



Innovative Applications of O.R.

A multiple criteria decision making approach to manure management systems in the Netherlands

Solomie A. Gebrezgabher^{a,*}, Miranda P.M. Meuwissen^b, Alfons G.J.M. Oude Lansink^b^a International Water Management Institute, PMB, CT 112, Cantonments, Accra, Ghana^b Business Economics, Wageningen University, Hollandseweg 1, 6706 KN Wageningen, The Netherlands

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ABSTRACT

The intensification of livestock operations in the last few decades has resulted in an increased social concern over the environmental impacts of livestock operations and thus making appropriate manure management decisions increasingly important. A socially acceptable manure management system that simultaneously achieves the pressing environmental objectives while balancing the socio-economic welfare of farmers and society at large is needed. Manure management decisions involve a number of decision makers with different and conflicting views of what is acceptable in the context of sustainable development. This paper developed a decision-making tool based on a multiple criteria decision making (MCDM) approach to address the manure management problems in the Netherlands. This paper has demonstrated the application of compromise programming and goal programming to evaluate key trade-offs between socio-economic benefits and environmental sustainability of manure management systems while taking decision makers' conflicting views of the different criteria into account. The proposed methodology is a useful tool in assisting decision makers and policy makers in designing policies that enhance the introduction of economically, socially and environmentally sustainable manure management systems.

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1. Introduction

The intensification of livestock operations in the European Union has caused increasing environmental impacts on the soil, the water and the air (Jongbloed & Lenis, 1998). Within the European Union, it is estimated that agriculture contributes 49% of CH₄ emissions and 63% of N₂O emissions (Sommer, Petersen, & Moller, 2004). Most of CH₄ emissions originate from livestock manure during storage while most N₂O emissions originate from field application of animal manure (Sommer et al., 2004). In order to abate these environmental hazards, a series of environmental regulations and directives have been implemented. The EU nitrate directive aims at reducing water pollution caused by nitrate from agriculture and the EU air quality directive sets limits on the emission of ammonia and nitrogen oxides to the atmosphere (Oenema, 2004). Manure management is becoming increasingly important in order to reduce environmental impacts (Karmakar, Lague, Agnew, & Landry, 2007). Manure management is defined as a decision-making process at all stages, i.e. from collection of manure in animal houses till after field application that aims to combine profitable agricultural production with minimal nutrient losses from

manure (Chadwick et al., 2011; Karmakar et al., 2007; Sommer et al., 2009).

The extent and impact of the manure problems became clear in the 1970s and especially, the 1980s (Langeveld et al., 2007). The problem is still a pressing issue today as it has long been difficult to implement effective strategies to change manure management practices. Alternative environmentally acceptable disposal routes with potential financial benefits are manure processing technologies that provide energy and manure products (Burton & Turner, 2003; Melse & Timmerman, 2009). However, these alternative manure processing technologies are not without problems. Although the main objective of manure processing is to reduce the environmental impact, not all of the technologies achieve a reduction in pollution (Petersen et al., 2007) and most of the technologies are considered to be too expensive for the livestock farmer to adopt (Burton, 2007). Consequently, a socially acceptable manure management system that simultaneously reduces environmental impacts while accounting for the socio-economic welfare of both farmers and society is needed (De Vos, Weersink, & Stonehouse, 2002).

Manure management involves a number of decision makers with different and often conflicting perceptions of what is acceptable in the context of sustainable development. Different interest groups attach different values to each of the economic, social and

* Corresponding author. Tel.: +233 302 784753; fax: +233 302 784752.

E-mail address: s.gebrezgabher@cgiar.rog (S.A. Gebrezgabher).

environmental objectives, and rank priorities differently. For instance, for the farmer, keeping manure disposal cost at a minimum is important while for the environmental organizations, reducing environmental impacts is more important. This calls for an integrated approach to modelling manure management systems that encompasses multiple objectives of decision makers. The traditional model of optimizing a single objective function over a set of feasible solutions is not enough to capture the complexity of the decision-making processes. In the presence of multiple and conflicting objectives, multiple criteria decision making (MCDM) methods are appropriate tools to support decision making (Pohekar & Ramachandran, 2003; Romero & Rehman, 2003).

To evaluate the economic and environmental sustainability of manure management systems and to support decision making, different types of methods based on either mathematical programming or simulation methods are used. The mathematical programming models are either single objective optimization models or multiple objective programming models. Giasson, Bryant, and Bills (2002) used a multiple objective programming model to support decision making with respect to manure allocation decisions at farm level. Alocilja (1997) developed a compromise programming model for phosphorus management for a dairy-crop operation by simultaneously minimizing excess phosphorus from manure and cost of feed. Stonehouse, De Vos, and Weersink (2002) used a mixed integer programming model to develop a decision-making tool for assessing the technical, environmental and economic performance of alternative manure-handling systems in the context of a whole farm planning model. Others used a linear programming model to optimize farm profitability by introducing the environmental aspects of manure management as constraints (Gebrezgabher, Meuwissen, Prins, & Oude Lansink, 2010; Hadrich, Wolf, Black, & Harsh, 2008). In addition to mathematical programming models, previous studies have used simulation methods. Kruseman et al. (2008) developed a micro-simulation model called manure and ammonia model (MAMBO) of livestock and agriculture to model the mineral flows within the sector and the resulting emissions. The simulation model is used as a tool to evaluate policies on non-point source emission. Van der Straeten, Buysse, Nolte, Lauwers, and Claeys Dand Van Huylenbroeck (2010) developed a simulation model for spatial optimization of manure allocation. Despite the wide range of studies on manure management problems, the integration of economic, social and environmental criteria, taking decision makers' preferences into account has not been addressed.

The objective of this study is to develop a decision-making tool to assess the economic, social and environmental sustainability of manure management systems. This paper examines trade-offs between economic, social and environmental impacts of manure management and integrates views from different decision makers. The methodology applied in this study can be used as a tool to assist decision makers and policy makers in designing policies that enhance the introduction of economically, socially and environmentally sustainable manure management systems.

The remainder of this paper is organized as follows. Section 2 introduces the MCDM modelling framework. Section 3 provides a brief description of manure processing technologies considered in this study, the case study and the data sources. Results are given in section 4. Conclusions and implications are given in section 5.

2. Modelling framework

Multiple criteria decision making is a well-known branch of decision making which deals with the process of making decisions in the presence of multiple and conflicting objectives (Pohekar & Ramachandran, 2003). MCDM thus seeks to assist the decision ma-

ker in identifying feasible alternative solutions that attempt to reach a balance among the multiple objectives. This task can be formulated as a multi-objective problem by applying a compromise programming (CP) to find the best compromise solution. Fig. 1 depicts the modelling framework for manure processing systems.

