ENGINEERING INFORMATICS AND SYSTEMS MODELING FOR OPTIMIZATION OF ANIMAL MANURE MANAGEMENT

BY

JIANGONG LI

DISSERTATION

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Doctoral Committee:
Professor Xinlei Wang, Chair
Clinical Assistant Professor Neslihan Akdeniz
Professor Richard S Gates
Professor Harrison Hyung Min Kim
Associate Professor Kaiying Wang

ABSTRACT

There is no doubt that animal feeding operations (AFO) significantly improve meat production at a lower cost. However, accumulative manure produced in AFOs cannot be efficiently utilized in a sustainable and economical way. How to develop animal manure management strategy is a challenge for both the local agricultural production industry and the ecological system. The overall goal of this dissertation research is to develop decision support models that enhance AFO manure management in the pursuit of sustainability and profitability. A systematic approach is proposed to assist in informatics management, analysis, and decision-making through the graphical user interface, cyber map service, operation research, geographic information systems (GIS), and techno-economic analysis.

To bridge existing information gaps between AFO productions, local conditions, and technologies, a cyber-map enabled decision support platform was developed. This platform integrates data for manure production, treatments, application regulations, agronomist recommendations, and local electronic maps with user interactions to examine potential alternative manure management plans.

To address the manure management problem of a single farm in a region that lacks adequate crop land for manure spreading, we present a modeling approach (Analytic target cascading, ATC) to optimize the design and operation of a swine manure management system by formulating economic, engineering, and environmental objectives into individual tasks. The conceptual design of a manure management plan was conducted by the decision support platform. Then, the ATC-based model identifies optimal capacities of main components, and operations of manure and crop management sequentially through updating the targets and responses in each iteration. A case study in Hangzhou, China (a swine farm with Anaerobic Digestion process + Ectopic

Fermentation) is presented to illustrate the decision process and the sensitivity of the economic parameters i.e., a configuration of mass flows in the system and the size of each process in different seasons under different economic scenarios. Additionally, the scenario analyses are discussed to provide further insights of opportunities and risks.

Manure is generated, processed, transported, and utilized in various ways. Manure management requires the coordination of animal feeding operations (AFOs), centralized processing facilities (CPF), and crop farms. Such a manure utilization chain is more than an individual farm scale, and it is a complex nexus between different production systems. To minimize annual manure utilization costs and identify the optimal manure flow patterns, a mixed-mode manure utilization chain (RMUC model) was proposed to ensure sustainable manure utilization for distributed animal farms. The model was implemented to evaluate the manure utilization chain in Hangzhou, China. The scenario analyses are discussed to estimate that the average solid and slurry manure utilization costs under existed and optimal logistics configurations.

The decision-making of management practices needs intensive knowledge and a scientific basis while accommodating unique local conditions. The RMUC model can be used to inspect potential configurations (numbers and capacities of facilities, transportation routes, crop farms), quantify performance (economic returns, available manure application lands, nutrient utilization efficiency), and analyze the synergies and trade-offs among different objectives. The scenario analysis suggests setbacks for manure land application and determines the availability of manure applicable lands.

The slurry-manure RMUC model was modified to analyze the operational cost and operational greenhouse gas emission of the slurry manure utilization chain in Hangzhou, China. The Pareto-optimal results of baseline scenario demonstrated how the GHG emission constraints affect the optimal configuration of the manure utilization chain, and how the improvement of those practices could change manure utilization cost, increase nutrient utilization, and reduce overall cost and GHG emission. A scenario analysis was conducted to allow the manure nutrient contents to vary within specific ranges. The results conceptually approved the benefits of accurate measurement of nutrient composition in manure management. Finally, we compared four different transportation modes and the results showed that adding a secondary storage station in each village will improve animal manure utilization.

This study is an example of dealing with systematic agricultural problems with social, environmental, and economic constraints. It assists in overcoming the barrier to implement high-quality analysis tools in optimization models for establishing an ideal approach to use the information and computational science.

