A multi-criteria decision making approach to manure management in the Netherlands

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 stakeholders and decision makers with different and conflicting views of what is acceptable in the context of sustainable development. This paper developed a decision-making aid based on a multi-criteria decision making (MCDM) approach to address the manure management problems. This paper has demonstrated the application of goal programming (GP) and compromise programming (CP) to evaluate key trade-offs between socio-economic benefits and environmental sustainability of manure management systems while at the same time taking decision makers' conflicting views of the different criteria into account. The proposed method is a useful tool in assisting decision makers and policy makers in designing policies to encourage economically and environmentally sustainable manure management systems.

Keywords: co-digestion; manure separation; alternative land use; gross margin; greenhouse gas balance; stakeholder preferences

1. Introduction

The intensification of livestock operations in the last few decades has resulted in an increased concern over the environmental impacts of livestock operations. These environmental concerns which have regional and global importance include concerns related to the soil, the water, and the air (Jongbloed and Lenis, 1998). Within the European Union, it is estimated that agriculture contributes 49% of CH_4 emissions and 63% of N_2O emissions (Sommer et al., 2004). Most of CH_4 emissions originate from livestock manure during storage while most N_2O 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 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). Hence, appropriate manure management systems are becoming increasingly important due to the intensification of animal husbandry, and the implementation of a series number of environmental regulations and protocols (Karmakar et al., 2007).

Growing public concerns combined with environmental regulations and protocols are obliging farmers to seek alternative mitigation options. The extent and impact of the problems related to manure management became clear in the 1970s and, especially, the 1980s (Langeveld et al.,2005). 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 and Turner, 2003; Melse and Timmerman, 2009). However, these alternative manure processing technologies are not without problems. Although the main objective is to reduce the environmental impact, not all of the technologies will achieve a reduction in pollution (Petersen et al.,2007) and most of the technologies are considered to be expensive for the livestock farmer to adopt (Burton, 2007). Consequently, a socially acceptable manure management system that simultaneously achieve the pressing environmental objectives while balancing the economic welfare of both farmers and society at large is needed (de Vos et al., 2002). Farm decision-makers must therefore balance the economic aspect of manure management with the environmental aspect of avoiding environmental damage.

Increasing sustainability concerns increase the number of decision variables that must be considered in manure management planning. Manure management decision involves a number of stakeholders and decision makers with different and more often than not conflicting perceptions of what is acceptable in the context of sustainable development. Different interest groups attach different values to each of the economic, environmental and social objectives, and rank priorities differently. For instance, for the farmer, keeping manure disposal costs at a minimum is important while for the environmental organizations, reducing the environmental pollution is more important. This calls for an integrated approach to modelling manure management systems that encompasses multiple and conflicting objectives of decision makers. The traditional model of optimizing a single objective function over a set of feasible solutions is not enough to capture all the elements of the decision making processes. It is now well accepted that the decision making process is extending beyond the classical model of optimizing a single objective function (Guitouni and Martel, 1997). In the presence of multiple and conflicting objectives, multiple criteria decision making (MCDM) methods are appropriate tools to support decision making (Pohekar and Ramachandran, 2003; Romero and Rehman, 2003).

The objective of this study is to develop a decision-making aid to assess the environmental, social and economic sustainability of manure management systems by taking a participatory decision making approach. This paper will examine key regional trade-offs arising between economic and environmental impacts of manure management systems. We use a combination of compromise programming (CP) and goal programming (GP) to assist decision makers and policy makers in designing policies to encourage economically and environmentally sustainable manure management systems.

The paper is organized as follows: section two presents the modeling framework. Section three presents the manure management systems considered in the study and the case study. Section four presents the results and section five concludes.

2. Modelling framework

Multi-Criteria Decision Making (MCDM) is a well-known branch of decision making which deals with the process of making decisions in the presence of multiple objectives (Pohekar and Ramachandran, 2003). A complex decision-making problem usually involves multiple and conflicting objectives. MCDM model thus seeks to assist the decision maker in identifying feasible alternative solutions that attempt to reach a balance among the multiple objectives. This task can be formulated as a multiobjective problem by applying a compromise programming (CP) to find the best compromise solution. Figure 1 depicts the modelling framework for manure management systems. First, criteria to measure the economic, social and environmental objectives are determined. By integrating the necessary input information for each of the manure management systems considered, a payoff matrix is constructed to enable decision makers to make trade-offs among the different criteria. After the weights to the criteria that reflect their relative importance is determined, the best compromise solution is determined.

