	8.7^{A}
5.6:1	7.3^{B}	7.2^{B}

Prod. Rate vs. Temp

	3000 lbs/hr	4000 lbs/hr
85 C	8.8^{A}	8.2^{A}
65 C	11.5^{B}	10.7^{B}

Prod. Rate vs. Ret. Time

	3000 lbs/hr	4000 lbs/hr
30 sec	8.8^{A}	8.2^{AB}
60 sec	8.8^{A}	7.7^{B}

Production Rate vs. Die L:D

	3000 lbs/hr	4000 lbs/hr
8:1	8.8^{A}	8.2^{B}
5.6:1	7.3^{C}	6.8^{D}

Temp. vs. Ret. Time

	85 C	65 C
30 sec	8.8^{A}	11.5^{B}
60 sec	8.8^{A}	12.5^{C}

Temp. vs. Die L:D

	85C	65C
8:1	8.8^{A}	11.5^{B}
5.6:1	7.3^{C}	9.8^{D}

Ret. Time vs. Die L:D

	30 sec	60 sec
8:1	8.8^{A}	8.8^{A}
5.6:1	7.3^{B}	7.4^{B}

$^{A, B, C, D}$ Within each design, means with differing superscripts are significantly different ($p<0.05$) according to Tukey's Studentized Range

Figure 4.5 An Inconsistent Relationship between PDI and kWh/ton

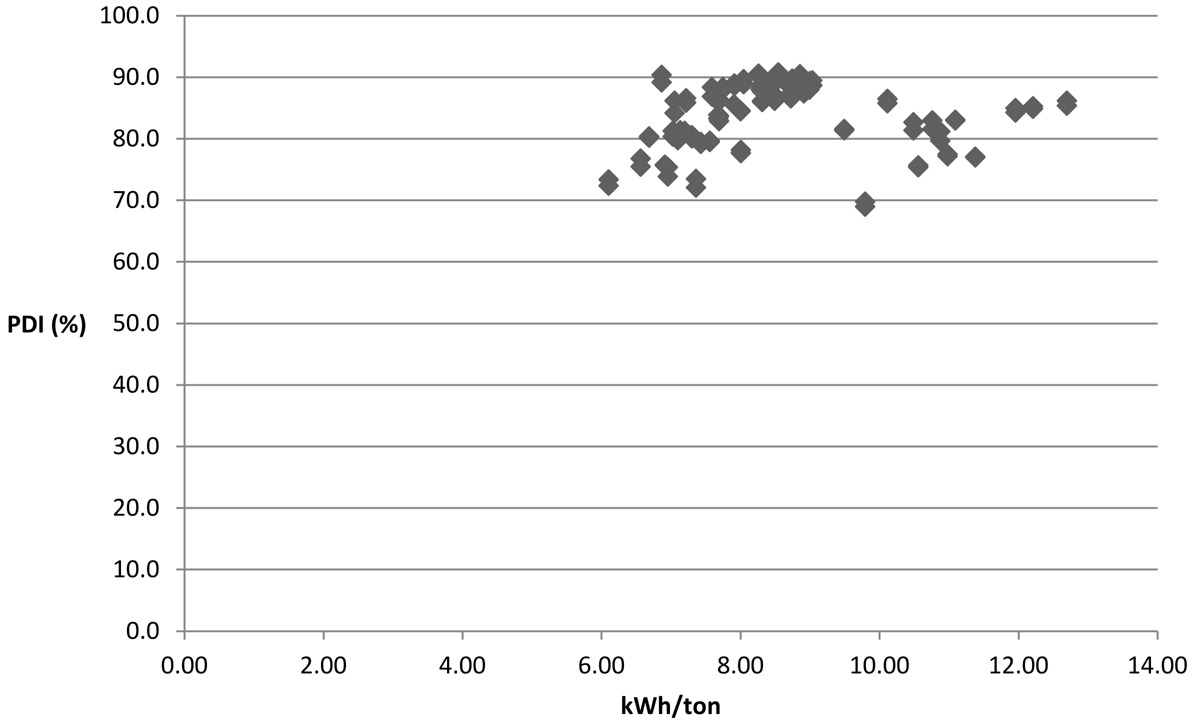
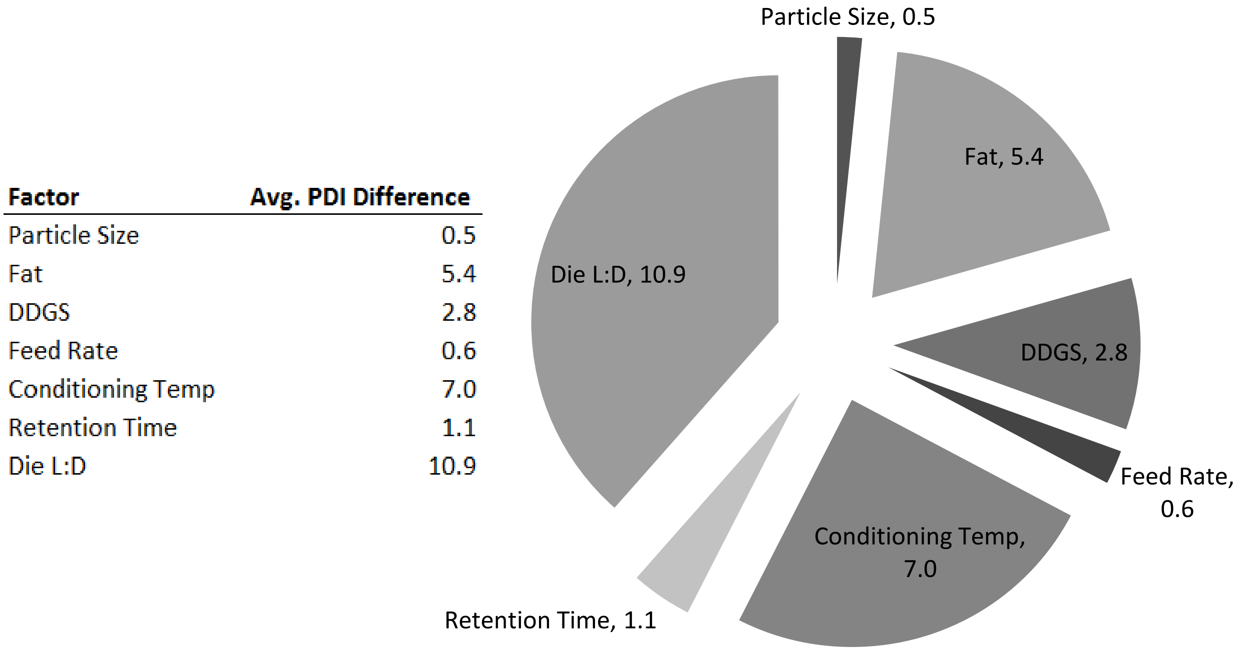