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NOMENCLATURE

Indices	**Description**	**Chapter**
t	Productive season (t=1,2,3,4)	3
r	Crop rotation plan	3
m	Crop field	3
p	Fertilizer production line	3
i	Animal feeding operations (AFOs).	4,5
k	Manure types (slurry = 0, liquid = 1).	4,5
d	Manure processing facility and wastewater treatment sites (CPFs).	4,5
j	Villages with croplands.	4,5
Input data set	**Description**	
Area	Area of crop field m (ha).	3
T_a	The ambient temperature (°C)	3
D	The distance list from swine farm to crop field m (km)	3
Yield	Annual crop yield in crop field m with rotation plan r (ton/ha).	3
HNu	Harvested crop nutrient content (nu = N, P) for crop in crop rotation plan r (%).	3
FNu	Swine manure nutrient content from finishing barn or breeding barn (nu = N, P, %).	3
M	Manure production rate (A: breeding barn, B: finishing barn) (ton/day).	3
DMSP	The distance matrix from AFO site i to CPF site d (km).	4,5
DMSC	The distance matrix from AFO site i to crop farm village j (km).	4,5
DMPC	The distance matrix from CPF site d to crop farm village j (km).	4,5
DS	Manure spreading distance in crop farm village j (km).	4,5
ASs	Amount of solid manure that produced from AFO site i (ton).	4
AS	Amount of manure k that produced from AFO i (ton).	4,5
STC	Total solid concentration of manure k that produced from AFO i (%).	4
SVC	Volatile solid concentration of manure k that produced from AFO i (%).	4
NC	Nitrogen concentration of manure k that produced from AFO i (%).	4,5
PC	Phosphorus concentration of manure k that produced from AFO i (%).	4,5
KC	Potassium concentration of manure k that produced from AFO i (%).	5
CND	Nitrogen demand of crop farming village j (ton).	4,5
CPD	Phosphorus demand of crop farming village j (ton).	4,5
CKD	Potassium demand of crop farming village j (ton).	5
N	Animal inventory in AFO sit i.	5
caps	The processing capacity of solid manure at CPF site d (ton).	4
capl	The processing capacity of slurry manure at CPF site d (ton).	4,5
Parameters	**Description**	
Ccs	Annualized capital cost for solid manure processing (CNY/ton).	4
Ccl	Annualized capital cost for liquid manure processing (CNY/ton).	4,5
Ctfs	Fixed transportation cost of solid manure, being the sum of the unit cost of maintenance, insurance, labour and organization (CNY/km)	4
Ctfl	Fixed transportation cost of slurry manure, being the sum of the unit cost of maintenance, insurance, labour and organization (CNY/km)	4
Ctvs	Variable transportation cost of solid manure (CNY/km ton).	4

$Ctvl$	Variable transportation cost of slurry manure (CNY/km ton).	4
Co_{AD}	Unit operational cost of anaerobic digestion process (CNY/ton).	4
Co_{waste}	Unit operational cost of wastewater treatment process (CNY/ton).	4
$Cops$	Unit processing cost of solid manure (CNY/ton).	4
r_{gas}	Unit price of natural gas (CNY/m^3)	3,4
r_{OF}	Unit price of the organic fertilizer product (CNY/ton).	4
r_S	Unit price of raw solid manure (CNY/ton).	3
Decision variables	**Description**	
Cap_{AD}	The capacity of anaerobic digestion treatment (m^3)	3
Cap_{EF}	The capacity of ectopic fermentation treatment (m^3)	3
Cap_{LS}	The storage capacity of AD liquid fertilizer (m^3)	3
W	The slurry manure processed by solid and liquid separation (ton/day)	3
$S_{1.or\ 2}$	Solid mass flows of raw solid manure at productive season t (ton/day)	3
$X_{1\ or\ 2}$	Mass flows of slurry manure at productive season t (ton/day)	3
X_{12}	The amount of AD digestate used by EF system at productive season t (ton/day)	3
X_{13}	The amount of AD digestate used by crop farms at productive season t (ton/day)	3
$Y_{1or\ 2}$	Mass flows of liquid at productive season t (ton/day)	3
DL	Demand of liquid fertilizer from crop farm at season t (ton/season).	3
Z	The farming decision of crop rotation plan r at crop field m.	3
$CAPs$	The processing capacity of solid manure at CPF site d (ton).	4
CAP^{L0}	The processing capacity of slurry manure at CPF site d (ton).	4,5
XC^{L0}	Amount of slurry manure transported to crop farming village from AFO site i (ton).	5
XJ	Amount of manure k transported to crop farming village j from AFO i (ton).	4,5
XDs	Amount of solid manure transported to CPF site d from AFO i (ton).	4
XD	Amount of manure k transported to CPF site d from AFO i (ton).	4,5
XJD	Amount of slurry fertilizer that transported to crop farm j from the CPF site d (ton).	4,5
XPD	Amount of liquid fertilizer processed by waste treatment plant at CPF site d (ton).	4,5
Symbol	**Quantity**	
$AccS$	Accumulated liquid fertilizer supply (ton).	3
$AccD$	Accumulated liquid fertilizer demand (ton).	3
$Conc_{odor}$	Concentration of odor gas (OU/m^3)	3
CD	The liquid fertilizer demand of crop in land m with rotation plan r (ton).	3
Co_{Sep}	Operational cost of solid-liquid separation system (CNY).	3
Co_{AD}	The energy cost for operating anaerobic digestion system (CNY).	3
co_{trans}	Unit transportation cost of liquid fertilizer (CNY/ton).	3
Cf	Annual operational cost of crop fertilization of liquid fertilizer (CNY).	3
Dnu	Nutrient (nu=N, P) demand of crop rotation plan r at crop field m at productive season t (ton).	3
DL	The crop demands of liquid fertilizer in season t (ton).	3
$Freq_{odor}$	Odor annoyance-free frequency (%).	3