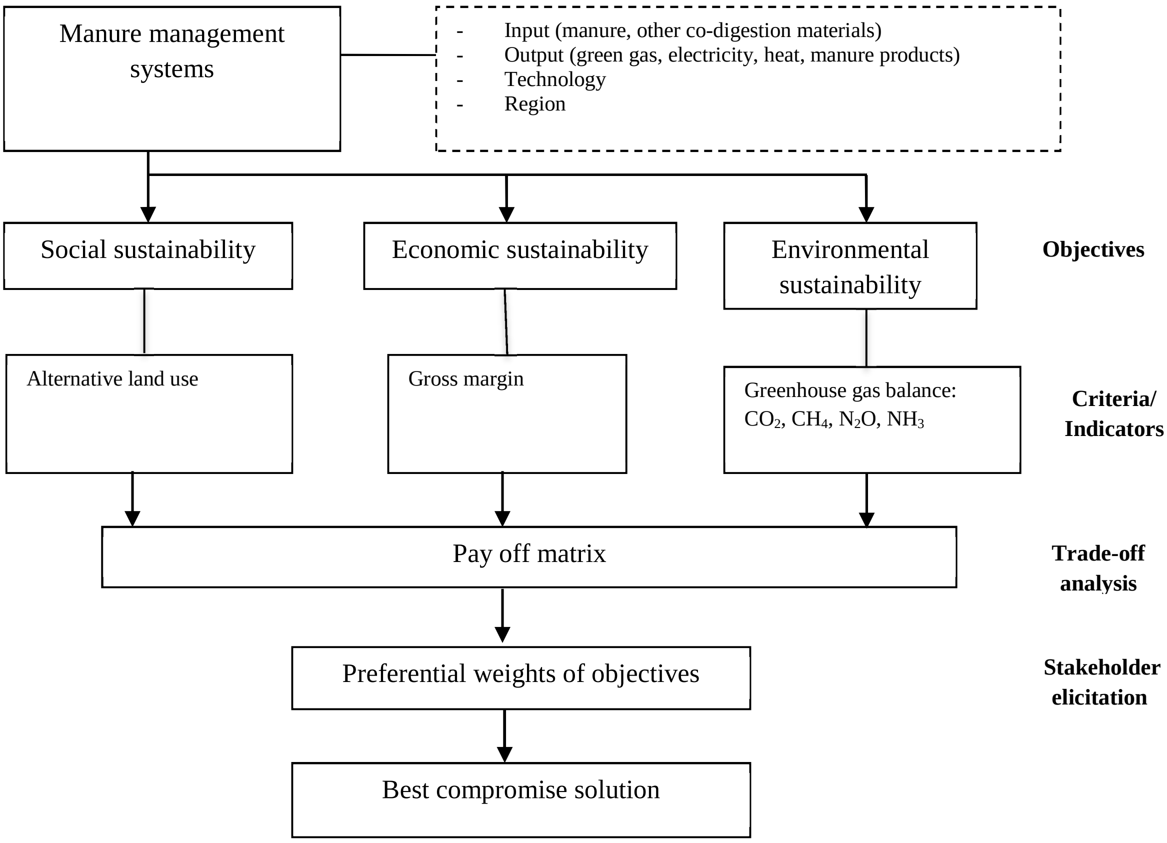


Figure 1 Conceptual framework of MCDM analysis of manure management systems

2.1 Basic model

This study evaluates manure management systems based on four criteria. In this section we will briefly describe the main features of the basic model.

Maximization of gross margin

One of the major considerations in deciding upon investment in manure processing technologies 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 less total costs. Total costs include annualized investment and fixed costs, variable operating and maintenance costs, biomass costs and digestate (processed manure) disposal costs.

$$Z_1 = \sum_{i=1}^{I}\sum_{j=1}^{J} P_{ij}\,Y_{ij} - \sum_{i=1}^{I}\sum_{j=1}^{J}\left[(IC_{ij} + fc_{ij})\frac{(1+d)^{t_{ij}}d}{(1+d)^{t_{ij}}-1}\right]Y_{ij} - \sum_{i=1}^{I}\sum_{j=1}^{J}\left(cb_{ij} + om_{ij}\right)Y_{ij} - \sum_{i=4}^{I}\sum_{j=1}^{J} tc_{ij}\,Y_{ij}^{dig} \quad (1)$$

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, IC_{ij} and fc_{ij} are the annualized investment and fixed cost of j^{th} technology, d is the discount rate, t_{ij} is the investment life of the j^{th} technology, cb_{ij} and om_{ij} are respectively the biomass and operating cost per unit of output i produced by the j^{th} technology and tc_{ij} is the transportation cost of digestate (Y_{ij}^{dig}) produced by j^{th} technology.

Minimization of greenhouse gases emissions (GHG)

It is well established that the livestock sector is a major contributor to greenhouse gases (GHG) emissions. This criterion measures the total GHG emissions net of avoided CO_2 emission from replacing primary energy by green energy (if applicable). The total GHG includes CO_2, CH_4 and N_2O emissions. The latter two are expressed in kg CO_2 equivalent.

$$Z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J} CO_{ij}Y_{ij} - E_pCO_p$$

$$E_p = Y_{ij}sf \quad (2)$$

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.