First, criteria to measure the economic, social and environmental objectives are determined. By integrating the necessary input information for each of the manure processing systems considered, a pay-off matrix is constructed to enable decision makers to understand trade-offs among the different criteria. After the weights to the criteria that reflect their relative importance are determined, the best compromise solution is determined.

2.1. Compromise programming

Compromise programming (CP) belongs to the class of multiple criteria analytical methods called “distance-based” methods (Romero & Rehman, 2003). It is an extension and a complement to other MCDM technique, the multi-objective programming (MOP) which seeks to solve the problem of simultaneous optimization of several criteria. This is done by identifying the set that contains Pareto efficient solutions for all the criteria. This can be stated as:

$$\begin{aligned} \text{Eff } Z(y) &= [Z_1(y), Z_2(y), \dots, Z_n(y)] \\ \text{s.t. : } & F[Z_1(y), Z_2(y), \dots, Z_n(y)] \end{aligned} \quad (1)$$

where y is a vector of decision variables, $Z_j(y)$ is the mathematical expression for the j th criteria, *Eff* means the efficient solution and F is the feasible set that contains Pareto efficient solutions for all the criteria. The MOP attempts to generate the efficient set which is a subset of the feasible set (El-Gayar & Leung, 2001). Once these efficient solutions are identified, they can be further analyzed using compromise programming to find the best compromise solution.

Compromise programming defines the best solution as the one in the set of efficient solutions with the smallest distance from an ideal point (Romero & Rehman, 2003; Zeleny, 1982). The first step in CP is to construct a pay-off matrix which shows the ideal and anti-ideal values for each of the criteria by optimizing each of the criteria separately over the efficient set. The pay-off matrix shows the degree of conflict between criteria. The ideal point is used as a reference point in CP as the aim is to obtain a solution by choosing a point in the efficient solution which is closest to the ideal value. To achieve this, a distance function is introduced as a proxy measure for human preferences with regards to achieving a solution closest to the ideal value. The normalized distance, d_j , between the j th criteria and its ideal assuming a maximization problem is given by:

$$d_j = \frac{Z_j^* - Z_j(y)}{Z_j^* - Z_{*j}} \quad (2)$$

where Z_j^* and Z_{*j} are the ideal and anti-ideal values for the j th criteria respectively. The normalization factor is the absolute deviation between the ideal and anti-ideal solution and is used to obtain consistent results when the criteria are measured in different units (Zeleny, 1982).

In order to obtain the set of efficient solutions nearest with respect to the ideal point, the following CP model is proposed (Zeleny, 1982; Yu, 1973):

$$L_p(W) = \left[\sum_{j=1}^n W_j^p \left[\frac{Z_j^* - Z_j(y)}{Z_j^* - Z_{*j}} \right]^p \right]^{1/p} = \left[\sum_{j=1}^n (W_j d_j)^p \right]^{1/p} \quad (3)$$

where p is a metric defining the family of distance functions which reflects the importance attached to the deviation of each criterion

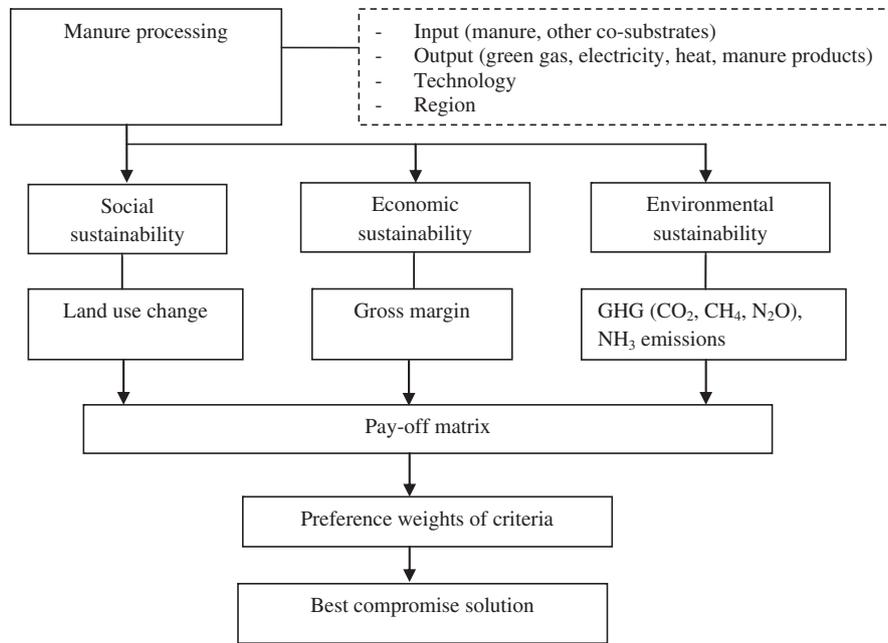


Fig. 1. Conceptual framework of MCDM analysis of manure processing systems.

from its ideal value. W_j is the preference weight attached to the j th criterion.

The L_p metrics are used to calculate the distances between solutions belonging to the efficient set and an ideal point. The value $p = 1$ implies that all deviations are equally important. As p increases, the larger deviations are given more weights. The L_1 and L_∞ define a subset of the efficient set in which all other compromise solutions fall (Linares & Romero, 2000; Romero & Rehman, 2003; Yu, 1973). Then the compromise solution is chosen so as to minimize d_j . In a bi-objective case metrics $p = 1$ and $p = \infty$ define two bounds of the compromise set and the other best compromise solutions fall between these two bounds (Yu, 1973). For more than two objectives, the L_1 solution implies the maximization of the aggregate achievement (maximum efficiency) while the L_∞ solution implies the minimization of the maximum discrepancy between achievements of different objectives. A way to minimizing a linear combination between the bounds $p = 1$ and $p = \infty$ is given by:

$$\begin{aligned} \min \quad & (1 - \lambda)D + \lambda \sum_{j=1}^n W_j d_j \\ \text{s.t.} \quad & W_j d_j \leq D \quad j = 1, \dots, n \\ & F[Z_1(y), \dots, Z_n(y)] \end{aligned} \quad (4)$$

where D represents the maximum degree of discrepancy. When $\lambda = 1$, we have the L_1 solution of maximum aggregated achievement and for $\lambda = 0$, we have the L_∞ solution of minimum discrepancy. For values of λ belonging to the open interval $(0, 1)$, we get intermediate solutions (if they exist) which are trade-offs or compromises between the two opposite poles. Therefore, the compromise set can be approximated through variations in the value of parameter λ .

2.2. Preference weight elicitation

To implement the CP framework described in the previous section, the preference weights attached to each of the criteria by several social groups should be determined. Individual decision maker's preference weights are determined from pairwise comparison procedure i.e. each of the decision makers provide a pair-wise

comparison of all the criteria and then the individual preference weights are aggregated to obtain social group weights.