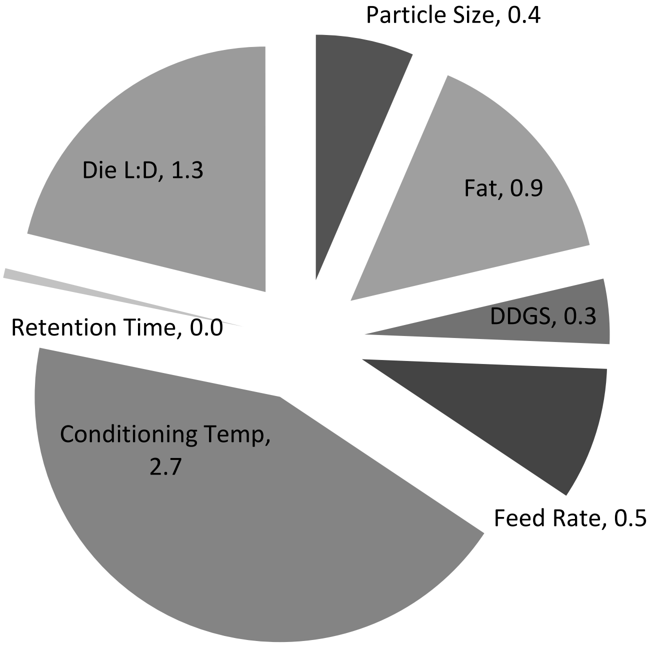
Figure 4.6 Average PDI Difference between Base and Experimental Levels of Each Factor for the Seven Relevant Treatment Comparisons



Factor	Avg. PDI Difference
Particle Size	0.5
Fat	5.4
DDGS	2.8
Feed Rate	0.6
Conditioning Temp	7.0
Retention Time	1.1
Die L:D	10.9