Minimization of ammonia emissions (NH_3)

Another important gaseous emission to the atmosphere from livestock operations is ammonia emissions. This criterion measures the total ammonia emissions from manure management systems.

$$Z_3 = \sum_{i=1}^{I} \sum_{j=1}^{J} NH_{ij} Y_{ij} \tag{3}$$

Where NH_{ij} is the NH_3 emissions per unit of output i from j^{th} technology.

Minimization of land use for energy crops

his criterion measures the land required for the production of co-substrate mainly silage maize (if applicable).

$$Z_4 = \sum_{i=1}^{I} \sum_{j=1}^{J} LU_{ij} Y_{ij} \tag{4}$$

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

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

Biomass availability

The sum of the total amount of biomass processed by each technology should be less than or equal to the biomass available for processing in the region.

$$\sum_{i=1}^{I} \sum_{j=1}^{J} b_{ij} Y_{ij} \leq QB \tag{5}$$

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

Demand requirement

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.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} Y_{ij}^{energy} \geq D \quad (6)$$

Where D is the energy demand from biogas.

Land availability

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.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} LU_{ij}Y_{ij} \leq L \quad (7)$$

Where L is the land available for producing silage maize in the region.

2.2 Compromise programming

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

$$Eff\ Z(x) = [Z_1(x), Z_2(x), \dots, Z_n(x)]$$

$$s.t.: \quad F[Z_1(x), Z_2(x), \dots, Z_n(x)] \quad (8)$$

where x is a vector of decision variables, $Z_j(x)$ is the mathematical expression for the j^{th} objective, *Eff* means the efficient solution (minimizing or maximizing), F is the feasible set.

Compromise programming defines the best solution as the one in the set of efficient solutions whose point is the least distance from an ideal point (Zeleney, 1982; Romero and Rehman, 2003). The first step in CP is to construct a payoff matrix which shows the ideal and anti-ideal values for each of the objectives by optimizing each of the objectives separately over the efficient set. The payoff matrix shows the degree of conflict between objectives. 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. The normalized distance, d_j, between the j^{th} objective and its ideal assuming a maximization problem is given by:

$$d_j = \frac{Z_J^* - Z_j(x)}{Z_j^* - Z_{*j}} \quad (9)$$

For a minimization criteria, the normalized distance is given by:

$$d_j = \frac{Z_j(x) - Z_j^*}{Z_j^* - Z_{*j}} \quad (10)$$

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

The final step in generating the compromise set is to select a distance measure. The distance measure between each solution and the ideal point used in CP is the family of L_p-metrics and is given as:

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

$$L_p(W) = \left[\left(\sum_{j=1}^{n} W_j\, d_j\right)^p\right]^{1/p} \quad (11)$$

Where p is metric defining the family of distance functions which reflects the importance attached to the deviation of each objective from its ideal value. W_j is the preferential weight attached to the j^{th} objective.

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 significant and as p increases, the larger deviations are given more weights. The general property of the L_p metrics is that L_1 is the largest distance and L_∞ is the shortest distance and hence the possible distance measures are bounded by L_1 and L_∞ metric distances (Romero and Rehman, 2003). 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 maximum aggregate achievement (maximum efficiency) while the L_∞ solution implies maximum discrepancy between achievements of different objectives is minimized. A way to minimizing a linear combination between the bounds $p=1$ and $p=\infty$ is given by:

$$min\ (1-\lambda)D+\lambda\sum_{j=1}^{n}W_j\,d_j$$

s.t.:

$$W_j d_j \leq D \quad j=1,\dots,n$$

$$F[Z_1(x),\dots,Z_n(x)] \tag{12}$$

where D represents the maximum degree of discrepancy. When λ=1, we have the L_1 solution of maximum aggregated achievement and for λ=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.

2.3 Preferential weight elicitation

To implement the CP framework described in the previous section, the preferential weights attached to each of the criteria by several social groups should be determined. This is done first by identifying relevant stakeholder groups then determining individual stakeholder's preference weights from pairwise comparison procedure and then aggregating individual preference weights to obtain group weights. For this study, the social groups comprise of government, farmers, dairy processing company and researchers. These social groups are assumed to represent the different and conflicting views of society as a whole.