N, P	Nitrogen and phosphorus content in manure at season t (ton/ton manure).	3
$Ndays_t$	Number of days in productive season t	3
Q_w, Q_g, Q_{in}	Heat loss through digester envelope of the slurry portion, gas portion and inlet manure (J).	3
S_0	Concentration of VS in raw manure (kg/m^3)	3
PAN	Plant available nitrogen content in manure at season t (ton/ton manure).	3
Po	Annual operational profit of swine manure treatment (CNY).	3
UC	Unit capital cost of anaerobic digestion (AD), ectopic fermentation (EF), liquid fertilizer storage (LS) and manure separation (Sep) (CNY/ton).	3
CAP_d^{L0}	The processing capacity of slurry manure at CPF site d in slurry manure facility location module (ton).	4
CAP_d^{LB}, CAP_d^{UB}	The lower bound and upper bound of the processing capacity of slurry manure at CPF site d in slurry manure facility location module (ton).	4
$Ccops$	Annual unit cost for solid manure processing (CNY/ton).	4
$Copps$	Opportunity cost for solid manure processing (CNY/ton).	4
$Ccopl$	Annual unit cost for slurry manure processing at CPF site d (CNY/ton)	4,5
$Coppl$	Opportunity cost for slurry manure processing at CPF site d (CNY/ton).	4
$Ccol$	Unit collection cost of slurry manure at CPF site d (CNY/ton).	4,5
Clo	Unit operational cost of slurry manure at CPF site d (CNY/ton).	4,5
Rs	Unit revenue of selling solid manure (CNY/ton).	4
Rl	Unit revenue of slurry manure at CPF site d (CNY/ton).	4
SE	Separation efficiency of total solid, nitrogen, phosphorus and potassium.	4
$Copl$	Unit processing cost of slurry manure at CPF site d (CNY/ton).	4
PAS	Processing amount of slurry manure at the candidate site d (ton).	4,5
$PSTC$	Total solid concentration of influent slurry manure at CPF site d (%).	4
$PSVC$	Volatile solid concentration of influent slurry manure at CPF site d (%).	4
PNC	Nitrogen concentration of influent slurry manure at CPF site d (%).	4
PPC	Phosphorus concentration of influent slurry manure at CPF site d (%).	4
PKC	Potassium concentration of influent slurry manure at CPF site d (%).	4
EAS	Amount of Effluent at CPF site d (ton).	4
ENC	Nitrogen concentration of liquid fertilizer produced from CPF site d (%).	4,5
EPC	Phosphorus concentration of liquid fertilizer produced from CPF site d (%).	4,5
EKC	Potassium concentration of liquid fertilizer produced from CPF site d (%).	5
GF	Gas production factor of liquid and slurry manure at CPF site d (m^3 CH_4/m^3).	3,4,5
$EFcf$	GHG emission factor of livestock manure land application (kg CO_2 e T^{-1}).	5
Xc	Amount of slurry manure transported to crop farming village from AFO site i (ton).	5
Cuc	Unit crop utilization cost for slurry manure at AFO site i (CNY/ton).	5
Euc	Unit GHG emission for slurry manure at AFO site i (kg CO_2 e T^{-1}).	5
Euf	Unit GHG emission for slurry manure processing at CPF site d (kg CO_2 e T^{-1}).	5
εx	Deviation tolerance to coordinate values from responds Xc to target Xc^{L0}.	5
εp	Deviation tolerance to coordinate values from responds PAS to target CAP^{L0}.	5
ε_{GHG}	GHG target in ε- constraint method.	5