2.2.1. Elicitation of individual preference weights from pairwise comparisons

Individual decision maker's preferences with respect to a set of criteria can be represented by means of pairwise comparison method in the context of the analytic hierarchy process (AHP) developed by Saaty (1980). These pairwise comparisons are performed by asking decision makers to respond to a series of pairwise comparisons. The pairwise comparisons are made on a scale of relative importance based on a 9 point Saaty scale ranging from equal importance which is equivalent to a numeric value of 1 to absolute importance which is equivalent to a numeric value of 9 (Saaty, 1980). The pairwise comparisons are used both to compare the alternatives with respect to the various criteria and to estimate criteria weights (Loken, 2007).

The results from all pairwise comparisons are put into a pairwise comparison (PC) matrix. Hence, each decision maker provides a PC matrix. This method allows the conversion of qualitative estimates elicited from decision makers to quantitative estimates. For n number of criteria to be evaluated, there are $n(n - 1)/2$ associated pairwise comparisons. From these values, a square matrix $n \times n$ is built and each entry a_{ij} of the square matrix represent the judgement made by the k th decision maker when the i th criterion is compared with the j th criterion as follows:

$$A = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (5)$$

It is assumed that elements of the matrix are reciprocal i.e.,

$$a_{ij} = 1/a_{ji} \quad \text{for } i \neq j \quad \text{and } a_{ii} = 1, \quad \forall i, j \quad (6)$$

Once the matrix of comparisons of criteria is constructed, the individual preference weights are computed and the consistency of the judgements is determined. An important aspect of AHP is

the idea of consistency which represents a type of cardinal transitivity between judgements (Saaty, 1980). That is to say matrix A is consistent if:

$$a_{ij} \times a_{jk} = a_{ik}, \quad \forall i \neq j \neq k \tag{7}$$

In practice, however, due to the existence of noise or imperfect judgements, the matrices or judgements might prove to be not perfectly consistent. The question is: what to do with an inconsistent PC matrix from which the final weights are to be computed? Gonzalez-Pachon and Romero (2004) proposed a method with the objective to approximate the original PC matrix. That is, they try to search a new matrix that differs as little as possible from the original PC matrix and achieves as much consistency and reciprocity as possible. The result is a new consistent matrix $M = (m_{ij})$ which is a modified version of $A = (a_{ij})$. Following Gonzalez-Pachon and Romero (2004), the following GP model is formulated to obtain a consistent matrix:

Achievement function:

$$\begin{aligned} \min \quad & \sum_s (n_s + p_s) + \sum_r (n_r + p_r) + \sum_t (n_t + p_t) \\ \text{s.t.} \quad & m_{ij} - a_{ij} + n_s - p_s = 0, \quad s = 1, 2, \dots, n(n-1), \quad (\text{Similarity condition}) \\ & m_{ij}m_{ij} + n_r - p_r = 1, \quad r = 1, 2, \dots, n(n-1)/2, \quad (\text{Reciprocity condition}) \\ & m_{ij}m_{jk} - m_{ik} + n_t - p_t = 0, \quad t = 1, 2, \dots, n(n-1)(n-2), \quad (\text{Consistency condition}) \\ & L \leq m_{ij} \leq U \forall_{ij} \end{aligned} \tag{8}$$

where a_{ij} are the elements of the original matrix, the m_{ij} are the elements of the new PC matrix determined from the GP model, the L and U are respectively the lower and upper bound values for the elements of the PC matrix. The bounds are imposed to satisfy the scale conditions used in the derivation of the original PC matrix. Thus in the case of Saaty's scale $L = 1/9$ and $U = 9$. The n and p are the deviation variables. It can be observed that there are three goals to be achieved that correspond to the conditions of similarity, reciprocity and consistency. The aim is to keep as much as the information contained in the original PC matrix but simultaneously holding the reciprocity and consistency conditions. In our case, since it is assumed that PC matrix verifies reciprocity condition, this is not imposed in the exercise. The reciprocity condition for the new matrix is guaranteed.

After the new PC matrix is obtained, the final weights are then obtained from the consistent matrix by adopting a Goal Programming (GP) approach (Gonzalez-Pachon & Romero, 2004; Linares & Romero, 2002). To infer the weights from PC matrix M , the following GP model is formulated:

Achievement function:

$$\begin{aligned} \min \quad & \sum_{i=1}^n \sum_{j=1}^n (n_{ij} + p_{ij}) \\ \text{s.t.} \quad & m_{ij}w_j^{kq} - w_i^{kq} + n_{ij} - p_{ij} = 0, \quad i, j = 1, \dots, n, i \neq j \\ & \sum_{i=1}^n w_i^{kq} = 1, \\ & w_i^{kq} > 0, \quad \forall_i \end{aligned} \tag{9}$$

where $i = 1, 2, \dots, n$ criteria to be assessed by $q = 1, 2, \dots, m$ social groups and w_i^{kq} is the preference weight attached to the i th criterion by the k th member of the q th social group that are determined from the GP model and the n_{ij} and p_{ij} are deviation variables.

2.2.2. Aggregation of individual preference weights

After the individual preference weights are determined, the next step is aggregation of individual weights to derive group weights. The aim is to reach a consensus among the participating decision makers within one social group on the importance of the criteria (Greening & Bernow, 2004). This is done by searching

for a consensus matrix or social preference weights that differ as little as possible from the individual preference weights.

Following the AHP in the previous section let N_q be the number of members of the q th social group, w_i^q be the preference weight attached to the i th criterion by the q th social group. The w_i^{kq} is already computed in the previous step from the individual pc matrix. To determine the w_i^q preference weight attached to the i th criterion by the q th social group, the following goal programming (GP) model is formulated:

Achievement function:

$$\begin{aligned} \min \quad & \sum_{i=1}^n \sum_{k=1}^{N_q} (n_{ik} + p_{ik})^\pi \\ \text{s.t.} \quad & W_i^q + n_{ik} - p_{ik} = w_i^{kq} \quad i \in \{1, \dots, n\}, k \in \{1, \dots, N_q\} \end{aligned} \tag{10}$$

where n_{ik} and p_{ik} are respectively the negative and positive deviation variables measuring the under achievement and over-achievement, between the preference weight attached to the i th criterion by the q th social group (w_i^q) and the weight attached to this criterion by the k th member of the q th social group (w_i^{kq}). π is a parameter representing a general metric and acts as a weight attached to the sum of deviation variables. As π increases, more importance is given to the greater deviation, i.e. the opinion of the individual that is significantly in disagreement with respect to the consensus obtained (Gonzalez-Pachon & Romero, 1999; Linares & Romero, 2002; Yu, 1973). For $\pi = 1$, which we assume in our case, the sum of individual disagreements is minimized and the achievement function can be interpreted as an additive group utility function leading to the best group optimum from the point of view of the majority (Gonzalez-Pachon & Romero, 1999). Therefore, by formulating and solving q similar models, we get the $(m \times n)$ w_i^q weights assigned to each criterion by each social group.

