# EVALUATION OF SWINE ODOR MANAGEMENT STRATEGIES IN A FUZZY MULTI-CRITERIA DECISION ENVIRONMENT[1]

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**Abstract:** The paper evaluates swine odor management strategies using the fuzzy extension of the Analytical Hierarchy Process (AHP), which is a multiple criteria decision making approach based on fuzzy scales. The evaluation is conducted using data from our cost effectiveness study of odor management strategies and our on farm studies relating odor to various management practices. These strategies include manual oil sprinkling, automatic oil sprinkling, wet scrubber, diffusion-coagulation-separation (DCS) deduster, pelleting feed, and draining shallow pit weekly. The criteria employed to evaluate the strategies are odor reduction efficiency, costs, nutrients in manure, and other benefits. Two producer profiles are considered: (a) producers who are pressured to achieve maximum reduction in odor emissions; and (b) producers who are constrained with limited financial resources. Both of these profiles are reflective of current situations for some producers. The results show that, as the scale fuzziness decreases, the preference of the first producer profile over the strategies from high to low is DCS deduster, pelleting feed, automatic oil sprinkling, manual oil sprinkling, draining pit weekly, and wet scrubber while the preference of the second producer profile is draining pit weekly, DCS dedusters, automatic oil sprinkling, wet scrubbers, pelleting feed, and manual oil sprinkling.

**Keywords:** swine production, odor management, multi-criteria decision, Analytical Hierarchy Process, fuzzy sets.

**JEL Codes:** Q12, Q19, C44, C69, D81.

## Introduction

The adverse effects of odor emissions from swine production facilities have been well documented and have become an environmental concern for the swine industry. Technically, odor compounds emitted from swine operations include, among others, ammonia, hydrogen sulfide, methane, and dusts. Building exhaust, manure storage, land application of manure, and disposing of dead pigs are all sources of odor emissions. Various management strategies have been developed to reduce odor emissions at these sources (see Table 1). These management strategies include: (1) animal dietary changes that directly affect odor-causing constituents of manure (such as the use of additives and pelleted feeds); (2) changes in the management or technology used in swine barns that have a direct impact on odor emissions (such as air treatment technologies and oil sprinkling); (3) manure additives that change the characteristics of manure and thus affect its odor emissions; (4) manure storage technologies that reduce or prevent emissions of volatile odorous components (such as lagoon covers and biofiltration); (5) technology or management that reduces odor emissions in land application of manure (such as soil injection); and (6) site choice and site manipulation (e.g., consideration of wind patterns, natural topography, or topography augmentation with plantings, etc.).

Effective evaluation and analysis of these odor control alternatives can provide swine producers with information on efficient odor management technologies and hence reduce the cost of odor management (Miller et al., 2002). The existing literature generally features the reporting of the technical efficiency and engineering costs of a specific technology or management system rather than a systematic comparison of many strategies (O'Neill et al., 1992; Huang et al., 2003). There are two basic problems in the evaluation of odor management strategies. First, the criteria for evaluations are generally multiple and in conflict. For example, a strategy can be very efficient in odor reduction but also very expensive to apply. Such a strategy would be highly valued based on a benefit criterion but low valued on a cost criterion. Second, the descriptions and measurements of both the criteria and management strategies can be a result of imprecise subjective judgements or incomplete objective information. This is particularly true in the odor management evaluation case because the marginal effect of a strategy on odor reduction is difficult to be precisely measured (Miller et al., 2002). Moreover, our cognitive ability to compare the strategies with diverse attributes is a concern, even if these attributes are well defined and scientifically measured (Fedrizzi, 1987). The first problem can be solved by the use of multiple criteria decision making techniques. However, the second problem involves uncertainty in measurements and preferences that can not be properly solved without the application of fuzzy set theory.

The Analytical Hierarchy Process (AHP) developed by Saaty (1977) is a decision approach designed to aid in the solution of complex multiple criteria decision problems and has successfully been used in a wide variety of application domains. This method models a complex decision problem into a hierarchy descending from an overall objective at the top to various criteria, sub-criteria, and so on until the decision alternatives at the lowest level. Pairwise comparisons are used to determine the relative importance (performance) among criteria (alternatives) in terms of how much more important (better) criterion (alternative) A is than criterion (alternative) B. A set of comparison matrices of all elements in a level of hierarchy with respect to an element of the immediately higher level are thus obtained, and the weights (the degree of relative importance among criteria or relative performance among alternatives) for each matrix and global weights (overall ranking of the alternatives) are then calculated. The resulting global weights can be interpreted as the alternatives' utilities and the ratios of weights as the marginal rates of substitution (Kangas, 1992). However, in this approach, both the pairwise comparison ratios and the resulting weights are specific real numbers and the problem of imprecise subjective judgements and incomplete information is not adequately addressed.

Fuzzy set theory is a useful tool for solving the problem of imprecise subjective judgement and incomplete objective information. According to Kaufman and Gupta (1988), fuzzy set theory is "a body of concepts and techniques that gave a norm of mathematical precision to human cognitive processes which in many ways are imprecise and ambiguous by the standards of classical mathematics". With the concepts and techniques of fuzzy set theory, we can further refine the multiple criteria decision making problem (Cheng and Mon, 1994). For instance, the AHP uses a 1 to 9 real number scale to describe the relative importance between two criteria or two alternatives with respect to a criterion. Since the concept of relative importance such as "strong importance" is linguistically ambiguous, triangular or trapezoidal fuzzy numbers 1 to 9 can be used to represent the fuzziness in criterion definitions as well as the uncertainty in subjective judgements and incomplete objective information. Hence, fuzzy multiple criteria decision making techniques such as the fuzzy extension of Saaty's AHP is a useful tool for the evaluation of swine odor management strategies.

The purpose of this paper is to evaluate the swine odor management strategies currently available to swine producers using the fuzzy extension of the AHP approach.

Specifically, triangular fuzzy numbers $\tilde{1}$ to $\tilde{9}$ are used to build judgement matrices through a pairwise comparison technique. The structural model of odor management strategy evaluation is depicted in Figure 1. Our model includes four criteria that could influence the odor management choice set and 21 strategies for reducing odor emissions from different sources. Since the relative importance of each criterion may differ from producer to producer, two types of producers (decision makers) are considered here: (a) producers who are pressured to achieve the largest reduction in odor emissions; and (b) producers who are constrained with limited financial resources. Comparison matrices of the evaluation criteria are separately constructed for each of the two producer profiles. Comparisons among the odor management strategies with respect to an evaluation criterion are derived based on data from the existing scientific literature.

This paper is intended to illustrate how the following questions can be answered using the proposed model and approach: (a) what is the most favorable strategy of odor management at the above mentioned different odor emissions sources? (b) what is the most favorable strategy of odor management from a whole farm perspective? and (c) what is the most favorable combination of odor management strategies from a whole farm perspective? This study has useful implications to swine consultants and producers for odor management decision making.

## A fuzzy AHP approach

The AHP is a theory for dealing with complex technological, economic, and socio-political problems (Saaty, 2000; Zahedi, 1986). Basically, the AHP is a multiobjective and multicriteria decision making approach that employs a pairwise comparison procedure to arrive at a scale of preferences among a set of alternatives. To apply this approach, it is necessary to break down a complex unstructured problem into its component parts; arrange these parts or variables into a hierarchic order; assign numerical values to our judgements on the relative importance of each variables; and synthesize the judgements to determine which variables have the highest priority and should be acted upon to influence the outcome. The breakdown involves structuring the problem as a hierarchy, which helps us to understand each part within its appropriate context.