Figure 4.7 Average Energy Consumption (kWh/ton) Difference between Base and Experimental Levels of Each Factor for the Seven Relevant Treatment Comparisons

Factor	Avg. kWh/ton Difference
Particle Size	0.4
Fat	0.9
DDGS	0.3
Feed Rate	0.5
Conditioning Temp	2.7
Retention Time	0.0
Die L:D	1.3



Summary and Conclusions

Based on the results of this research the tumble box provides for the most consistently repeatable evaluations of pellet durability. Therefore, it remains the superior method compared to the Holmen line of pellet testers. This is due to the following: (1) the larger sample size (500g vs. 100g) provides for a more representative sample that will less likely contain disproportionally high or low durability pellets, and (2) the tumble box equipment is also simpler in design reducing equipment error. Thus, there are fewer sources of error causing variation in measured PDI. The tumble box is also superior because tests can be run often and sequentially without concern of equipment variation.

Results demonstrated that it may be possible for facilities to compare pellet durability while using different testing methods. Regression equations can be used to predict the PDI that might be reported for one test based on the known results of another. The more destructive NHP tester may not be the best choice when evaluating low durability pellets, while the less destructive tumble box tester may not be the best choice when evaluating high durability pellets.

Pellet density and hardness observations suggest that pellet durability is best tested by methods using a large quantity of sample and that closely represent actual handling practices. For example, high PDI pellets were found to have both high and low fracture force, suggesting that fracture force is not a complete predictor of pellet durability as evaluated by the tumble box method. However, the data does demonstrate that hard pellets do make for durable pellets, and so making an effort to produce such pellets is worthwhile. The data on physical attributes also suggested that high final pellet moisture leads to high PDI values. This data supports an effect of cooling on final pellet quality and also raises questions as to whether the standard method for testing pellets adequately addresses moisture content.

Die L:D ratio was found to be the most influential factor affecting PDI, with decreasing the die thickness and going from an 8:1 ratio to a 5.6:1 ratio leading to an average decrease in PDI of 10.9. Increasing conditioning temperature (average increase of 7.0 PDI) and decreasing fat level (average increase of 5.4 PDI) were also found to have a substantial influence. Particle size (0.5 PDI) and feed rate (0.6 PDI) were found to have little overall effect on pellet durability.

Increasing the conditioning temperature from 65°C to 85°C had the greatest impact on lowering energy consumption (2.7 kWh/ton). This was more than double the impact of next most influential factor, a thinner die L:D ratio (average decrease of 1.3 kWh/ton.) No other factor exhibited an influence on energy consumption greater-than or equal-to 1.0 kWh/ton. An increase in retention from 30 seconds to 60 seconds had nearly no impact on energy consumption (<0.1 kWh/ton.)

The pelleting process was found to be consistent enough for potential regression modeling of both pellet durability and energy consumption. For pellet durability, a regression equation was developed having an R^2 value of 0.92. The average residual PDI was 1.1, translating into an approximate 1% variation between the model predictions and observed values. For energy consumption, a regression equation was developed having an R^2 value of 0.95. The average residual kWh/ton value was 0.3 kWh/ton, or an approximate 3% variation between the model predictions and observed values. In addition to predicting the impact of each factor on pellet durability and energy consumption, these models may be useful when some factors (e.g. production rate and ingredient inclusion) cannot be varied due to demand or supply constraints. In these cases certain factors could be fixed and the remaining factors could be varied to give the best possible solution within those constraints.

It is evident that energy efficiency and pellet durability are not mutually exclusive. With the proper information at hand it is possible to manipulate factors in such a way as to preserve pellet durability while maintaining the lowest possible energy consumption. With increasing ingredient and energy costs, knowing which factors within a facility affect production efficiency and feed quality should be considered a necessity. By taking into consideration current pricing, factor effects, and animal feed efficiency, a feed mill could be viewed not as a cost center, but as a tool for maximizing feed value. The practices suggested and presented in this work are offered as a basis for this purpose.

Future Research

The pellet durability values in these experiments generally fell between 70 and 90 PDI, as measured by the standard method. Further analysis of pellets with standard method values above 90 PDI and below 50 PDI would allow for greater interpretation of how the methods compare when testing extreme pellet durabilities. Also, the methods could be further compared by analyzing pellets from multiple diet types (e.g. protein supplements, high fiber feeds, European rations) in order to examine the effects formulation has on the relationships found in these experiments.