Constant	Quantity	
B_o	The maximum rate of biogas production (0.481 m^3 CH_4/kg SV)	3
$Thred_{odor}$	Threshold of odor gas concentration that is faint to human (72 OU/m^3)	3
η_{sep}	Separation efficiency of liquid solid separator (0.57 for scraper;)	3
$\eta_{loss.nu}$	Nutrient loss (N=0.3, P=0.1) in manure treatment process.	3
η_{heater}	The efficiency of the heater.	3
h_{biogas}	The heating value of biogas (2.3 E7 J/m^3)	3
$co_{scraper}$, co_{Sep}, co_{EF}, co_S	Unit operational cost of scraping system, solid-liquid separation, ectopic fermentation system, raw solid manure storage (CNY/ton).	3
cf	Transportation fixed cost (CNY/ton).	3
cv	Transportation variable cost (CNY/ton km).	3
CF	Volume of the fermentation bed per unit of manure (m3/ton day).	3
Cp	Heat capacity of liquid manure (4.186 kJ/kg).	3
f_a	Capital recovery factors.	3
f_{orgN}	Organic nitrogen to total nitrogen.	3
$loss_{NH3}$	Ammonia loss in land application.	3
mf	Organic nitrogen mineralization factor.	3
U_sA_s, U_gA_g	Heat transfer coefficient for slurry and gas (W/K).	3
CF_{OF}	Mass conversion factor for solid livestock manure to organic fertilizer (ton/ton).	4
$\varepsilon_{N,P,K}$	Nitrogen, Phosphorus and Potassium loss in manure land application (Hutchings et al, 2013).	4,5
$P_{N,P,K}$	Unit price for commercial nitrogen, phosphorus and potassium (CNY/kg).	4
Bo	The maximum rate of biogas production (CH_4/kg SV).	4
HRT	Hydraulic retention time (days).	3,4,5
$T_{digester}$	Digester temperature (^oC).	3,4,5
K	Kinetic coefficient.	3,4
$EFt.v$	GHG emission factor of medium-duty vehicle (kg CO_2 e T^{-1} km^{-1}).	5
$EFt.p$	GHG emission factor for pipeline (kg CO_2 e T^{-1} km^{-1}).	5
EFp	GHG emission factor of CPF anaerobic digestion process (kg CO_2 e T^{-1}).	5
$EFpw$	GHG emission factor of CPF anaerobic digestion process with waste treatment process (kg CO_2 e T^{-1}).	5
$EFcl$	GHG emission factor of CPF fertilizer land application emission (kg CO_2 e T^{-1}).	5
Nex	Annual N excretion rates (kg N animal^{-1} yr^{-1}).	5
VS	Volatile solid excreted for animal (kg DM animal^{-1} yr^{-1}).	5
$MCFs_{land}$	CH4 conversion factor of land application at 20 ^oC (%).	5
Os_{gas}	Percentage of volatilized nitrogen by injection land application (%).	5
Os_{leach}	Percentage of leaching nitrogen (%).	5
EF_{leach}	GHG emission factor for nitrogen leaching and runoff on soil ((kg CO_2 e).	5
EF_{dep}	GHG emission factor for nitrogen atmospheric deposition on soil ((kg CO_2 e).	5
$Credit_{N,P,K}$	GHG emission of Synthetic nitrogen, phosphorus and potassium (kg CO_2 e kg^{-1}).	5

CHAPTER 1: INTRODUCTION

The demand for animal production is growing with the growth of population and economic gains. The animal production industry has been shifting from family-size to larger, confined animal feeding operations for decades (Rodríguez-Ortega et al., 2017). This development significantly improves animal production at a lower cost but creates new challenges on manure management considering interactions between agricultural production systems, environmental impacts, and food security (Ribaudo et al., 2003; Makara and Kowalski, 2018). Most animal operations concentrate in some particular regions that have advantages of climate, processors, transportation access, labor, and market. (Flotats et al., 2009). Such a fact gives animal feeding operations (AFOs) the economic benefits but might cause an issue with manure management in the local community, such as air pollution, and water eutrophication (Heinonen-Tanski et al., 2006; Moller et al., 2007b; Martens and Böhm, 2009). Recently, large-scale animal production has facing new challenges, such as greater manure production, high transportation cost of manure, and the challenge or limited crop land to accept manure as a fertilizer. Ensuring an effective manure utilization chain becomes one of many challenges for animal protein production.