As shown in figure 1, a typical AHP model consists of at least three hierarchical levels. The top level defines the overall objective of analysis (in our case, this is to evaluate strategies that reduce odor and nutrient emissions from swine operations). The second level includes all relevant and important evaluation criteria that influence the overall objective (in our case, this consists of odor reduction efficiency, costs, nutrients in manure, and other benefits). The second level is identified and structured into a hierarchy descending from the overall objective. The priority weights of structured criteria are then determined through pairwise comparison to reflect the preferences of different producer profiles. The matrix derived from the pairwise comparison using a nine-point scale is called comparison or judgement matrix. The theoretical foundation of the prioritization procedure proceeds as follows (Saaty, 2000): Assume that we are given n stones, $A_1,\ldots, A_n$ whose weights $w_1,\ldots, w_n$, respectively, are known to us. Let **A** be the matrix of pairwise ratios whose rows give the ratios of the weights of each stone with respect to all others and then multiply it on the right by the vector of weights **w**. The result of this multiplication as shown here is n**w**.

$$
\begin{array}{c} \\ A_1 \\ \\ A_2 \\ \\ \cdots \\ A_n \end{array}
\begin{array}{c} A_1 \quad A_2 \quad \cdots \quad A_n \\
\begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \end{array}
\begin{bmatrix} w_1 \\ w_2 \\ \cdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ \cdots \\ w_n \end{bmatrix} \qquad (1)
$$

Thus, to recover the scale (priority weights) from the matrix of ratios (comparisons), we must solve the following equation:

$$\mathbf{Aw} = \mathrm{n}\mathbf{w}, \qquad (2)$$

or

$$(\mathbf{A}-\mathrm{n}\mathbf{I})\mathbf{w} = \mathbf{0}, \qquad (3)$$

where **A** is the comparison matrix, n is the largest eigenvalue of matrix **A**, **I** is a identity matrix, and **w** is the eigenvector of matrix **A**. To make **w** unique, we normalize its entries by dividing by their sum. Therefore, in our case, the relative priorities of evaluation criteria can be obtained given the comparison matrix of the four criteria. Note that **A** satisfies the reciprocal property $a_{ji} = 1/a_{ij}$, for all $i$ and $j$.

The third level in a typical AHP states management alternatives to be evaluated by the criteria (in our case, this consists of all odor and nutrient management strategies to be considered). Management strategies are grouped by odor emission sources at which the strategies are targeted. In our case, these sources include swine finishing buildings, operation sites, manure storage, land application of manure, and disposing of dead pigs, appearing in the model as a level between the criteria and the strategies. This enables us to identify which strategy is the most favorable of odor and nutrient management at each emission source. Also, this is necessary because it is difficult, if not impossible, to compare two strategies used to reduce odor or nutrient emissions at different sources in terms of odor reduction efficiency. Pairwise comparisons are then applied to construct comparison matrices of the strategies in the same group with respect to each of the evaluation criteria. In our case, five strategy groups and four evaluation criteria could generate as many as 20 such comparison matrices for each producer profile. Similar to the derivation of the weights of the criteria as discussed above, the weights (priorities) of strategies in each group with respect to an evaluation criterion can be obtained from the eigenvector of the corresponding comparison matrix. The overall weights of the strategies of each group are hence computed for each producer profile based on weights of evaluation criteria and weights of the strategies with respect to each criterion. Finally, the strategy, which has the relatively highest overall weight in a group, will be identified as a producer profile's most preferred odor management strategy for reducing odor emissions from the corresponding source.

As already noted, pairwise comparisons in a conventional AHP model are based on a 1 to 9 real number scale and relative weights are calculated from the normalized eigenvector with respect to the largest eigenvalue of the comparison matrix. According to Cheng and Mon (1994), this approach can be improved by employing a triangular fuzzy number scale and using interval arithmetic to solve the fuzzy eigenvector. Typically, a triangular fuzzy number can be defined by a triplet ($a_1$, $a_2$, $a_3$) and its membership function can be expressed as (Kaufmann and Gupta, 1991)

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < a_1, \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2, \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \le x \le a_3, \\ 0, & x > a_3. \end{cases} \tag{4}$$

Moreover, by defining the interval of confidence, the triangular fuzzy number can characterized as (Cheng and Mon, 1993)

$$\forall \alpha \in [0, 1], \quad \tilde{A}_\alpha = [a_1^{(\alpha)}, a_3^{(\alpha)}] = [(a_2 - a_1)\alpha + a_1, -(a_3 - a_2)\alpha + a_3]. \tag{5}$$

From Kaufmann and Gupta (1988), the inverse of a triangular fuzzy number $\tilde{A}^{-1}$ can be approximated as P = $(1/a_3, 1/a_2, 1/a_1)$ and the corresponding interval of confidence at level $\alpha$ can be expressed as

$$\tilde{A}^{-1} = [\frac{1}{a_3 - (a_3 - a_2)\alpha}, \frac{1}{a_1 + (a_2 - a_1)\alpha}]. \tag{6}$$

The fuzzy numbers to represent the intensity of judgements of a decision maker over two criteria or strategies compared are defined in Table 2, where a fuzzy number $\tilde{x}$ expresses the meaning of "about *x*" (see Figure 2). It is noticeable that each characteristic function is defined by three parameters of the triangular fuzzy number and the actual range of the function is also determined. The scale used to compare two criteria or strategies is discrete, from fuzzy number $\tilde{1}$ to $\tilde{9}$ with $\tilde{1}$ representing almost equal importance of two factors and $\tilde{9}$ being about the highest possible importance of one factor over the other, as shown in Table 3. Following Cheng and Mon (1994), the fuzzy AHP approach is summarized below:

Step 1. To compare the relative importance or performance score, triangular fuzzy numbers $\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ are used to construct the judgement matrix, as

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \frac{1}{\tilde{a}_{12}} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{\tilde{a}_{1n}} & \frac{1}{\tilde{a}_{2n}} & \cdots & 1 \end{bmatrix} \tag{7}$$

where

$$\tilde{a}_{ij} = \begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}, \ or \ \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}, & i \neq j, \\ 1, & i = j. \end{cases}$$

Step 2. A fuzzy eigenvalue $\tilde{\lambda}$ is a fuzzy number solution to

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x} \tag{8}$$

where $\tilde{A}$ is an $n \times n$ fuzzy matrix containing fuzzy numbers $\tilde{a}_{ij}$ and $x$ is a non-zero n×1 fuzzy vector containing fuzzy numbers. Applying regular fuzzy multiplication and addition, Equation (8) is equivalent to

$$(\tilde{a}_{i1} \otimes \tilde{x}_1) \oplus \cdots \oplus (\tilde{a}_{in} \otimes \tilde{x}_n) = \tilde{\lambda} \otimes \tilde{x}_i, \tag{9}$$

for 1<= $i$ <= $n$, where $\tilde{A} = [\tilde{a}_{ij}]$, $\tilde{x}^t = (\tilde{x}_1, \ldots, \tilde{x}_n)$ and the $\tilde{a}_{ij}$ and $x$ are fuzzy numbers, ⊗ and ⊕ denote fuzzy multiplication and addition, respectively.

Step 3. Fuzzy multiplication and addition is performed using interval arithmetic and α-cuts. Let's define, for 0<α<=1 and all *i*, *j*,

$$\tilde{a}_{ij}^{\alpha} = [a_{ijl}^{\alpha}, a_{iju}^{\alpha}], \quad \tilde{x}_{i}^{\alpha} = [x_{il}^{\alpha}, x_{iu}^{\alpha}], \quad \tilde{\lambda}^{\alpha} = [\lambda_{l}^{\alpha}, \lambda_{u}^{\alpha}] \tag{10}$$

Substituting (10) in (9), we have, for $1<=i<=n$,

$$[a_{i1l}{}^{\alpha} x_{1l}{}^{\alpha}, a_{i1u}{}^{\alpha} x_{1u}{}^{\alpha}] \oplus \cdots \oplus [a_{inl}{}^{\alpha} x_{nl}{}^{\alpha}, a_{inu}{}^{\alpha} x_{nu}{}^{\alpha}] = [\lambda_l{}^{\alpha} x_{il}{}^{\alpha}, \lambda_u{}^{\alpha} x_{iu}{}^{\alpha}] \tag{11}$$

or

$$a_{i1l}{}^{\alpha} x_{1l}{}^{\alpha} + \cdots + a_{inl}{}^{\alpha} x_{nl}{}^{\alpha} = \lambda_l{}^{\alpha} x_{il}{}^{\alpha}, \ \ a_{i1u}{}^{\alpha} x_{1u}{}^{\alpha} + \cdots + a_{inu}{}^{\alpha} x_{nu}{}^{\alpha} = \lambda_u{}^{\alpha} x_{iu}{}^{\alpha}. \tag{12}$$

Step 4. Estimate fuzzy number $a_{ij}$ with a linear combination of its upper and lower bounds at level α. The estimator is defined as

$$\hat{a}_{ij}^{\alpha} = \delta\, a_{iju}^{\alpha} + (1-\delta) a_{ijl}^{\alpha} \quad \forall \delta \in [0,1]. \tag{13}$$

where δ is interpreted as an index of optimism of the decision maker in Cheng and Mon (1994). A larger index indicates a higher degree of optimism and δ = 0, 0.5, 1 represents a pessimistic, moderate, and optimistic decision maker, respectively.