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 Analytic hierarchy process (AHP) developed by Saaty (1980). These pairwise comparisons are performed by asking decision makers or stakeholders 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 the pairwise comparisons are put into a matrix (PC matrix). It is assumed that elements of the matrix are reciprocal i.e. the comparison matrices we construct comprise of paired reciprocal comparisons. From these values, a square matrix *n x n* is built and each entry a_{ij} of the square matrix represent the judgement made by the k^{th} stakeholder when the i^{th} criterion is compared with the j^{th} criterion as follows:

$$A=[a_{ij}]=\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \tag{13}$$

Once the matrix of comparisons of criteria is constructed, the individual preference weights are computed and aggregated by adopting a goal programming approach (Linares and Romero, 2002; Gonzalez-Pachon and Romero, 2004). To infer the weights from pc matrix *A*, the following GP model is formulated based on (Gonzalez-Pachon and Romero, 2007):

$$Min \sum_{i=1}^{n} \sum_{j=1}^{n} (n_{ij} + p_{ij})$$

s.t.

$$a_{ij} w_j^{kq} - w_i^{kq} + n_{ij} - p_{ij} = 0, \qquad i,j = 1,\dots,n,\ i \neq j$$

$$\sum_{i=1}^{n} w_i^{kq} = 1,$$

$$w_i^{kq} > 0,\ \forall_i \tag{14}$$

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 to be determined from the GP model and the n_{ij} and p_{ij} are deviation variables.

After the individual preference weights are determined, the next step is aggregation of individual weights to derive group weights. The aim to reach a consensus among the participating stakeholders within one social group on the importance of the criteria (Greening and Bernow, 2004). 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 weights attached to the i^{th} criterion by the q^{th} social group, the following goal programming (GP) model is formulated:

Achievement function:

$$Min \sum_{i=1}^{n} \sum_{k=1}^{N_q} (n_{ik} + p_{ik})$$

s.t.

$$W_i^q + n_{ik} + p_{ik} = w_i^{kq} \qquad i \in \{1,\dots,n\},\ \ k \in \{1,\dots,N_q\} \tag{15}$$

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}).

3. Application to manure management systems

This section describes the manure management technologies considered in this study, case study and how the data used in the analysis were derived.

3.1 Manure management technologies

If livestock intensification continues, there is a need for development and application of strategies and technologies to mitigate the associated environmental problems. There is a growing interest in technologies that minimize environmental impacts and that add value to manure. Different 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 et al., 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). Biogas production from manure contributes to reduction of CO_2 emissions via substitution of fossil fuels and by reducing CH_4 emissions from the manure during storage (Moller et al., 2007). The feedstock used in the digestion can either be 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 can either be converted into electricity and heat in a combined heat and power unit (CHP) or can be directly upgraded to natural gas standards (green gas). The other technology considered in our study is manure separation that results in two fractions: a liquid fraction with a low dry matter and a solid fraction. The purpose of separation is to achieve a manure fraction with a higher fertilizing value and a limited volume that will result in a reduced transportation cost of manure disposal.

3.2 Case study description

The livestock operations in Netherlands are characterised by large-scale intensive farms which are mainly concentrated in the eastern and southern part of the country (Melse and 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 surface land area of the province of Overijssel is 3400 km^2 (340,000 ha) with agriculture holding about 70% of the land and forest and nature holding 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 CO_2 emissions reduction by reducing its total emissions by 2200 kilotons by 2020. The total CO_2 emissions 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 in 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 region with most of the agricultural land area under grassland (utilizing about 23,353 ha) and silage maize (7217 ha). Arable land comprises of only 6% of the total utilized agricultural area (1953 ha), with cereals holding the greatest 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 will produce at least 10% of the target share of biogas in the total energy demand from renewable sources i.e. 1.28 PJ.

3.3 Model parameterization and assumptions

The data used in the development of the basic model was gathered from different sources (see appendix A for details). Technical and economic data pertaining to anaerobic digestion option come from operating biogas plants in the Netherlands while technical and economic data pertaining to manure separation are based on Melse and Verdoes (2005). Environmental data are from life cycle analysis (LCA) studies (Zwart K, 2006; Van der Voet et al., 2008; De Vries et al., 2010). 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. Energy maize and grass silage are the dominant feedstocks used for co-digestion. Based on existing plant performance of biogas plants in the Netherlands, co-digestion of manure yields 118 m^3 of biogas per ton of biomass assuming that the substrate mixture comprises of 50% cattle manure and 50% other co-substrates (Gebrezgabher et al., 2011). Digestion of manure as the only substrate results in biogas yield of 22.5 m^3 per ton of manure based on data from demonstration project of “De Marke” (Kool et al., 2005). Farm scale biogas plants in the Netherlands have digestion capacity of up to around 36,000 tons/year. Feedstock and digestate transport have a significant effect on the economic and environmental performance of the system. Transport of feedstocks (such as maize and food waste) 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 € 58.30ct./m3 and for green electricity of € 15.2ct./kwh is assumed (EZ, 2009). SDE is a follow-up to the former MEP (Environmental quality of electricity production) scheme which subsidizes the exploitation of new sustainable energy projects i.e. production of renewable gas and electricity. Total costs are inclusive of annualized investment and fixed costs, feedstock costs, operating and maintenance costs and digestate disposal costs. Investment costs are total of the whole installation and is annualized assuming discount rate of 10% and investment life of 15 years for co-digestion 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 CO_2, CH_4, N_2O, and NH_3. Gaseous emissions were expressed in CO_2-eq using conversion factors of 1, 21, 310 for CO_2, CH_4, and N_2O respectively (IPCC, 2001). Total GHG emission is inclusive of 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 CO_2 equivalent are based on a number of studies (Melse and Verdoes, 2005; Amon et al., 2006; Zwart, 2006; Van der Voet et al., 2008; De Vries et al., 2010; Zwart and Kuikman, 2011). 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 system. Ammonia emissions are expected to occur when applying digestate due to a higher level of mineral nitrogen (Amon et al., 2006). Total ammonia emissions is inclusive of ammonia emissions during production of co-substrate (if applicable) and emissions during storage and application of digestate (Kool et al., 2005; Melse and Verdoes ,2005; Amon et al., 2006; Zwart, 2006; Clemens et al., 2006; De Vries et al., 2010;).