For local communities that do not have intensive animal production, manure utilization mainly focuses on individual AFO practices. Selecting and designing manure management is always a challenge with risks. The design and decisions based on the perspectives of stakeholders are the trade-offs between technology cost, government regulations, and the treatment preferences of the local livestock industry (Bernet and Béline, 2009; Pan et al., 2016). However, the manure related policies and operational expenditure are changing along with the alteration of environmental policies and social concern, such as updating manure application standards and the decreasing of the challenge of crop farmers to receive manure (Ribaudo et al., 2003; Makara and Kowalski, 2018). Further requirements on manure management design include a need for optimal design and a feasibility analysis regarding the innovation system and restriction. It is expected to connect additional requirements to the decision-making process and improve the design methodology that can meet manure management's further challenges. In an animal production intensive region, the complexity of manure utilization becomes more than an engineering problem, which requires higher-level planning, such as network design, allocation of limited resources, and nutrient distribution (Flotats et al., 2009). Current studies on regional animal development planning focus on the assessment of the environmental impacts and nutrient run-off risks of land application practices (Qiu et al., 2017). The economy of local manure management has been at the analysis level based on empirical equations and land suitability analysis (Qiu et al., 2017; Pergola et al., 2018; Jia et al., 2018). Although strategic level and tactic level design were discussed and optimized for many agricultural production chains such as the biomass supply chain (Pan et al., 2015; Lin et al., 2015), no single source was found to summarize a complete methodology for estimating the manure utilization cost and optimizing the configuration of regional manure utilization chains. Additionally, not a sole source discusses how the technology, policy, and local condition affect the configuration of manure utilization chains. Researchers have developed some computer-based models and decision-aid tools for animal manure management, which are highly fragmented and specifically targeted on a single objective. Those tools generally assist farm owners or farm designers in evaluating some alternative processes when addressing environmental concerns with less time and expenditure, such as manure treatment selection, crop nutrient plans, which are called manure management decision-support systems (NRCS, 2009). Based on extensive experimental results and advanced computational methods, the analytic models and optimization equations have been designed for specific purposes, such as the predictive model of manure nutrient contents, odor dispersion model, shortest transportation distance model, etc. (de Figueiredo and Mayerle, 2014). There is an urgent need to develop a systems-level decision support approach that can integrate existing models and tools to solve the problems of on-farm manure management designs and regional manure utilization configurations.

1.1 Objectives

The overall goal of this dissertation research is to develop systematic decision-support models and methods to enhance AFO manure management in sustainable and profitable ways. The framework is to help farmers to make informed decisions on 1) **which** manure management plan will work for the animal farms at local conditions, 2) **how** to use the information to optimize the manure management design. The framework is also designed to help policymakers to understand 1) **what** opportunities and risks are animal farmers and crop farmers exposed in manure utilization, 2) **how** the policy affects manure utilization chains. In order to achieve this goal, the specific objectives are as follows:

1) To evaluate geospatial and environmental factors that affect the decision-making process of manure management.
2) To develop the optimization framework for on-farm manure management configuration and short-term operation management.
3) To assess the opportunity and risks of an innovative on-farm manure management plan.
4) To develop the optimization framework for demonstrating a sustainable design of a regional manure utilization chain.
5) To evaluate the manure utilization chains and analyze the improvement strategies.