Step 5. With α and δ fixed, Equation (7) becomes

$$\tilde{A} = \begin{bmatrix} 1 & \hat{a}_{12}^{\alpha} = \delta a_{12u}^{\alpha} + (1-\delta) a_{12l}^{\alpha} & \cdots & \hat{a}_{1n}^{\alpha} = \delta a_{1nu}^{\alpha} + (1-\delta) a_{1nl}^{\alpha} \\ \frac{1}{\hat{a}_{12}^{\alpha} = \delta a_{12u}^{\alpha} + (1-\delta) a_{12l}^{\alpha}} & 1 & \cdots & \hat{a}_{2n}^{\alpha} = \delta a_{12u}^{\alpha} + (1-\delta) a_{12l}^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{\hat{a}_{1n}^{\alpha} = \delta a_{1nu}^{\alpha} + (1-\delta) a_{1nl}^{\alpha}} & \frac{1}{\hat{a}_{2n}^{\alpha} = \delta a_{12u}^{\alpha} + (1-\delta) a_{12l}^{\alpha}} & \cdots & 1 \end{bmatrix} \quad (14)$$

From Equation (14), let $\alpha$ = 0.2, 0.4, …, 1, and $\delta$ = 0, 1 to compute the eigenvector corresponding to the largest eigenvalue. Hence, we obtain the whole interval of possible weight variations for each criterion and for each odor management strategy at different $\alpha$ levels.

Step 6. The overall weight of a strategy is obtained from mathematically combining the weights of criteria and the weights of the strategy with respect to each of the criteria (i.e., the normalized eigenvectors of the comparison matrices of criteria and strategies)

$$W_{S_i} = \sum_{j=1}^{4} W_{C_j} * W_{S_i}^{C_j}, \qquad i = 1, 2, \cdots, n \quad (15)$$

where $W_{S_i}$ denotes the overall weight of strategy $S_j$, $W_{Cj}$ denotes the weight of criterion $C_j$, and $W_{S_i}^{C_j}$ denotes the weight of strategy $S_i$ with respect to criterion $C_j$.

## Odor management strategy evaluation

*Weight the criteria for each of the two producer profiles*

Odor emissions from swine operations can be reduced by the use of odor management strategies and techniques. Research has shown that these strategies employed to control odor emissions from various sources significantly differ not only in odor reduction efficiency but also in costs needed for the implementation of a strategy

(Table 1). In addition, studies also suggest that some odor management strategies may generate less quantifiable benefits. For instance, dietary manipulation influences the odor intensity of swine excretion and simultaneously improves growth performance and changes nutrient contents in manure (Schiffman et al., 2000), which could have an impact on acres needed for manure disposal and costs for land application. Furthermore, odor abatement strategies can differ widely in maintenance and management required for proper operation. All these and other differences in odor management strategies constitute the fundamental factors that affect producers' odor abatement decision making. It is quite natural that odor reduction efficiency, costs, nutrients in manure, and other benefits are considered as appropriate criteria in the evaluation of swine odor management strategies. However, due to our limited knowledge of the influences of the strategies on nutrients in manure and on other benefits, we use evaluation criteria-- odor reduction efficiency and costs only in this analysis.

As already discussed, the priority weights of the evaluation criteria vary from producer to producer. For producers who are pressured to achieve significant reduction in odor emissions from their swine production activities, the performance of a strategy in odor reduction efficiency is of greater importance. However, costs are also an important factor of odor management strategy selection for this producer profile because, no matter how efficient a strategy may be, it must be within the affordability of the producer. Also, other things being equal, producers would choose strategies that simultaneously control odor and enhance profitability whenever possible. Similarly, costs are more important than odor reduction efficiency in strategy selection for producers who have financial constraints. For this producer profile, odor management is important but they are also concerned about the costs resulting from the application of odor control strategies. Therefore, they would regard costs as a slightly more important factor than odor reduction efficiency in decision making. The comparison matrices of the criteria are built for both producer profiles (Table 4 and 5). For producers who are pressured to achieve the largest reduction in odor emissions, compared with costs, odor reduction efficiency is of strong importance (represented by fuzzy number $\tilde{5}$). For producers who have constrained financial resources, we assume that costs are of moderate importance compared with odor reduction efficiency (represented by fuzzy number $\tilde{3}$).

*Weight odor management strategies with respect to a criterion*

From Table 1, there are numerous odor emission control strategies available to swine producers. Each of these strategies can stand alone as a single component of odor management system. Some strategies are alternatives to one another while some can be combined to further reduce odor emissions from the swine operation system. For example, air treatment technologies such as oil sprinkling, wet scrubbers, and DCS dedusters are typical substitutes. Draining the manure pit weekly in addition to an air treatment technology can further reduce odor emissions from shallow pit barns. In the evaluation process, strategies are compared with each other according to their relative performance regardless of whether there are alternatives or not. However, this issue should be considered when odor management recommendations are made.

Methodologically, mere subjective judgements can be employed to weight the odor management strategies with regard to a given criterion no matter whether we have a well defined or generally accepted measurement procedure (as e.g. for length, time or mass) for the strategies under the criterion. In real decision making, this is often the case.

We have criteria that are not well defined or generally accepted; we have measurement procedures that are not clearly rigorous for the criteria themselves. However, it is difficult to make reasonable and consistent comparisons among strategies with respect to criterion such as odor reduction efficiency in the absence of data from existing scientific research. This is because the measurement of odor reduction efficiency of a strategy is technically difficult and usually beyond our intuitive comprehension. In addition, many odor management strategies are jointly applied and their individual effects cannot be identified without careful statistical analysis (Miller et al. 2002). Moreover, data regarding the performances of each strategy with respect to the evaluation criteria should be measured on a comparable basis. Unfortunately, such data do not exist in current literature for all strategies listed in Table 1. Based on data availability, the focus of this analysis is on the evaluation of manual oil sprinkling, automatic oil sprinkling, wet scrubbers, DCS dedusters, pelleting feed, and draining pit weekly. Odor reduction efficiency and costs of these strategies are shown in Table 6, in which the relative importance of the strategies with respect to the two criteria is also respectively assumed based on their performance indicators. The judgement matrix through a pairwise comparison between the strategies with respect to odor reduction efficiency and costs are shown in Table 7 and 8, respectively.

*Overall weights of the strategies for each of the two producer profiles*

The overall weights of the six strategies are computed for the two producer profiles. By varying $\delta$ from 0 to 1, we obtained the upper and lower bounders of the overall weights of the six strategies at $\alpha$ level from 0.2 to 1. The results of the evaluation for producers who are pressured to achieve the largest reduction in odor emissions are reported in Table 9 and Figure 3. The evaluation results for producers who are constrained with limited financial resources in Table 10 and Figure 4.