4. Results

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

4.1 Pay-off matrix and trade-off analysis

As a first step in the search for optimal manure management strategy, the pay-off matrix is generated for the four criteria. Table 1 shows the pay-off matrix that shows the ideal and anti-ideal values for each of the objectives considered. The ideal values are obtained by optimizing each objective separately over the constraint set while the other objectives act as constraints. The 4 x 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 objectives obtained from the maximization of gross margin while the last row shows the values of the same objectives obtained from minimization of land use change. The elements of the main diagonal represent the ideal values for each criterion where all the objectives 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 and the environmental criteria. This conflict is especially significant between gross margin and NH_3 emissions and land use change as the maximization of gross margin implies high emissions of NH_3 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. This is compatible with the outcomes of studies by De Vries et.al., (2010) and Zwart and Kuikman (2011) on environmental performance of co-digestion in Netherlands which resulted in net negative GHG emissions due to the replaced amount of fossil based energy and the resulting savings in GHG emissions. 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 NH_3 emissions around 11% higher than its minimum level. There is a strong conflict between GHG emissions savings and land use change as the highest GHG emissions savings is only compatible with high land use change and minimization of land use change is compatible with low GHG emissions savings. There is a relatively weak conflict between NH_3 emissions and land use change criteria. The ideal value for land use change is achieved with a level of NH_3 emissions at around 6% higher than its minimum value while the ideal value for NH_3 emissions is achieved with a level of land use change at around 3% higher than its minimum value.

Table 1 Pay-off matrix for the four criteria considered

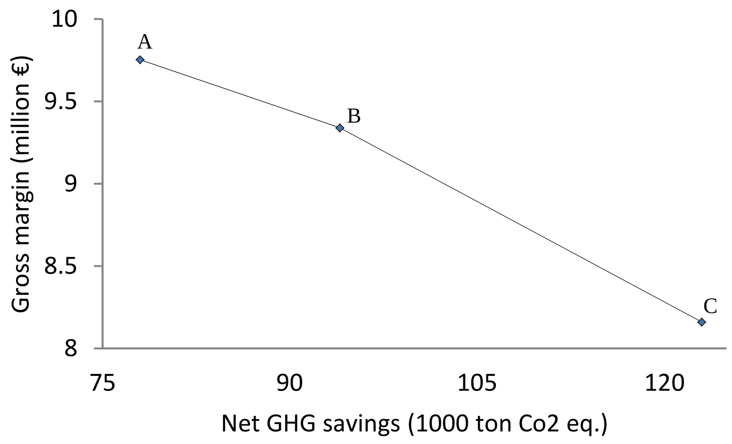
Objective optimized	Gross margin (million €)	GHG emissions (1000 ton Co_2 eq.)	NH_3 emissions (ton)	Land use (ha)
Gross margin	**9.75**	-<u>78</u>	<u>122</u>	<u>1804</u>
GHG emissions	8.16	**-123**	115	<u>1804</u>
NH_3 emissions	<u>5.87</u>	-105	**103**	1298
Land use change	6.77	-82	110	**1254**

The solutions in the pay-off matrix have been presented and analysed in the objective space. The same can be done in the decision variable space i.e. manure processed by each of the technologies considered and the associated energy and subsidy levels. The amount of manure processed by each processing technology under optimization of one objective at a time are shown in Table 2. For example, when gross margin is maximized, around 14% of the total manure available for processing will be allocated to CHP, 26% to green gas and 56% to manure only option to produce a total energy of 1.28 PJ and results in total subsidy of € 17.48 million. When land use change is minimized, 69% of the manure available for processing will be allocated to manure only option and 31% to green gas option to produce 1.28 P.J of energy and results in total subsidy of € 14.72 million.