3. Application to manure processing

This section describes the manure processing technologies considered in this study, the basic model, case study and the data used in the analysis.

3.1. Manure processing technologies

Different manure processing technologies that are based on biological and physical processes have been developed and applied to reduce the emissions of greenhouse gases and ammonia and to produce energy. Technologies considered in this study are manure digestion (anaerobic digestion) and manure separation. Anaerobic digestion is a biological process with potential to allow farmers to adopt more sustainable livestock waste management practices (Masse, Talbot, & Gilbert, 2011). The process is known for many years and is widely used for waste stabilization, pollution control, improvement of manure quality and biogas production (Weiland, 2006). The feedstock used in the digestion are either manure only or a mixture of manure and other co-substrates such as energy crop (silage maize), grass or wastes from food processing companies. The biogas produced in anaerobic digestion is either converted into electricity and heat in a combined heat and power unit (CHP) or is directly upgraded to natural gas standards (green gas). The other technology considered in our study is manure separation producing two fractions: a liquid fraction with a low dry matter and a solid fraction. The purpose of separation is to achieve a solid fraction with a higher fertilizing value and a limited volume that reduces transportation cost of manure disposal. The four options considered in this study are therefore, CHP, green gas, manure only digestion and manure separation.

3.2. Basic model

This study evaluates the manure processing options based on four criteria applying the compromise programming model described in section 2.1. The criteria that are considered relevant for manure management decisions are:

- Criterion 1: Maximization of gross margin.
- Criterion 2: Minimization of greenhouse gases (GHG) emissions.
- Criterion 3: Minimization of ammonia (NH3) emissions.
- Criterion 4: Minimization of land use change.

These criteria were subsequently evaluated by selected social groups. For this study four groups of decision makers were chosen, namely, provincial government, farmers, dairy processing company and academic group. Provincial government representatives are important decision makers in manure management practices through their involvement in providing permits for setting up manure processing systems and in providing subsidy to encourage sustainable manure management practices. Farmers are directly involved in manure management on their farm. Dairy processing companies are important decision makers especially in light of the dairy chain’s growing interest to encourage sustainable production systems at dairy farms. For instance, as part of its broader sustainable dairy chain initiative, the Dutch dairy sector is aiming to achieve energy-neutral production by 2020 and invested 250 million Euros in sustainability every year (Gebrezgabher, Meuwissen, & Oude Lansink, 2012). Researchers (academic group) presumably have a more objective look on manure management. These four social groups are assumed to represent the different and conflicting views of society as a whole.

In the following sections we briefly describe the main features of the basic model.

3.2.1. The decision criteria

3.2.1.1. Maximization of gross margin. One consideration in deciding upon investment in manure processing technology is its profitability. This objective implies the maximization of the annual gross margin of manure processing applied in the region. The gross margin is calculated as total revenues from sales of the output from manure processing minus total costs. Total costs are variable operating and maintenance costs, feedstock costs, digestate disposal costs and fixed costs such as start-up cost, labor cost and depreciation.

$$Z_1 = \sum_{i=1}^I \sum_{j=1}^J P_{ij} + Y_{ij} - \sum_{i=1}^I \sum_{j=1}^J (cb_{ij} + om_{ij})Y_{ij} - \sum_{i=1}^I \sum_{j=1}^J fc_{ij}Y_{ij} - \sum_{i=4}^I \sum_{j=1}^J tc_{ij}Y_{ij}^{dig} \tag{11}$$

where P_{ij} is the price of output i produced from j technology, Y_{ij} is the quantity of output i produced from j technology, cb_{ij} and om_{ij} are respectively the feedstock and operating cost per unit of output i produced from j th technology, IC_{ij} and fc_{ij} are the fixed cost of j th technology, and tc_{ij} is the transportation cost of digestate (Y_{ij}^{dig}) produced by j th technology.

3.2.1.2. Minimization of greenhouse gases emissions (GHG). This criterion measures the total GHG emissions net of avoided CO₂ emission from replacing primary energy by green energy (if applicable). Total GHG are CO₂, CH₄ and N₂O emissions. The latter two are expressed in kg CO₂ equivalent.

$$Z_2 = \sum_{i=1}^I \sum_{j=1}^J CO_{ij} + Y_{ij} - E_p CO_p \tag{12}$$

$$E_p = Y_{ij} sf$$

where CO_{ij} is the GHG emissions per unit of output i from j th technology, E_p is primary energy to be replaced (natural gas or electricity), CO_p is emission factor for avoided energy and sf is the substitution factor.

3.2.1.3. Minimization of ammonia emissions (NH₃). Another important gaseous emissions from livestock operations is ammonia emissions. This criterion measures the total ammonia emissions from manure processing systems.

$$Z_3 = \sum_{i=1}^I \sum_{j=1}^J NH_{ij} Y_{ij} \tag{13}$$

where NH_{ij} is the NH₃ emissions per unit of output i from j th technology.

3.2.1.4. Minimization of land use for energy crops. This criterion measures the land required for the production of co-substrate mainly silage maize (if applicable).

$$Z_4 = \sum_{i=1}^I \sum_{j=1}^J LU_{ij} Y_{ij} \tag{14}$$

where LU_{ij} is the land use rate per unit of output i from j th technology.

The constraints of the basic model are manure available for processing, energy demand requirement from biogas in the region and land available for producing the co-substrate silage maize.

3.2.2. Model constraints

3.2.2.1. Manure availability constraint. The sum of the total amount of manure processed by each technology should be less than or equal to the manure available for processing in the region.

$$\sum_{i=1}^I \sum_{j=1}^J b_{ij} Y_{ij} \leq QB \tag{15}$$

where b_{ij} is the manure needed per unit of output i from j th technology and QB is the total manure available for processing in the region.

3.2.2.2. Demand requirement constraint. The sum of the total renewable energy produced from each technology has to be larger than or equal to the region’s energy demand from biogas.

$$\sum_{i=1}^I \sum_{j=1}^J Y_{ij}^{energy} \geq D \tag{16}$$

where D is the energy demand from biogas.

3.2.2.3. Land availability constraint. The sum of land utilized by each technology has to be less than or equal to the land available for producing energy crop in the region.

$$\sum_{i=1}^I \sum_{j=1}^J LU_{ij} Y_{ij} \leq L \tag{17}$$

where L is the land available for producing energy maize in the region.

3.3. Case study

The livestock operations in the Netherlands are characterised by large-scale intensive farms which are mainly concentrated in the eastern and southern part of the country (Melse & Timmerman, 2009). The study area is the region of Salland which is found in the eastern part of the Netherlands in the province of Overijssel.