## Results and Discussion

*What is the most favorable strategy of odor management at different odor emissions sources?*

From Table 9 and Figure 3, for producers under odor reduction pressure, when there is no fuzziness in the evaluation process (i.e., $\alpha = 1$), the order of preferences over the examined strategies abating odor emissions from swine finishing buildings from high to low are DCS dedusters, pelleting feed, auto oil sprinkling, manual oil sprinkling, draining pit weekly, and wet scrubbers. However, as fuzziness increases (i.e., $\alpha \rightarrow 0$), this preference order becomes less clear (Figure 3). It is difficult to distinguish the relative importance between DCS dedusters and pelleting feed and among auto oil sprinkling, manual oil sprinkling, and draining pit weekly when there is a high fuzziness in the parameter. Also, the latter three apparently have lower weights than the former two, suggesting that DCS dedusters and pelleting feed are among the best options with reasonable robustness for this producer profile. It is worth noting that wet scrubbers are almost always the least favorable strategy independent of change in fuzziness (see Figure 3). This result is not surprising because, compared with other strategies, wet scrubbers have no outstanding advantage either in terms of odor reduction efficiency or in terms of costs of application.

For producers who are constrained with limited financial resources, our results reveal a different story (see Table 10 and Figure 4). Draining the manure pit weekly stands out alone as the most favorable strategy at all $\alpha$ levels because of its dominant cost advantage over the other strategies. The second best strategy for this producer profile is DCS dedusters and then followed by auto oil sprinkling. But the difference between the two becomes indiscernible as fuzziness increases. Wet scrubbers are more favorable than pelleting feed regardless of changes in fuzziness though the difference in preference between the two is rather marginal. Manual oil sprinkling ranks the least favorable in the absence of fuzziness but as fuzziness increases, it can be as preferable as wet scrubbers and pelleting feed.

So far we have illustrated how a fuzzy AHP approach can be used to identify the relative preference of strategies for abating odor emissions from swine finishing buildings. As long as generally accepted comparisons can be made for strategies employed to reduce odor emissions from other sources, we can obtain the relative preference over the strategies in the same fashion.

*What is the most favorable strategy of odor management from a whole farm perspective?*

There are two difficulties in directly applying the fuzzy AHP approach to the evaluation of odor management strategies from a whole farm perspective. First, as noted earlier, it is difficult to compare odor reduction efficiency between strategies used at different emission sources. Second, there would be too many strategies to be compared and this could result in serious inconsistency in comparison matrices and hence lead to incorrect outcomes (Saaty, 1980). Saaty has recommended the maximum size of $n = 10$ for a matrix of pairwise comparisons and the number of strategies available at the farm level is usually greater than 10. Here we propose the following procedure that can be a tentative solution to these problems. Step one, renormalize the overall weights of strategies obtained from the above-discussed approach based on emission source grouping. This is necessary because the weights have been normalized for strategies within the same group and therefore the weight of a strategy in one group may not be compared with the weight of a strategy in another since the two groups may contain different numbers of strategies. Step two, compare the relative importance of the emission sources in odor management at the farm level with the fuzzy AHP and hence calculate the weights of the emission sources. The pairwise comparisons among emission sources can be assisted by odor complaint survey data that contain information regarding the frequency of the odor problem caused by each emission source, which is helpful to identify the priority of the emission sources in odor management at the farm level. Step three, use an equation similar to Equation (15) to synthesize the renormalized weight of a strategy with the weight of the corresponding emission source at which the strategy is used. The strategy that has the greatest weight can be regarded as the most favorable from a whole farm perspective.

*What is the most favorable combination of odor management strategies from a whole farm perspective?*

As cited in Tarp and Helles (1995), Kangas (1992) shows that the overall weights derived from the AHP represent the strategies' utilities to the decision maker. Therefore, the most favorable combination of odor management strategies can be derived from producers' utility maximization problem subject to a budget constraint. Schmoldt et al. (1994) put forward an integer programming model for project selection in which AHP-derived weights were used as objective function coefficient estimates. Similarly, the swine producer's utility maximizing problem can represented as

$$Maximize \quad Z = \sum_{i=1}^{n} w_i x_i \tag{16}$$

$$subject\ to: \sum_{i=1}^{n} c_i x_i \le total\ budget$$

$$\sum_{j=1}^{m} x_j \le 1, \quad when\ x_1, \cdots, x_m\ are\ substitutes\ one\ another$$

where $w_i$ denotes the overall weight of strategy $i$ derived from the AHP approach for strategy evaluation at the whole farm level, $c_i$ is the budget requirement for strategy $i$, and $x_i$ stands for strategy $i$ with a value either 0 or 1. The first constraint states that costs for implementing the most favorable strategy bundle should be equal to or less than the total budget while the second constraint states that no more than one should be chosen from a group of strategies that are substitutes one another. It should be noted that this is the minimum set of constraints that are important. Obviously, other constraints can also be included. For instance, we usually have more than one group of strategy substitutes and we should add constraints similar to the second for each strategy group. The solution for this integer programming problem consists of a vector $\boldsymbol{x} = [x_1, x_2, \ldots, x_n]$ where each $x_i$ is either 0 or1. In vector $\boldsymbol{x}$, elements with a value 1 represent the corresponding strategies that constitute the most favorable combination under a given budget constraint from the whole farm perspective.

## Conclusions

Odor management strategy evaluation is complicated because it involves a considerable amount of fuzziness, vagueness, ambiguity, or uncertainty in the modeling and decision making process. Consequently, we employed a fuzzy AHP approach to deal with this evaluation problem. Specifically, we used fuzzy numbers $\tilde{1}$ to $\tilde{9}$ to capture the fuzziness and uncertainty in the evaluation process. Using this approach, we proposed a structural model for swine odor management strategy evaluation and evaluated six strategies abating emissions from swine finishing buildings. We divided producers into two producer profiles: (a) producers who are pressured to achieve maximum reduction in odor emissions; and (b) producers who are constrained with limited financial resources. Both of these profiles are reflective of current situations for some producers. Our results show that, as the scale fuzziness decreases, the preference of the first producer profile over the strategies from high to low is DCS deduster, pelleting feed, automatic oil sprinkling, manual oil sprinkling, draining pit weekly, and wet scrubber while the preference of the second producer profile is draining the manure pit weekly, automatic oil sprinkling, DCS deduster and wet scrubber, pelleting feed, and manual oil sprinkling. In addition, we also discussed how this approach can be extended to identify the most favorable strategy from a whole farm perspective and the most favorable combination of odor management strategies from a whole farm perspective. Our analysis shows that the fuzzy AHP is an appropriate and useful approach for the evaluation of swine odor management strategies.

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**Table 1. Odor Emissions and Abatement Strategies**

| Source of Odor | Abatement strategies | Odor reduction efficiency | Nutrients in manure | Costs | benefits |
|---|---|---|---|---|---|
| Building exhaust | Formulation of low-protein amino acid supplemented diets | Reduce odor intensity by up to 16%, irritation intensity by up to 31%, and improve odor quality by up to 14% (Schiffman et al., 2000; Armstrong et al., 1999) | Reduce P excretion up to 44%, N up to 28% (Grandhi, 2001a,b). | Adding lysine, threonine and trytophan increases diet cost by 8%, but adding lysine alone results in almost no change in diet cost (de Lange et al., 1999) | Decrease manure land application costs |
| | Ingredient processing (pelleting feed) | Reduce odor emissions by 0.23 log OU/m3 compared with ground feed (Miller et al., 2002) | Decrease quantity of manure to the extent that FCR decreases. | Increase diet cost by $0.88-$2.21/pig marketed (Huang et al., 2003) | Pelleting feed improves digestibility, growth, productivity, and profitability. May slightly decrease manure land application costs |
| | Phase feeding | ? | Reduce nitrogen excretion by 5-10% (Lee et al., 2000; FASS, 2001) | Increasing number of phases from 2 to 4 decreases diet cost by $1.54/pig marketed (Bell, 1998) | May slightly decrease manure land application costs |
| | Split sex feeding | ? | Reduce nitrogen excretion by 5-8% (FASS, 2001) | Decrease diet cost but may increase labor and management cost | May slightly decrease manure land application costs |
| | Manure additives | Reduce odor 0-10% in indoor trial and 0-66% in outdoor trial (Stinson et al., 2000). Decrease odor up to 32%, H2S up to 47%, ammonia up to 15% (Heber et al., 2001). But generally, no effect. | Some additives can reduce N content in manure by about 10% but P and K contents remain unchanged (Heber et al., 2001). | Increase cost (labor and equipment) by $0.30-$1/pig marketed (ISU, 1998) | ? |
| | Sprinkling oil | Reduce odor by 0.18 log OU/m3 (Miller et al. 2002; Huang et al., 2003) | No effect | Increase cost by $0.51-$0.87/pig marketed (Huang et al., 2003) | Increase ADG |