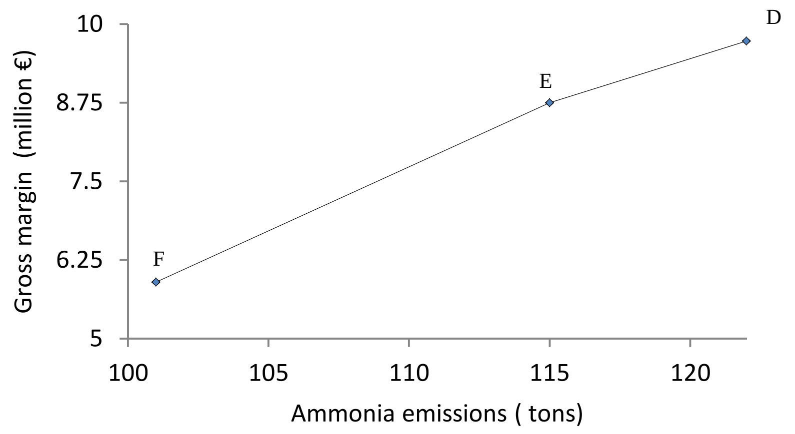
Table 2 Manure processed, energy produced and subsidy under different objective optimization

	Objective optimized			
	Gross margin	GHG emission	NH_3 emission	Land use
Manure processed by:				
CHP (ton)	110,460			
Green gas (ton)	160,180	270,640	194,680	188,180
Manure only digestion (ton)	342,860			425,320
Manure separation (ton)		342,860	418,820	
Total energy produced (PJ)	1.28	1.78	1.28	1.28
Total subsidy (million €)	17.48	19.57	14.08	14.72

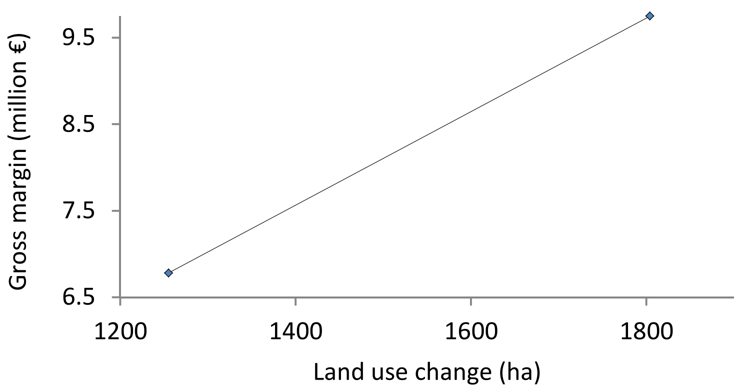
The pay-off matrix provides useful information to analyse the trade-offs among the four criteria by taking two criteria at a time. Figure 2 depicts the trade-off curves of two objectives measuring the relationship between those two objectives. The trade-off curve is obtained by liking the extreme efficient points generated by resorting to the constraint method. The basic idea in constraint method is to optimise 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 and Rehman, 2003). The ideal and anti-ideal points of each objective 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 (shadow prices) between the criteria. For instance, from the trade-off curve between gross margin and GHG emission savings, the slope of segment AB in figure 2 indicates that a one 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 set of points, then, 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 emission indicates that the shadow price of a 1 kg less 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 marginal rate of transformation is constant. The trade-off between GHG emissions saving and land use implies that the shadow price of a 1 ha of land in terms of GHG emissions saving is 179 tons (segment GH).



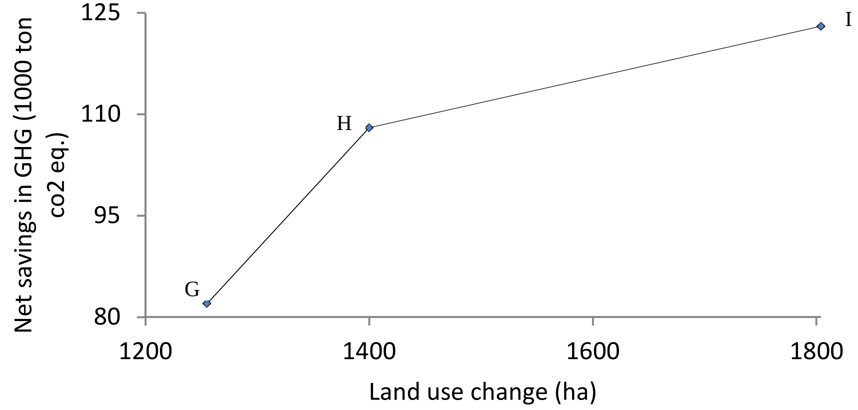
Trade-off curve between Gross margin and GHG savings



Trade-off curve between Gross margin and Ammonia emissions



Trade-off curve between Gross margin and Land use change



Trade-off curve between GHG savings and Land use change

Figure 2 Trade-off curves

4.2 Elicitation of individual preferential weights

Table 3 shows the individual preference weights obtained from the individual PC matrices by applying the model (14) defined in section 2.3. The PC matrices obtained are listed in Appendix B. The results show that there is a discrepancy in the level of importance given to each criterion by individuals within the same social group. Considering the preference weights of the government group, results show that member 1 and 3 give more 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 more 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 more importance to gross margin.