The total land area of the province of Overijssel is 3400 km² with agriculture covering about 70% of the land and forest and nature covering 14% of the land. The province has large quantities of organic waste from livestock operations which comprise of 1.7 million pigs, 0.63 million cows and 10 million chickens. The province aims to contribute to the national targets of CO₂ emissions reduction by reducing its total emissions by 2200 kilotons by 2020. The total CO₂ emission of Overijssel was 7200 kiloton in 1990 which means by 2020, the province aims to reduce its emissions to 5000 kiloton/year. The province aims to achieve this objective by promoting sustainable energy production (wind, solar and biomass) and energy savings from its industry, housing and transport sector. The share of emission savings from biomass processing in the total savings is estimated to be 50% which makes manure processing as the main potential emission reduction area. In its sustainable energy policy, the province is promoting the sustainable use of biomass by giving priority to the production of green gas and generation of renewable electricity and heat. The total energy demand of the province is 128 PJ. The province aims to produce 10% of the total energy demand from biogas by 2020. This makes manure management planning part of the sustainable energy planning of the province.

Salland, a dominion of Overijssel, with a total agricultural land area of 32,523 ha, consists mostly of sandy soil (CBS, 2010). The region is a cattle and pig dense area with most of the agricultural land area under grassland (utilizing about 23,353 ha) and silage maize (7217 ha). Arable land comprises only 6% of the total utilized agricultural area (1953 ha), with cereals covering the largest share of arable land. The total amount of manure produced in Salland is 1.6 million tons, of which 1.23 million tons is dairy manure. In our study we assume that 50% of the dairy manure is available for processing and that the region of Salland produces at least 10% of the target share of biogas in the total energy demand from renewable sources, i.e. 1.28 PJ.

3.4. Model parameterization and assumptions

The data used in the development of the basic model was gathered from different sources. Technical and economic data pertaining to anaerobic digestion option are from operating biogas plants in the Netherlands while data pertaining to manure separation are based on Melse and Verdoes (2005). Environmental data are from life cycle assessment (LCA) studies (De Vries, Corre, & Van Dooren, 2010; Van der Voet et al., 2008; Zwart, Oudendag, Ehlert, & Kuikman, 2006). Regional data are from official statistics of the Netherlands (CBS, 2010).

The feedstock for manure separation is manure, while the feedstock for digestion can either be manure or a mixture of manure and other co-substrates such as energy maize and grass silage. Based on existing plant performance of biogas plants in the Netherlands, co-digestion of manure yields 118 m³ of biogas per ton of feedstock digested assuming that the feedstock mixture comprises of 50% cattle manure and 50% other co-substrates (Gebrezgabher et al., 2012, chap. 5). Digestion of manure as the only feedstock results in biogas yield of 22.5 m³ per ton of manure (Kool, Hilhorst, & Van der Vegte, 2005). Feedstock and digestate transport have a significant effect on the economic and environmental performance of the system. Transport of feedstocks from source is done by a truck with an average distance of 20 km for CHP system and 40 km for upgrading system while for manure separation and manure only digestion, the processes for manure production and conversion are on the same site and thus transport of feedstocks is minimized (Van der Voet et al., 2008).

The SDE (sustainable energy production subsidy) level for green gas of € 58.30 ct./m³ and for green electricity of € 15.2 ct./kWh is assumed (EZ, 2009). SDE is a follow-up to the former MEP (Envi-

ronmental quality of electricity production) scheme which subsidizes the exploitation of new sustainable energy projects. Total costs are feedstock costs, operating and maintenance costs, digestate disposal costs and fixed costs (start-up cost, labor cost, depreciation and interest). Straight-line depreciation is used assuming investment life of 15 years for co-digestion and manure separation, and 10 years for manure only digestion. Investment and operational costs of manure separation technology are based on Melse and Verdoes (2005). The digestate, the manure product resulting after digestion or separation, is transported and applied to fields as animal manure with a total disposal cost of € 5/ton.

Environmental indicators selected in this study are CO₂, CH₄, N₂O, and NH₃. Gaseous emissions were expressed in CO₂-eq using conversion factors of 1, 21, 310 for CO₂, CH₄ and N₂O respectively (IPCC, 2001). Total GHG emissions represent emissions from handling and storage of manure, emissions from handling and transporting of co-substrates (if applicable), and emissions from storage and application of digestate. These calculations of the total GHG emissions expressed in CO₂ equivalent are based on a number of studies (Amon, Kryvoruchko, Amon, & Zechmeister-Boltenstern, 2006; De Vries et al., 2010; Melse & Verdoes, 2005; Van der Voet et al., 2008; Zwart & Kuikman, 2011; Zwart et al., 2006). In the case of manure digestion, GHG emissions savings are deducted from the total emissions from the system as energy produced from the system will replace fossil energy and thus resulting in emission savings. It is therefore important to know how much primary energy use is avoided due to the energy content of the renewable energy. Ammonia emissions are expected to occur when applying digestate due to a higher level of mineral nitrogen (Amon et al., 2006). Total ammonia emissions represent ammonia emissions during production of co-substrate (if applicable) and emissions during storage and application of digestate (Amon et al., 2006; Clemens, Trimborn, Weiland, & Amon, 2006; De Vries et al., 2010; Zwart et al., 2006; Kool et al., 2005; Melse & Verdoes, 2005). The list of all input variable used in the study can be found in (Gebrezgabher, 2012, chap. 5: <http://edepot.wur.nl/205477>).

4. Results

This section presents results of the MCDM models. First we present the results of the pay-off matrix and trade-offs among the four criteria considered. The results of the preferential weights aggregation from PC matrices are then presented. Finally the results of the compromise programming model are presented.

4.1. Pay-off matrix and trade-off analysis

As a first step in the search for an optimal manure management strategy, the pay-off matrix is generated for the four criteria. The pay-off matrix is useful in pointing out the degree of conflict among the criteria considered. Table 1 shows the pay-off matrix that shows the ideal and anti-ideal values for each of the criteria considered. The ideal values are obtained by optimizing each criterion separately over the constraint set while the other criteria act as constraints. The 4 × 4 square matrix shown in Table 1 is obtained by solving four LP problems. The first row of the pay-off matrix for example shows the values of the criteria obtained from the maximization of gross margin while the last row shows the values of the same criteria obtained from minimization of land use change. The elements of the diagonal represent the ideal values for each criterion where all criteria achieve their optimum values while the underlined values represent the anti-ideal (nadir) value for each criterion.

The pay-off matrix shows that there is a conflict between the economic, social and the environmental criteria. This conflict is

Table 1

Pay-off matrix for the four criteria (elements of the diagonal represent the ideal values and the underlined values represent anti-ideal values for each criterion).