| | | | | | |
|---|---|---|---|---|---|
| | Wet scrubber | Reduce odor by 27-66% (Heber et al., 1999) or 0.12 log OU/m3 (Miller et al., 2002; Huang et al., 2003) | No effect | Increase cost by $0.54/pig marketed (Huang et al., 2003) | ? |
| | DCS deduster | Reduce odor by 80% (Heber et al., 1999) or 0.21 log OU/m3 (Miller et al.; 2002; Huang et al., 2003) | No effect | Increase cost by $0.66/pig marketed (Huang et al., 2003) | ? |
| | Draining pit weekly vs. biweekly (for shallow pits) | Reduce odor by 0.01 log OU/m3 (Huang et al., 2003) | No effect | Increase cost by $0.06/pig marketed (Huang et al., 2003) | ? |
| | Bio-filtration | Open-bed filters remove odor by 75-90% (Nicolai and Janni, 1997). | No effect | An on-ground, open-bed, compost biofilter costs $0.50-$0.80 /pig marketed (Jacobson et al., 1998). An upflow biofiltration system costs $5.21/pig marketed (Cochran et al., 2000) | ? |
| | Shelterbelts or windbreak walls | Effective odor control by filtering emissions. Windbreak walls may reduce irritation leeward of the walls by up to 92% (Bottcher et al., 1998; Schiffman et al., 2000) | No effect | Shelterbelts are inexpensive but need a long time to grow. Windbreak walls cost $1.00/pig space to install the operating cost is low (Schiffman et al., 2000) | Shelterbelts also absorb CO2. |
| | Vertical stacks or chimneys | Better dispersal of exhaust odor. | No effect | Tall chimneys are too expensive for the benefit achieved because of the high airflow rates required in the summer (Heber et al., 1999). | ? |

| | | | | | |
|---|---|---|---|---|---|
| Manure storage (lagoons) | Covers (for outdoor manure storage) | Reduce odor emissions from outdoor storage by 50-99% (Heber et al., 1999), but may increase odor emissions in land application | May affect N content of manure. | Impermeable plastic covers cost $0.35-$0.45/pig marketed (Petersen, 1998) | ? |
| | Shelterbelts | Effective odor control (see above). | No effect | Inexpensive, $0.15/pig marketed (Heber et al., 1999) | Absorb CO2 but benefits are uncertain (Heber et al., 1999) |
| | Surface aeration (for lagoons) | Reduce odor emissions by over 80% (Heber et al., 1999) | ? | $0.50-$2.00/pig marketed for fixed costs and $0.50-$1.50/pig marketed for variable costs (Heber et al., 1999) | ? |
| | Liquid-Solid separation | Reduce odor from subsequent storage and treatment facilities (Bicudo, 2002); reduce odor by 20-30% (Zhang and Westerman, 1997). | N and P in the separated solids may be as high as 2% and 5%, respectively; their contents in slurry are greatly reduced (Bicudo, 2002). | Cost of screw-press separator installed on a 3,600 head capacity farm was $0.44/ pig finished ($0.35 fixed cost+$0.09 variable cost) (Bicudo, 2002) | Beneficial to producers who need to remove nutrients and transport them from farm (Bicudo, 2002) |
| Land application | Broadcast (air gun system irrigation, broadcast of manure from deep pit, or broadcast of relatively solid manure) | No reduction in odor emissions | Loss of nitrogen (30%) | Inexpensive | Fast to apply |
| | Broadcast with immediate incorporation | Reduce odor emissions by 50% | ? | Inexpensive | Little loss of nitrogen (3%) |
| | Injection with full soil coverage | Effectively reduce odor emissions by 85-90%. | Little loss of nitrogen (1%) (Heber et al., 1999). | Expensive, $0.40-$0.50/pig marketed or $0.003/gallon of slurry (Heber et al., 1999) | If equipment is available to inject, the fertilizer value of the extra nutrients saved more than justifies the cost (Heber et al., 1999) |

| | | | | | |
|---|---|---|---|---|---|
| Mortality disposal | Refrigerate | No odor emissions. | ? | On-farm refrigeration: total annual cost $1,038 (Foster et al., 1994) | ? |
| | Incinerate | Cause serious odor emissions. | ? | Incinerator (600 lb. Capacity): total annual cost $1,291 (Foster et al., 1994) | ? |
| | Compost | Cause odor emissions. | ? | Total annual cost: with carcass grinder and cutter $2,147; without carcass grinder and cutter $899 (Foster et al., 1994) | ? |
| | Bury | Cause little odor problem but illegal in some states. | ? | Low tangible cost (labor and fuel for digging the trench and filling it). | May pollute underground water and remain a potential disease source. |