Table 3 Individual preference weights from PC matrix

Stakeholder	Criteria			
	Gross margin	GHG emissions	NH_3 emissions	Land use change
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

These individual preference weights were subsequently aggregated by applying the model (15) defined in section 2.3 to obtain the preference weights attached by each social group to each criterion. The group preference weights attached to the four criteria are shown 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 more importance to land use change and gross margin. For the other two social groups, maximizing of profit is the most important criterion. For the farmer and researcher group, reduction of GHG emissions and reduction of NH_3 emissions are perceived to be equally important.

Table 4 Group preference weights

Social group	Criteria			
	Gross margin	GHG emissions	NH_3 emissions	Land use change
Government	0.093	0.664	0.111	0.133
Farmer	0.353	0.078	0.078	0.491
Researchers	0.608	0.100	0.089	0.203
Company	0.739	0.123	0.015	0.123

4.3 Results of compromise programming model

As shown in the trade-off analysis, the ideal solutions for all the criteria cannot be achieved simultaneously and hence we resort to a geometric measure of distance to find a feasible compromise solution that has a minimum deviation from the ideal vector. Assuming that all the criteria have equal preferential weights, the compromise solutions for L_1 and L_∞ metrices are shown in Table 5 by applying the CP model (11) defined in section 2.2. These solutions represent the range of efficient manure management plans that are best compromise solutions.

The compromise solution for L_1 in the objective space shows that the land use change and ammonia emissions criteria achieved close to their ideal values whereas the economic and environmental criteria (GHG emissions) are far away from their respective targets. Gross margin achieved 40% less than its ideal and GHG emissions achieved 15% less than its ideal value. Thus, this option is characterized by low gross margin and low GHG emissions saving 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 will be 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 values has improved by 17% for gross margin and only 4% for GHG emissions saving. The achievement of land use change has however worsened by 26% compared to its ideal value. The achievement of NH_3 emissions is worsened by only 7% compared to its ideal value implying that economic performance and GHG emissions savings can be improved without significantly increasing the ammonia emissions. Thus, this option is characterized by improved gross margin and GHG emissions saving with higher land use change. In the decision variable space, around 40% of the total manure will be allocated to CHP and green-gas option and 60% to manure-separation option to produce a total energy of 1.55 PJ.

Table 5 Compromise solution matrix and achievement of ideal value

	L_1	%	L_∞	%
Objective space:				
Gross margin (million €)	5.87	-40	7.49	-23
GHG emissions (1000 ton)	-105	-15	-100	-19
NH3 emissions (ton)	103	0	110	+7
Land use change (ha)	1298	+4	1575	+26
Manure processed (ton):				
CHP			57,000	
Green gas	195,000		180,000	
Manure only	419,000			
Manure separation			377,000	
Total energy produced (PJ)	1.28		1.55	
Total subsidy (million €)	14.08		15.56	

The L_1 solution represents the compromise that minimizes the maximum disagreement. This solution can be biased towards some of the objectives which in our case are land use change and ammonia emissions. The L_∞ solution represents the most balanced solution between achievements of the criteria considered. Therefore, if land use change is the pressing issue, then the decision maker might choose L_1 solution otherwise L_∞ solution might be chosen if the decision maker is looking for a solution that achieves the best equilibrium among the different objectives.

The preferences 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 group's weights. The model was solved for each group's vector of weights.

Table 6 Results of CP model with weights

Criteria	L_1	L_∞
Government group: W_i= (0.093, 0.664, 0.111, 0.133)		
Gross margin (million €)	9.04	7.43
GHG emissions (1000 ton)	-1.05	-1.17
NH3 emissions (ton)	122	113
Land use change (ha)	1804	1643
Farmer group weights: Wi= (0.353,0.078, 0.078, 0.491)		
Gross margin (million €)	6.76	7.16
GHG emissions (1000 ton)	-0.82	-1.01
NH3 emissions (ton)	110	108
Land use change (ha)	1254	1518
Company group weights: Wi= (0.739,0.123, 0.015, 0.123)		
Gross margin (million €)	8.82	8.82
GHG emissions (1000 ton)	-0.97	-0.97
NH3 emissions (ton)	115	115
Land use change (ha)	1804	1804

5. Conclusion

This paper has demonstrated the application of MCDM methods to manure management problems. It has shown how the integration of different MCDM methods could be a useful approach to address complex decision making in the context of manure management. The payoff matrix which is generated by optimizing each of the criteria separately is useful to illustrate the degree of conflict between the objectives. Applying a bi-objective programming technique and quantifying the trade-offs provide useful information to analyse the trade-offs between two criteria. Quantifying trade-offs is an essential ingredient in providing information to decision makers in setting priorities. In addition to that, the points of view of different stakeholders were integrated in the search for best compromise solution. This is done, first by determining individual preference weights from pairwise comparison procedure and then aggregating individual preference weights to obtain group weights. The preferences weights attached to each of the criteria were introduced into a compromise model to generate best compromise manure management plans. The methodology applied in this study can be a useful tool to assist decision makers and policy makers in designing policies to encourage economically and environmentally sustainable manure management systems.