Objective optimized	Gross margin (million €)	GHG emissions (1000 ton CO ₂ eq.)	NH ₃ emissions (ton)	Land use (ha)
Gross margin	9.75	<u>-78</u>	<u>122</u>	<u>1804</u>
GHG emissions	8.16	-123	115	<u>1804</u>
NH ₃ emissions	<u>5.87</u>	-105	103	1298
Land use change	6.77	-82	110	1254

especially evident between gross margin on the one hand and NH₃ emissions and land use change, i.e. the maximization of gross margin implies high emissions of NH₃ and high land use change and vice versa. The value for GHG emissions (which is minimized) is calculated as GHG emissions from the system net of GHG emissions savings. The savings from the system are more than the emissions from the system and hence we have a negative outcome for GHG emissions (GHG emissions savings). This is in line with the outcomes of studies by De Vries et al. (2010) and Zwart and Kuikman (2011) on environmental performance of co-digestion in the Netherlands. The outcomes from these studies showed net negative GHG emissions due to the replacement of fossil based energy by green energy. The ideal value is therefore the highest absolute value which means the highest net GHG emissions savings. Considering the two gaseous emissions criteria, the highest savings in GHG emissions is achieved with a level of NH₃ emissions around 11% higher than its minimum level. There is a strong conflict between GHG emissions savings and land use change as highest GHG emissions savings require high land use change and minimum land use change causes relatively low GHG emissions savings. There is a relatively weak conflict between NH₃ emissions and land use change criteria. The ideal value for land use change is achieved with a level of NH₃ emissions at around 6% higher than its minimum value while the ideal value for NH₃ emissions is achieved with a level of land use change at around 3% higher than its minimum value.

Table 2 shows the amount of manure processed by each processing technology under optimization of one criterion at a time. For example, when gross margin is maximized, around 14% of the total manure available for processing is allocated to CHP, 26% to green gas and 56% to manure only option to produce a total energy of 1.28 PJ and it results in a total subsidy of € 17.48 million. When land use change is minimized, 69% of the manure available for processing is allocated to manure only option and 31% to green gas option to produce 1.28 PJ of energy while this results in a total subsidy of € 14.72 million.

The pay-off matrix provides useful information to analyze the trade-offs among the four criteria by taking two criteria at a time. Fig. 2 depicts the trade-off curves of two criteria measuring the

relationship between those two criteria. The trade-off curve is obtained by connecting the extreme efficient points generated by using the constraint method. The basic idea in constraint method is to optimize one of the objectives while the others are specified as constraints. The efficient set is then generated by parametric variation of the right-hand side elements of those constraints (Romero & Rehman, 2003). The ideal and anti-ideal points of each criterion form the bounds of the trade-off curves. The slopes of the straight lines connecting the extreme efficient points represent the marginal rate of transformation (opportunity costs) between the criteria. For instance, from the trade-off curve between gross margin and GHG emissions savings, the slope of segment AB in Fig. 2 indicates that a 1 ton increase in GHG emissions savings implies a € 25.63 reduction in gross margin while for segment BC the shadow price of GHG in terms of gross margin is € 40.69. Given these sets of points, the decision maker chooses the preferred point. For instance, looking at segment AB, if the decision maker believes that the trade-off is worthwhile then point B is preferred to A; otherwise, point A is preferred to B. The trade-off between gross margin and ammonia emissions indicates that the shadow price of a 1 kg reduction of ammonia emissions in terms of gross margin ranges from € 140 (segment DE) to € 203.57 (segment EF) reduction in gross margin. The transformation curve between gross margin and land use change is linear implying that the shadow price (€ 5409.84) is constant. The trade-off between GHG emissions savings and land use implies that the shadow price of a 1 ha of land in terms of GHG emissions savings is 179 tons (segment GH).

Optimization of a single criterion gives solutions that are not optimal for all other criteria. Solutions corresponding to maximization of profit are not optimal from an environmental aspect of sustainability and solutions corresponding to minimization of land use change are not optimal from economic and environmental aspects of sustainability. In addition to that, the trade-off curves in Fig. 2 have a number of efficient points and thus it is important to find a compromise set. The compromise solutions are obtained by resorting to the compromise programming model described in Section 2.1. Thus, the solutions obtained by taking two criteria at a time in the pay-off matrix are further analyzed to find the best compromise using the CP technique.

To show how compromise solutions are obtained, the exercise is performed by taking gross margin and GHG emissions savings criteria. Assuming that the two criteria have equal preference weights, the compromise solutions are shown in the trade-off curve by plotting the solutions for the L_1 and L_∞ metrics as shown in Fig. 3. These two metrics form the boundary for the compromise set. For this case study, the L_1 and L_∞ solutions are close to each other (almost coinciding) which makes it easier for the decision maker to choose a manure management plan.

Table 2

Manure processed, energy produced and subsidy under different objective optimization.

	Objective optimized			
	Gross margin	GHG emission	NH ₃ emission	Land use
<i>Manure processed by:</i>				
CHP (ton)	110,460	0	0	0
Green gas (ton)	160,180	270,640	194,680	188,180
Manure only digestion (ton)	342,860	0	0	425,320
Manure separation (ton)	0	342,860	418,820	0
Total energy produced (PJ)	1.28	1.78	1.28	1.28
Total subsidy (million €)	17.48	19.57	14.08	14.72

4.2. Elicitation and aggregation of individual preference weights

In the elicitation of preference weights, first the consistency of the individual PC matrices was checked and then the individual preference weights were computed. PC matrices which were

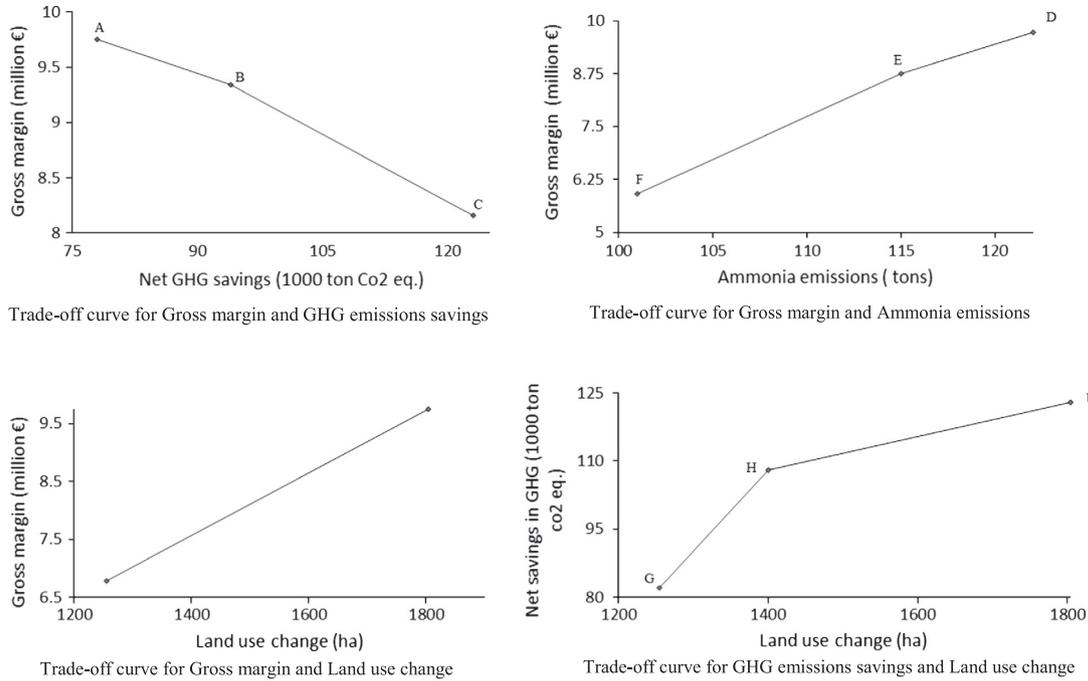


Fig. 2. Trade-off curves.