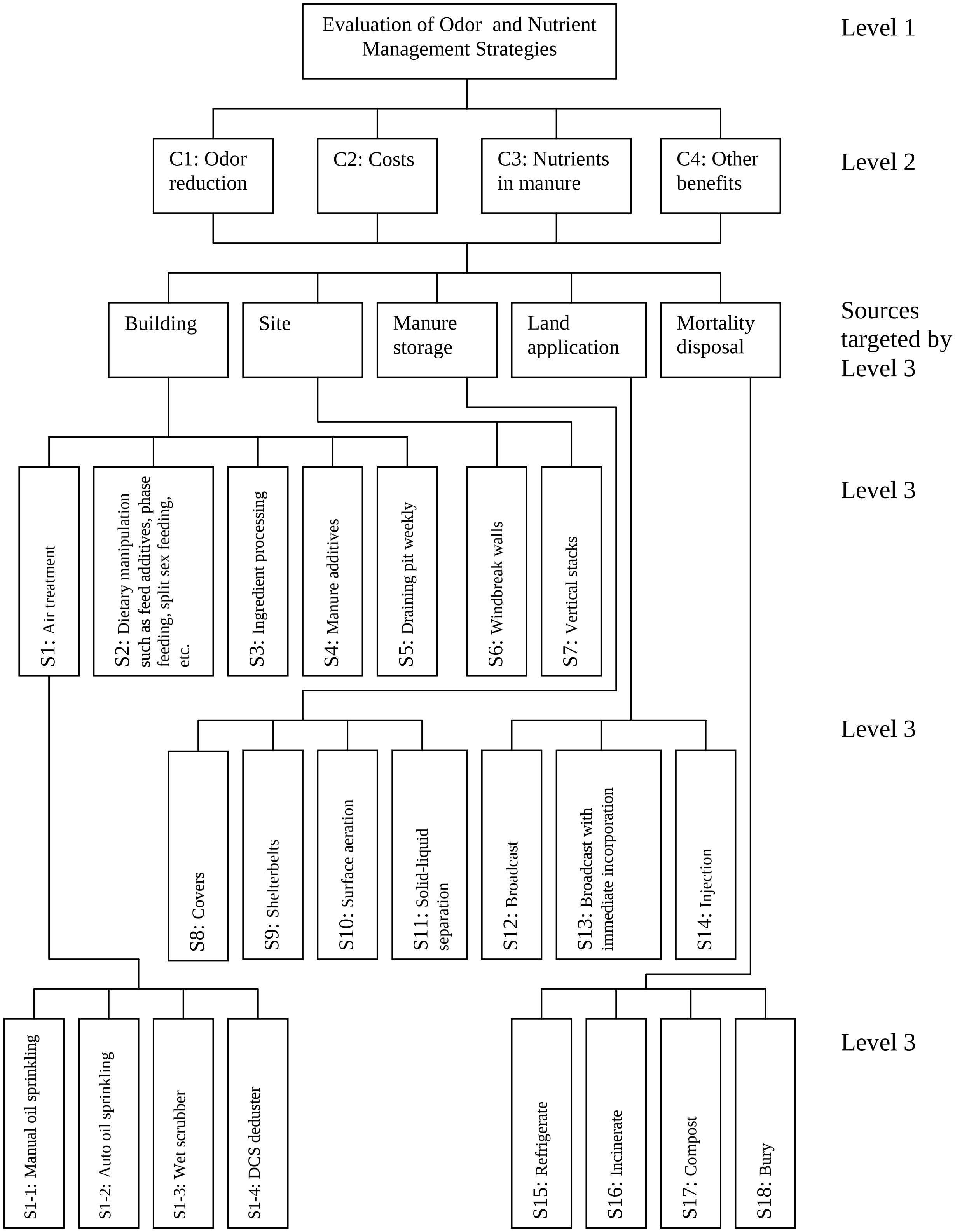


**Figure 1. Structure model of odor management strategy evaluation**

**Table 2. Characteristic (Membership) Function of the Fuzzy Numbers**

| Fuzzy number | Characteristic (membership) function |
|---|---|
| $\tilde{1}$ | (1,1,3) |
| $\tilde{x}$ | (x-2, x, x+2) for x = 3,5,7 |
| $\tilde{9}$ | (7,9,9) |

**Table 3. Meaning of Relative Strength of Fuzzy Scales**

| Intensity of importance | Definition |
|---|---|
| $\tilde{1}$ | Almost equal importance to the objective |
| $\tilde{3}$ | Moderate importance of one over another |
| $\tilde{5}$ | Strong importance |
| $\tilde{7}$ | Very strong importance |
| $\tilde{9}$ | Extreme importance |

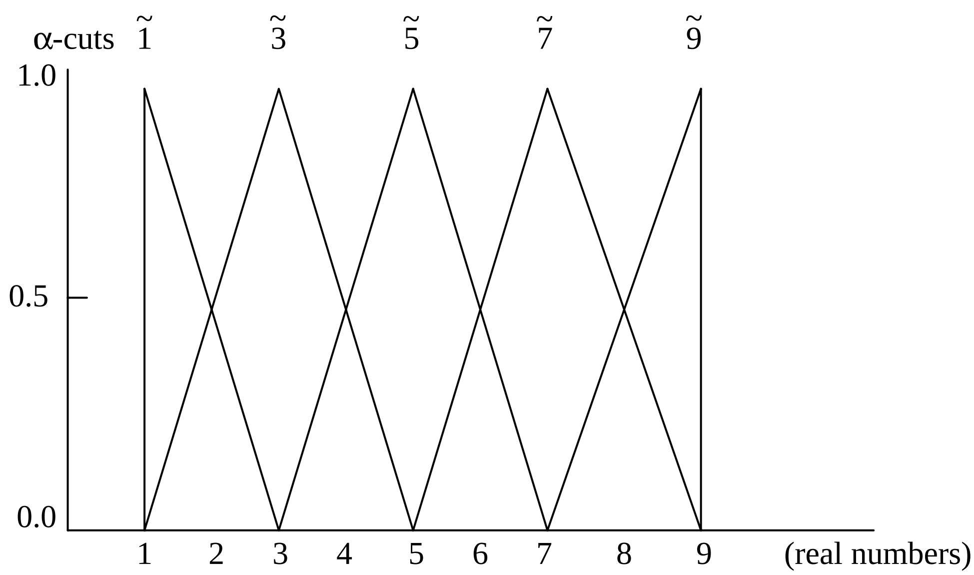


**Figure 2. Membership function for fuzzy number $\tilde{x}$**

**Table 4. Comparison Matrix of Evaluation Criteria for Producers who are Pressured to Achieve Maximum Odor Reduction**

| | C1: Odor reduction | C2: Costs |
|---|---|---|
| C1: Odor reduction | 1 | $\tilde{5}$ |
| C2: Costs | $1/\tilde{5}$ | 1 |

**Table 5. Comparison Matrix of Evaluation Criteria for Producers who are Constrained with Limited Financial Resources**

| | C1: Odor reduction | C2: Costs |
|---|---|---|
| C1: Odor reduction | 1 | $1/\tilde{3}$ |
| C2: Costs | $\tilde{3}$ | 1 |

**Table 6. Odor Reduction Efficiency and Costs for Six Strategies Abating Emissions from Buildings**

| Abatement strategy | Odor reduction efficiency (log OU/m3) | Relative importance using $S_5$ as the base value 1 | Costs ($ per pig marketed) | Relative importance using $S_3$ as the base value 1 |
|---|---|---|---|---|
| S1-1: Manual oil sprinkling | 0.18 | $\tilde{9}$ | 0.87 | $\tilde{5}$ |
| S1-2: Auto oil sprinkling | 0.18 | $\tilde{9}$ | 0.51 | $\tilde{7}$ |
| S1-3: Wet scrubber | 0.12 | $\tilde{5}$ | 0.54 | $\tilde{7}$ |
| S1-4: DCS deduster | 0.21 | $\tilde{9}$ | 0.66 | $\tilde{7}$ |
| S3: Pelleting feed | 0.23 | $\tilde{9}$ | 1.55 | 1 |
| S5: Draining pit weekly | 0.01 | 1 | 0.06 | $\tilde{9}$ |

**Table 7.** ***Odor Reduction*** **Comparison Matrix for Strategies Reducing Odor Emissions from Buildings**

| With respect to odor reduction efficiency | S1-1: Manual oil sprinkling | S1-2: Auto oil sprinkling | S1-3: Wet scrubber | S1-4: DCS deduster | S3: Pelleting feed | S7: Draining pit weekly |
|---|---|---|---|---|---|---|
| S1-1: Manual oil sprinkling | 1 | $\tilde{1}$ | $\tilde{3}$ | $1/\tilde{3}$ | $1/\tilde{3}$ | $\tilde{9}$ |
| S1-2: Auto oil sprinkling | $1/\tilde{1}$ | 1 | $\tilde{3}$ | $1/\tilde{3}$ | $1/\tilde{3}$ | $\tilde{9}$ |
| S1-3: Wet scrubber | $1/\tilde{3}$ | $1/\tilde{3}$ | 1 | $1/\tilde{5}$ | $1/\tilde{5}$ | $\tilde{5}$ |
| S1-4: DCS deduster | $\tilde{3}$ | $\tilde{3}$ | $\tilde{5}$ | 1 | $\tilde{1}$ | $\tilde{9}$ |
| S3: Pelleting feed | $\tilde{3}$ | $\tilde{3}$ | $\tilde{5}$ | $1/\tilde{1}$ | 1 | $\tilde{9}$ |
| S7: Draining pit weekly | $1/\tilde{9}$ | $1/\tilde{9}$ | $1/\tilde{5}$ | $1/\tilde{9}$ | $1/\tilde{9}$ | 1 |

**Table 8.** ***Costs Minimization*** **Comparison Matrix for Strategies Reducing Odor Emissions from Buildings**

| With respect to costs | S1-1: Manual oil sprinkling | S1-2: Auto oil sprinkling | S1-3: Wet scrubber | S1-4: DCS deduster | S3: Pelleting feed | S7: Draining pit weekly |
|---|---|---|---|---|---|---|
| S1-1: Manual oil sprinkling | 1 | $1/\tilde{3}$ | $1/\tilde{3}$ | $1/\tilde{3}$ | $\tilde{5}$ | $1/\tilde{7}$ |
| S1-2: Auto oil sprinkling | $\tilde{3}$ | 1 | $\tilde{1}$ | $\tilde{1}$ | $\tilde{7}$ | $1/\tilde{5}$ |
| S1-3: Wet scrubber | $\tilde{3}$ | $1/\tilde{1}$ | 1 | $\tilde{1}$ | $\tilde{7}$ | $1/\tilde{5}$ |
| S1-4: DCS deduster | $\tilde{3}$ | $1/\tilde{1}$ | $1/\tilde{1}$ | 1 | $\tilde{7}$ | $1/\tilde{5}$ |
| S3: Pelleting feed | $1/\tilde{5}$ | $1/\tilde{7}$ | $1/\tilde{7}$ | $1/\tilde{7}$ | 1 | $1/\tilde{9}$ |
| S7: Draining pit weekly | $\tilde{7}$ | $\tilde{5}$ | $\tilde{5}$ | $\tilde{5}$ | $\tilde{9}$ | 1 |