Under ASAE Standard S269.4, pellets are tested when they reach ambient temperature, without mention of moisture content. However, results from these experiments provided some evidence that final pellet moisture has an effect on durability. Further research should be completed focusing on this relationship. If final pellet moisture is found to have a consistent effect on durability, then some consideration should be given to revising the standard to address final moisture content as testing and/or reporting criteria.

These experiments determined that the pelleting process is consistent enough to warrant modeling the effects of various factors on both pellet durability and energy consumption. Further experiments should be conducted in various feed production environments (e.g. large commercial and integrated facilities) in order to refine the method described here. Additionally, future research might consider combining some of the objectives of this work and some of those found in the work presented by McKinney and Teeter (2004). It would be interesting to model both the feed processing and animal production aspects under a single, controlled experimental design in order to gain a better picture of the cost-benefit relationships from the feed mill to the animal.

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Appendix A – Pelleting Costs Assumptions and Calculations

Labor Costs

Labor costs were based on a requirement of needing a single employee to oversee the operation of the pelleting system. This employee was assumed to be paid \$8/hr.

$$Labor = \frac{\frac{\$}{hr}}{\frac{tons}{hr}} = \frac{\$}{ton} \qquad Labor = \frac{\frac{\$8}{hr}}{\frac{1.5\ tons}{hr}} = \frac{\$5.33}{ton} \qquad Labor = \frac{\frac{\$8}{hr}}{\frac{2.0\ tons}{hr}} = \frac{\$4.00}{ton}$$

Energy Costs

Energy costs were based on the value of \$0.0747/kWh for industrial use in Kansas as reported by the Department of Energy for August, 2011.

$$Energy = \left(\frac{\$0.0747}{kWh}\right)\left(\frac{x\ kWh}{ton}\right) = \frac{\$}{ton}$$

Steam Costs

Steam costs were based on the following assumptions: average ambient temperature of 68°F, specific heat of feed of 0.45BTU/lb°F, steam pressure of 30 PSIG, 100% steam quality, 75% boiler efficiency, energy content of natural gas of 1000 BTU/ft^3, \$5.23/1000ft^3 of natural gas for industrial use in Kansas as reported by the Department of Energy for August, 2011.

$$BTU\ Required\ @\ Conditioner = Mass\ (lbs) \times Specific\ Heat\ \left(\frac{BTU}{lb\text{°F}}\right) \times\ \Delta T(\text{°F})$$

$$BTU\ @\ 65\text{°C}\ (149\text{°F}) = 2000lbs\ \times \frac{0.45BTU}{lb\text{°F}} \times (149\text{°F} - 68\text{°F}) = \frac{72{,}900\ BTU}{ton}$$

$$BTU\ @\ 85\text{°C}\ (185\text{°F}) = 2000lbs\ \times \frac{0.45BTU}{lb\text{°F}} \times (185\text{°F} - 68\text{°F}) = \frac{105{,}300\ BTU}{ton}$$

$$Steam\ Cost = \left(\frac{BTU\ @\ Conditioner}{75\%\ Boiler\ Efficiency}\right)\left(\frac{ft^3}{1000BTU}\right)\left(\frac{\$5.23}{ft^3}\right)$$

$$\frac{\$}{ton} @ 65℃ = \left(\frac{72{,}900\,\frac{BTU}{ton}}{0.75}\right)\left(\frac{ft^3}{1000BTU}\right)\left(\frac{\$5.23}{1000ft^3}\right) = \frac{\$0.51}{ton}$$

$$\frac{\$}{ton} @ 85℃ = \left(\frac{105{,}300\,\frac{BTU}{ton}}{0.75}\right)\left(\frac{ft^3}{1000BTU}\right)\left(\frac{\$5.23}{1000ft^3}\right) = \frac{\$0.73}{ton}$$

Maintenance Costs

Maintenance costs were based on estimated annual pellet mill maintenance costs and average annual production from 2006 through 2011. Pellet mill maintenance costs included pellet mill roll rebuilds, mainshaft seals, and mainshaft bearings.

$$Maintenance\ Costs = \frac{\frac{\$500}{yr}}{\frac{135\ tons}{yr}} = \frac{\$3.70}{ton}$$