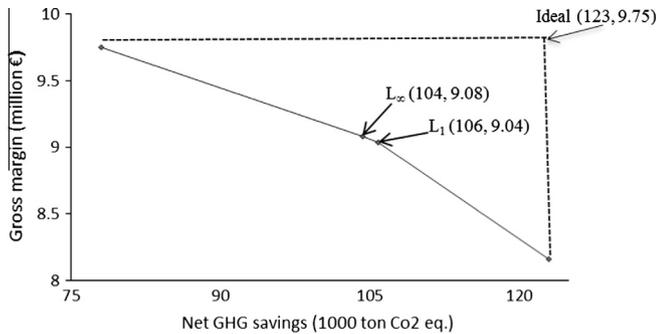


Fig. 3. Trade-off curve for gross margin and GHG saving and the compromise solutions.

inconsistent were improved by applying model (8) described in Section 2.2. After the individual preference weights were determined, the group weights for each of the criteria were derived.

Table 3 shows the individual preference weights obtained from the individual PC matrices before and after modifying the inconsistent PC matrices. It should be noted that only those inconsistent matrices were included in the search for a consistent matrix. Considering the consistency of the matrices, PC matrices of two members of the farmer group (member 2 and 4) and two members of the company group did not satisfy the conditions of consistency at a threshold consistency index of 0.20 according to Saaty's consistency index. Results show that member 1 and 3 give higher importance to reduction of GHG emissions while member 2 gives equal importance to the economic and environmental criteria. For the farmer group, member 1 and 2 give higher importance to land use change while gross margin and GHG emissions are equally important for member 3 and gross margin is more important for member 4. For the academic group, gross margin is more important for member 2 and 3 while member 1 gives equal importance to all criteria. For the company group, both members give higher importance to gross margin.

Table 3 Individual preference weights from original PC matrix and consistent PC matrix.

Decision maker	Criteria			
	Gross margin	GHG emissions	NH3 emissions	Land use change
<i>Original PC matrices</i>				
Government 1	0.045	0.682	0.136	0.136
Government 2	0.300	0.300	0.300	0.100
Government 3	0.093	0.664	0.111	0.133
Farmer 1	0.303	0.076	0.015	0.606
Farmer 2	0.110	0.022	0.022	0.846
Farmer 3	0.353	0.353	0.118	0.176
Farmer 4	0.703	0.078	0.078	0.141
Academic 1	0.250	0.250	0.250	0.250
Academic 2	0.700	0.100	0.100	0.100
Academic 3	0.608	0.122	0.068	0.203
Company 1	0.738	0.123	0.015	0.123
Company 2	0.700	0.100	0.100	0.100
<i>Improved consistent PC matrix</i>				
Farmer 2	0.314	0.063	0.063	0.560
Farmer 4	0.703	0.078	0.078	0.141
Company 1	0.667	0.111	0.111	0.111
Company 2	0.427	0.427	0.085	0.061

The weights after improving the PC matrices for which judgments were inconsistent are presented in the second section (improved consistent PC matrix) of Table 3. For the two members of the farmer group and member 1 of the company group, the weights inferred are close to the weights inferred from the original matrices indicating that the similarity condition is given more weight for these matrices. Considering member 2 of the company group, the weights inferred are not close to the weights inferred from the original matrix indicating that the consistency condition is given more weight than the similarity condition.

These individual preference weights were subsequently aggregated by applying the GP model (10) in order to obtain the preference weights attached by each social group to each criterion. The group preference weights attached to the four criteria are shown

Table 4
Group preference weights.

Social group	Criteria			
	Gross margin	GHG emissions	NH ₃ emissions	Land use change
Government	0.093	0.664	0.136	0.107
Farmer	0.314	0.076	0.063	0.547
Academic	0.608	0.100	0.089	0.203
Company	0.667	0.111	0.111	0.111

Table 5
Results of the compromise programming model.

	L_1	L_∞	Ideal value
<i>Objective space</i>			
Gross margin (million €)	5.87	7.49	9.75
GHG emissions (1000 ton)	-105	-100	-123
NH ₃ emissions (ton)	103	110	103
Land use change (ha)	1298	1575	1254
<i>Manure processed (ton)</i>			
CHP	0	57	
Green gas	195	180	
Manure only digestion	419	0	
Manure separation	0	377	
Total energy produced (PJ)	1.28	1.55	
Total subsidy (million €)	14.08	15.56	

in Table 4. The results show that the most important criterion for the government group is reduction of GHG emissions followed by land use change while the farmer group gives higher importance to land use change and gross margin. For the other two social groups, maximizing gross margin is the most important criterion.

4.3. Results of compromise programming model

As shown in the trade-off analysis, the ideal solutions cannot be achieved for all criteria simultaneously. Hence we resort to a geometric measure of distance to find a feasible compromise solution that has a minimum deviation from the ideal vector. Applying the CP model described in Section 2.1 and assuming that all criteria have equal preference weights, the compromise solutions for L_1 and L_∞ metrics are shown in Table 5. These solutions represent the range of efficient manure management plans that are best compromise solutions.

The compromise solution for L_1 shows that land use change and NH₃ emissions are close to their ideal values whereas the gross margin and GHG emissions are far away from their ideal values. Gross margin achieved 40% less than its ideal and GHG emissions achieved 15% less than its ideal value. Thus, this option is charac-

terized by low gross margin and low GHG emissions savings with reduced land use change and ammonia emissions. The values of the decision variables corresponding to the compromise solution for L_1 metric show that around 68% of the total manure is processed by manure only option and the remaining 32% by green gas option to produce a total energy of 1.28 PJ.

The compromise solution for L_∞ generates a more balanced achievement of the criteria compared to the L_1 solution. Under this option, the achievement of the ideal value has improved by 17% for gross margin. For land use change, the L_∞ solution is worsened by 26% compared to its ideal value. The achievement of NH₃ emissions is 7% below its ideal value implying that economic performance can be improved without significantly increasing the NH₃ emissions. Thus, as $P \rightarrow \infty$, the solution trades off NH₃ emissions and land use change for gross margin. This option is characterized by improved gross margin with higher land use change. The values of the decision variables corresponding to the L_∞ solution show that around 40% of the total manure is allocated to CHP and green gas option and 60% to manure separation option.