**Table 9. Results for Producers who are Pressured to Achieve *Maximum Odor Reduction***

| Strategy or criteria | Weights | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | α = 0.2 | | α = 0.4 | | α = 0.6 | | α = 0.8 | | α = 1 | |
| | δ = 1 | δ = 0 | δ = 1 | δ = 0 | δ = 1 | δ = 0 | δ = 1 | δ = 0 | δ = 1 | δ = 0 |
| | Weights of Criteria | | | | | | | | | |
| Odor reduction efficiency | 0.868 | 0.773 | 0.861 | 0.792 | 0.853 | 0.808 | 0.844 | 0.822 | 0.833 | 0.833 |
| Costs | 0.132 | 0.227 | 0.139 | 0.208 | 0.147 | 0.192 | 0.156 | 0.178 | 0.167 | 0.167 |
| | Weights of Strategies with respect to Odor Reduction Efficiency | | | | | | | | | |
| Manual oil sprinkling | 0.243 | 0.101 | 0.211 | 0.109 | 0.184 | 0.119 | 0.161 | 0.129 | 0.140 | 0.140 |
| Auto oil sprinkling | 0.175 | 0.101 | 0.162 | 0.109 | 0.152 | 0.119 | 0.145 | 0.129 | 0.140 | 0.140 |
| Wet scrubber | 0.069 | 0.064 | 0.067 | 0.062 | 0.066 | 0.061 | 0.064 | 0.062 | 0.063 | 0.063 |
| DCS deduster | 0.286 | 0.354 | 0.305 | 0.347 | 0.316 | 0.339 | 0.321 | 0.329 | 0.318 | 0.318 |
| Pelleting feed | 0.207 | 0.354 | 0.234 | 0.347 | 0.261 | 0.339 | 0.288 | 0.329 | 0.318 | 0.318 |
| Draining pit weekly | 0.021 | 0.026 | 0.021 | 0.025 | 0.021 | 0.024 | 0.022 | 0.023 | 0.022 | 0.022 |
| | Weights of Strategies with respect to Costs | | | | | | | | | |
| Manual oil sprinkling | 0.101 | 0.043 | 0.086 | 0.047 | 0.076 | 0.051 | 0.068 | 0.056 | 0.062 | 0.062 |
| Auto oil sprinkling | 0.205 | 0.123 | 0.190 | 0.127 | 0.174 | 0.130 | 0.156 | 0.133 | 0.136 | 0.136 |
| Wet scrubber | 0.149 | 0.123 | 0.147 | 0.127 | 0.144 | 0.130 | 0.140 | 0.133 | 0.136 | 0.136 |
| DCS deduster | 0.108 | 0.123 | 0.113 | 0.127 | 0.119 | 0.130 | 0.126 | 0.133 | 0.136 | 0.136 |
| Pelleting feed | 0.023 | 0.026 | 0.023 | 0.026 | 0.023 | 0.025 | 0.024 | 0.024 | 0.024 | 0.024 |
| Draining pit weekly | 0.415 | 0.560 | 0.441 | 0.548 | 0.465 | 0.534 | 0.487 | 0.520 | 0.506 | 0.506 |
| | Overall Weights | | | | | | | | | |
| Manual oil sprinkling | 0.224 | 0.088 | 0.193 | 0.096 | 0.168 | 0.106 | 0.147 | 0.116 | 0.127 | 0.127 |
| Auto oil sprinkling | 0.179 | 0.106 | 0.166 | 0.113 | 0.155 | 0.121 | 0.146 | 0.130 | 0.139 | 0.139 |
| Wet scrubber | 0.079 | 0.077 | 0.078 | 0.075 | 0.077 | 0.075 | 0.076 | 0.074 | 0.075 | 0.075 |
| DCS deduster | 0.262 | 0.302 | 0.278 | 0.301 | 0.287 | 0.299 | 0.290 | 0.294 | 0.287 | 0.287 |
| Pelleting feed | 0.182 | 0.280 | 0.205 | 0.280 | 0.226 | 0.278 | 0.246 | 0.275 | 0.269 | 0.269 |
| Draining pit weekly | 0.073 | 0.148 | 0.079 | 0.134 | 0.086 | 0.122 | 0.094 | 0.112 | 0.102 | 0.102 |

**Table 10. Results for Producers who are Constrained with *Limited Financial Resources***

| Strategy or criteria | Weights | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | α = 0.2 | | α = 0.4 | | α = 0.6 | | α = 0.8 | | α = 1 | |
| | δ = 1 | δ = 0 | δ = 1 | δ = 0 | δ = 1 | δ = 0 | δ = 1 | δ = 0 | δ = 1 | δ = 0 |
| | Weights of Criteria | | | | | | | | | |
| Odor reduction efficiency | 0.417 | 0.178 | 0.357 | 0.192 | 0.313 | 0.208 | 0.278 | 0.227 | 0.250 | 0.250 |
| Costs | 0.583 | 0.822 | 0.643 | 0.808 | 0.687 | 0.792 | 0.722 | 0.773 | 0.750 | 0.750 |
| | Weights of Strategies with respect to Odor Reduction Efficiency | | | | | | | | | |
| Manual oil sprinkling | 0.243 | 0.101 | 0.211 | 0.109 | 0.184 | 0.119 | 0.161 | 0.129 | 0.140 | 0.140 |
| Auto oil sprinkling | 0.175 | 0.101 | 0.162 | 0.109 | 0.152 | 0.119 | 0.145 | 0.129 | 0.140 | 0.140 |
| Wet scrubber | 0.069 | 0.064 | 0.067 | 0.062 | 0.066 | 0.061 | 0.064 | 0.062 | 0.063 | 0.063 |
| DCS deduster | 0.286 | 0.354 | 0.305 | 0.347 | 0.316 | 0.339 | 0.321 | 0.329 | 0.318 | 0.318 |
| Pelleting feed | 0.207 | 0.354 | 0.234 | 0.347 | 0.261 | 0.339 | 0.288 | 0.329 | 0.318 | 0.318 |
| Draining pit weekly | 0.021 | 0.026 | 0.021 | 0.025 | 0.021 | 0.024 | 0.022 | 0.023 | 0.022 | 0.022 |
| | Weights of Strategies with respect to Costs | | | | | | | | | |
| Manual oil sprinkling | 0.101 | 0.043 | 0.086 | 0.047 | 0.076 | 0.051 | 0.068 | 0.056 | 0.062 | 0.062 |
| Auto oil sprinkling | 0.205 | 0.123 | 0.190 | 0.127 | 0.174 | 0.130 | 0.156 | 0.133 | 0.136 | 0.136 |
| Wet scrubber | 0.149 | 0.123 | 0.147 | 0.127 | 0.144 | 0.130 | 0.140 | 0.133 | 0.136 | 0.136 |
| DCS deduster | 0.108 | 0.123 | 0.113 | 0.127 | 0.119 | 0.130 | 0.126 | 0.133 | 0.136 | 0.136 |
| Pelleting feed | 0.023 | 0.026 | 0.023 | 0.026 | 0.023 | 0.025 | 0.024 | 0.024 | 0.024 | 0.024 |
| Draining pit weekly | 0.415 | 0.560 | 0.441 | 0.548 | 0.465 | 0.534 | 0.487 | 0.520 | 0.506 | 0.506 |
| | Overall Weights | | | | | | | | | |
| Manual oil sprinkling | 0.160 | 0.053 | 0.131 | 0.059 | 0.110 | 0.065 | 0.094 | 0.072 | 0.081 | 0.081 |
| Auto oil sprinkling | 0.193 | 0.119 | 0.180 | 0.123 | 0.167 | 0.128 | 0.153 | 0.132 | 0.137 | 0.137 |
| Wet scrubber | 0.115 | 0.113 | 0.118 | 0.114 | 0.119 | 0.116 | 0.119 | 0.117 | 0.118 | 0.118 |
| DCS deduster | 0.182 | 0.165 | 0.182 | 0.169 | 0.180 | 0.173 | 0.180 | 0.178 | 0.182 | 0.182 |
| Pelleting feed | 0.099 | 0.085 | 0.099 | 0.087 | 0.098 | 0.090 | 0.097 | 0.094 | 0.097 | 0.097 |
| Draining pit weekly | 0.251 | 0.465 | 0.291 | 0.447 | 0.326 | 0.428 | 0.357 | 0.407 | 0.385 | 0.385 |