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Appendix A Data

Table A1 Economic data of manure processing technologies

	Unit	CHP[1]	GG[1]	MO[2]
Technical data:				
Energy Yield	MJ/ton	978.46	3287.48	140.94
Digestate	ton/ton	0.8	0.8	0.8
Economic data:				
Investment cost	€/MJ	0.0146	0.0015	0.0635
O & M cost	€/MJ	0.0046	0.0046	0.006
Biomass cost	€/MJ	0.012	0.0042	0
Fixed cost	€/MJ	0.0023	0.0003	0.0023
Digestate cost	€/ton	5	5	

[1]Gebrezgabher et al., 2011; [2]Kool et al., 2005

Table A2 Environmental data for manure digestion

	Emission	unit	Digestion	Data source
Manure :				
Storage	N_2O	kg/ton	0.0006	Zwart and Kuikman, 2011
	CH_4	kg/ton	0.2325	Zwart and Kuikman, 2011
Maize:				
Fertilization	N_20	kg/ton	0.27	Zwart and Kuikman, 2011
Crop production	CO_2	kg/ton	30	Zwart and Kuikman, 2011
	NH_3	Kg/ton	17	Zwart et al., 2006
Transport	CO_2	kg /ton	0.876	Zwart and Kuikman, 2011
Storage	N_2O	kg/ton	0.00035	Zwart and Kuikman, 2011
	CH_4	kg/ton	0.16	Zwart and Kuikman, 2011
Other co-product:				
Grass: CO_2	CO_2	kg/ton	82.7	van der Voet et al., 2008;
Grass: CH_4	CH_4	kg/ton	0.147	van der Voet et al., 2008;
Grass: N_2O	N_2O	kg/ton	0.404	van der Voet et al., 2008;
Other co-product	CO_2	kg/ton	0.876	Zwart and Kuikman, 2011
Digestate:				
Storage	CH_4	kg/ton	1	Kool et al., 2005; Amon et al., 2006
	N_2O	kg/ton	0.04	Kool et al., 2005; Amon et al., 2006
Transport	CO_2	kg/ton	1.314	Kool et al., 2005; Amon et al., 2006
Application	CH_4	kg/ton	0.002	Amon et al., 2006
	N_2O	kg/ton	0.0027	Amon et al., 2006
	NH_3	kg/ton	0.22	Amon et al., 2006

Appendix B Pairwise comparison matrices of each member of the social group

Government 1

	Profit	GHG	NH_3	Land
Profit	1	0.20	0.33	0.33
GHG	5	1	5	5
NH3	3	0.20	1	3
Land	3	0.20	0.33	1

Government 2

	Profit	GHG	NH_3	Land
Profit	1	1	1	3
GHG	1	1	0.25	3
NH3	1	4	1	5
Land	0.33	0.33	0.20	1

Government 3

	Profit	GHG	NH_3	Land
Profit	1	0.14	4	0.25
GHG	7	1	6	5
NH3	0.25	0.17	1	0.25
Land	4	0.20	4	1

Farmer 1

Profit	1	4	4	0.50
GHG	0.25	1	5	0.17
NH3	0.25	0.20	1	0.11
Land	2	6	9	1

Farmer 2

Profit	1	5	5	0.13
GHG	0.20	1	0.25	0.20
NH3	0.20	4	1	0.20
Land	8	5	5	1

Farmer 3

Profit	1	2	3	0.50
GHG	0.50	1	3	2
NH3	0.33	0.33	1	0.50
Land	2	1	2	1

Farmer 4

Profit	1	9	9	5
GHG	0.11	1	0.33	5
NH3	0.11	3	1	0.20
Land	0.20	0.20	5	1

Academic 1

Profit	1	1	1	1
GHG	1	1	1	1
NH3	1	1	1	1
Land	1	1	1	1

Academic 2

Profit	1	7	7	7
GHG	0.14	1	0.14	1
NH3	0.14	7	1	7
Land	0.14	1	0.14	1

Academic 3

Profit	1	5	9	3
GHG	0.20	1	9	3
NH3	0.11	0.11	1	0.11
Land	0.33	0.33	9	1

Company 1

Profit	1	6	6	6
GHG	0.17	1	8	0.25
NH3	0.17	0.13	1	0.17
Land	0.17	4	6	1

Company 2

Profit	1	7	7	7
GHG	0.14	1	5	7
NH3	0.14	0.20	1	6
Land	0.14	0.14	0.17	1