The L_1 solution represents the compromise that minimizes the maximum disagreement. This solution is biased towards land use change and ammonia emissions. The L_∞ solution represents the most balanced solution between achievements of the criteria considered where gross margin, GHG emissions, NH₃ emissions and land use change achieve 77%, 81%, 93% and 79% of their ideal values, respectively. Therefore, if land use change is the pressing issue, then the decision maker chooses the L_1 solution where it achieves 97% of its ideal value. If the decision maker is looking for a solution that achieves the best equilibrium among the different criteria, then the L_∞ solution is chosen.

The preference weights attached to each of the criteria were finally introduced into the compromise model. Table 6 presents the results of the CP model assuming the different social groups' weights. The model was solved for each of the three social groups' vector of weights and thus creating three scenarios. The first scenario corresponds to the case of provincial government decision maker, the second scenario to the farmer decision maker and the third scenario to company decision maker. The corresponding results for both metrics are shown. Under government group weights scenario, the compromise solution for L_1 shows that gross margin achieved 93% of its ideal value, GHG emissions achieved 85%, NH₃ emissions achieved 83% whereas land use change achieved only 56% of its ideal value. The compromise solution for L_∞ under government group weight scenario shows that GHG emission is close to its ideal value whereas gross margin is 24% below its ideal value. Thus, as $P \rightarrow \infty$, the solution trades off gross margin for GHG emissions saving. Under farmer group weights scenario, the solution for L_1 shows that land use change and NH₃ emissions are close to their ideal values whereas gross margin and GHG emissions are respectively 31% and 33% below their ideal values. The solution for

Table 6
Compromise solutions for the three decision makers.

Criteria	Government $W_i^a = (0.09, 0.66, 0.14, 0.11)$		Farmer $W_i = (0.31, 0.08, 0.06, 0.55)$		Company $W_i = (0.67, 0.11, 0.11, 0.11)$	
	L_1	L_∞	L_1	L_∞	L_1	L_∞
Gross margin (million €)	9.04	7.43	6.76	7.69	9.75	7.88
GHG emissions (1000 ton)	-105	-117	-82	-102	-78	-97
NH ₃ emissions (ton)	122	113	110	107	122	115
Land use change (ha)	1804	1643	1254	1482	1804	1804
<i>Manure processed (1000 ton)</i>						
CHP	0	0	0	0	103	103
Green gas	270	251	188	225	167	167
Manure only digestion	0	0	425	0	0	0
Manure separation	344	363	0	388	342	342

^a $W_i = (\text{Gross margin, GHG emissions, NH}_3 \text{ emissions, Land use change})$.

L_∞ under farmer group weight scenario shows an improvement in the achievement of gross margin and GHG emissions savings. Under company group weights scenario, the solution for L_1 shows that only gross margin is close to its ideal value. The solution for L_∞ shows that all the criteria are far away from their ideal values. Therefore, depending on which decision maker group weights are assumed, a variety of best compromise manure management plans are generated.

5. Discussion and conclusions

Sustainable manure management is a complex decision-making problem that needs the simultaneous inclusion of several criteria and several decision makers. This paper used several MCDM tools to analyze the trade-offs between economic, social and environmental sustainability of various manure processing systems at the regional level and integrated the views of different decision makers.

The trade-offs between the different criteria were analyzed using a multi-objective programming (MOP) and generating payoff matrix. Decision maker group preference weights were elicited and aggregated using analytical hierarchy process (AHP) and goal programming (GP). Best compromise manure management plans were generated using a compromise programming (CP). Results from the MOP showed that there is a conflict between the different criteria. This conflict is occurring between GHG emissions savings and land use change, as the highest GHG emissions savings are only compatible with high land use change and minimization of land use change is compatible with low GHG emissions savings. Results from aggregation of preference weights of decision makers showed that decision makers in manure management have different and conflicting interests. The most important criterion for the provincial government is reduction of GHG emissions, for farmers it is reduction of land use change, for dairy processing company and for academic group, it is maximization of gross margin. Assuming that all criteria have equal preference weights, the CP generated the compromise solutions for L_1 and L_∞ metrics. Results from CP showed that the L_1 solution is biased towards NH_3 emissions and land use change, i.e. both NH_3 emissions and land use change are close to their ideal values whereas gross margin and GHG emissions are far away from their ideal values. The L_∞ solution showed the best equilibrium among the different criteria, i.e. gross margin achieved 77% of its ideal value, GHG emissions achieved 81%, NH_3 emissions achieved 93% and land use change achieved 79% of its ideal value.

The technical and economic data used in this study are from operating manure processing plants in the Netherlands. Land use is estimated based on average maize yield per hectare in the Netherlands. The environmental data are average emissions reported by life cycle assessment (LCA) studies (De Vries et al., 2010; Van der Voet et al., 2008; Zwart et al., 2006). There are uncertainties in GHG and NH_3 emissions due to variations in composition of co-substrates used and efficiency of the manure processing technology. Nevertheless, the study used emission data reported by LCA studies which are compatible with the Dutch conditions.

The preference weights attached to each of the criteria were elicited from a small number of decision makers. The question is: how representative are these preference weights? One of the advantages of the analytical hierarchy process (AHP) is that it is not necessary to involve a large sample. This method also gives an insight into the consistency of the judgment of decision makers. Several authors conducted AHP surveys with a small sample size ranging from 9 to 23 decision makers (Diaz-Balteiro, Gonzalez-Pchon, & Romero, 2009; Linares & Romero, 2002; Marchamalo & Romero, 2007; Nordstrom, Romero, Eriksson, & Ohman, 2009). In

this study, provincial government representatives, manager and member of the corporate environmental affairs and sustainability department (dairy processing company group) and experts (academic group) were selected. The farmer group was selected randomly and the opinion of these farmers is not representative of farmers in the Netherlands. Presumably, there are differences in perceptions of farmers about the different sustainability criteria depending on their demographic and socio-economic characteristics. Conducting surveys among farmers that capture differences in demographic and socio-economic characteristics and clustering those farmers with similar characteristics into groups would give a more representative view of farmers.

The methodology applied in this study can be used as a tool to assist decision makers and policy makers in designing policies that enhance the introduction of economically, socially and environmentally sustainable manure management systems. Quantifying trade-offs gives an insight into the conflicts and trade-offs among the different sustainability criteria and thus support decision making. The best compromise solution, compared to the solutions obtained when each criterion is optimized separately, provides an alternative solution that strikes a balance among all the criteria considered. This enhances the decision maker's understanding of how such best compromise solution balances the different sustainability criteria. The methodology proposed in this study can be applied to address manure management problems in different regions. It provides a diversity of sustainable solutions for different situations and is flexible as to adapt to local conditions and future changes.

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