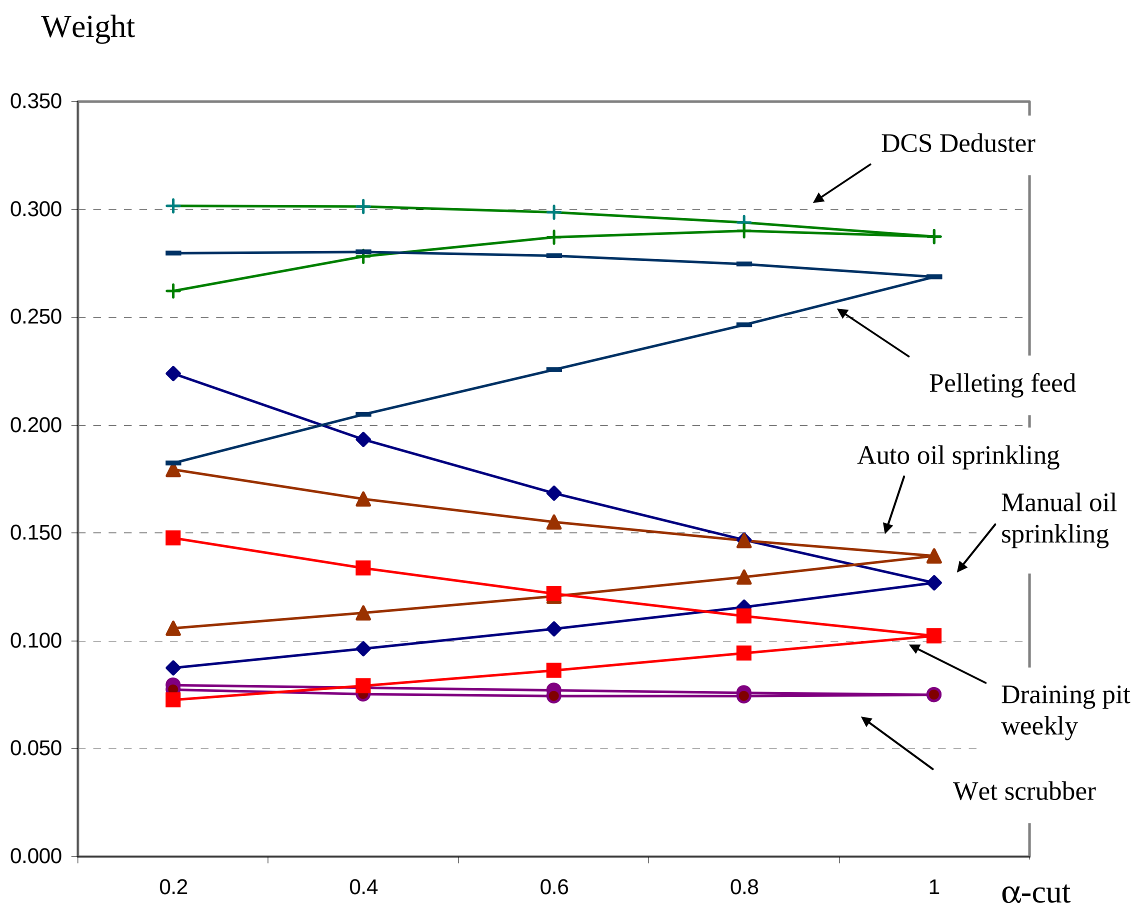


**Figure 3. Overall weights of strategies for producers under odor reduction pressure**

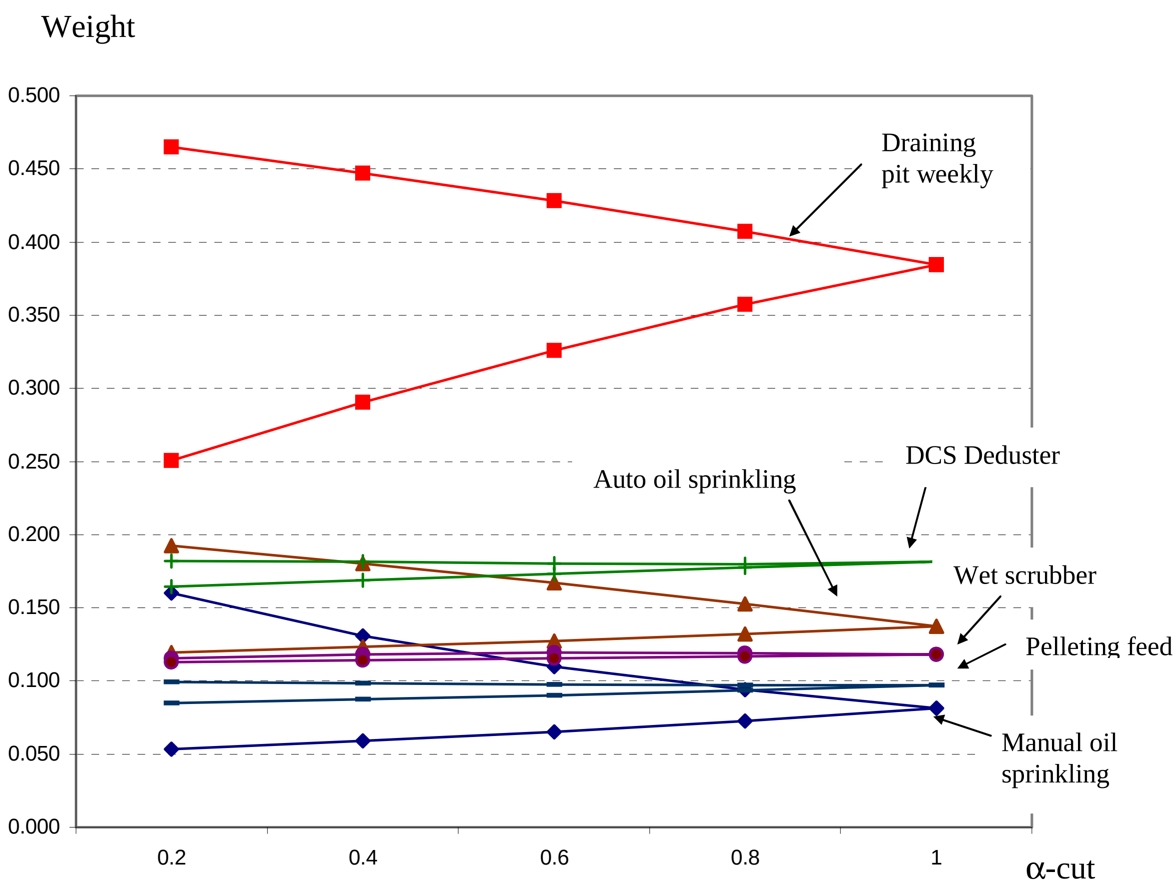


**Figure 4. Overall weights of strategies for producers with limited financial resources**