1.2 Organization of the thesis

Chapter 1 gives a general idea about the research topic and the background information about understanding the objectives of this research. Chapter 2 provides a literature review on animal manure management and decision support tools, which includes three parts: 1) an overview of animal manure production and utilization problem; 2) the scope of animal manure management; and 3) studies on the existing decision support tools and optimization methods. The decision support platform for manure management assessment and selection is presented in Appendix A. With the information from the platform, an on-farm manure management optimization framework is developed in Chapter 3, including the analysis of an innovative swine manure management plan in Hangzhou, China for assessing the potential opportunity and risks. Chapter 4 focuses on the optimization framework for the manure utilization chain in Hangzhou, China, aiming at estimating the utilization cost and analyzing the impact of setback distance on manure utilization cost. Chapter 5 focuses on the slurry manure utilization chain in Hangzhou, aiming at estimating the potential improvement of manure management, including solid-liquid separation, water usage reduction, measurement of manure composition and application of electric vehicle and portable pipeline pumping. An overall summary of this dissertation research and recommendations for future work are addressed in Chapter 6.

CHAPTER 2: LITERATURE REVIEW

Animal manure management is a challenge that involves animal production, manure utilization chain, and crop production. The computer-based model and decision-aid tools will generally assist farm owners or farm designers in evaluating some alternative processes when addressing environmental concerns with less time and expenditure. This chapter summarizes literature to illustrate the components in animal manure management, the scope of manure management, the methodology of optimal designs and management evaluation. Then, the modeling approaches are recognized and proposed as one of the most potent techniques to transfer real-world issues to solvable and scientific problems. Finally, the summary section describes findings and ideas from the literature that can conduct this study.

2.1 Animal manure production and utilization problem

Many countries are experiencing a transformation of food animal production in recent years. This change includes the industrialization of food animal breeding and the plan of sustainable animal manure management (Hu et al., 2017b). Modern animal feeding operations (AFOs) raise a larger number of animals in a small area. Unlike small scale or “free-range” farms, such a production model aggregates hundreds or thousands of single species animals, fosters advances in breeding and mechanics, improves production and supply chain efficiencies, and reduces the production cost. AFOs tend to be clustered in a particular region to leverage the advantages of climate, processors, transportation access, labor, and market. However, spatial clustering presents challenges for manure management in the local community, such as air pollution and water eutrophication (Heinonen-Tanski et al., 2006; Moller et al., 2007b; Martens and Böhm, 2009). The development of the AFO in China started in 2006. Over the past 14 years, this industry experienced rapid development with little environmental regulations, however it has been more recently hampered by strengthened environmental regulations (Bai et al., 2019a; Bai et al., 2019b; Niles and Wiltshire, 2019). Chinese governments forbade livestock production in some regions to prevent water pollution from animal manure since 2015. The number of slaughtered pigs decreased by 46 million head per year from 2014 to 2017 (Bai et al., 2019a). Ensuring an effective manure utilization chain is necessary for environmental well-being and sustainable food supply.

Animal manure from AFOs is generated, processed, transported, and utilized in various ways and involves hundreds or thousands of units in a local manure utilization chain. In this sense, manure utilization chain management is a set of actions to guide the manure from the source to the end-users needing nutrients (Poffenbarger et al., 2017; Sharara et al., 2018). For local communities that do not have intensive animal production, manure utilization mainly focuses on individual AFO practices. Manure is either applied to self-owned croplands or cooperated crop farms, which merely damage the local environment. Manure management restrictions and actions include on-site pollution control (heavy metals, nutrient run-off, and pathogens) and nutrient management plans (Moller et al., 2007b). While some regions do not have sufficient croplands for manure application, the complexity of manure utilization becomes more than an engineering problem, as it requires higher-level planning that accounts for the cluster effect of manure generation and utilization (Flotats et al., 2009; Takahashi et al., 2020).

Selecting and designing the manure processing plan is always a challenge with risks. The innovation design typically requires high capital cost while considering has excellent economic performance and environmental-friendly in theory. However, many examples, such as the nitrification and denitrification process, showed the innovation design mostly could not reach the theoretical performance in actual operation and sometimes worked not correctly as it was in other farms (Vanotti et al., 2007; Vanotti et al., 2008; Frandsen et al., 2011). The conventional design, such as deep pits, the lagoon with agitator and composting, is safe to use, and most cost less than the innovation design (Frandsen et al., 2011). However, the designs and decisions that are proved practicable today could be invalid in the future due to the policy changes, breeding practice improvement, and environmental variation. In the Corn Belt states of the United States, animal feeding farms use deep-pit design mostly and benefits from the low manure processing cost due to the abundant croplands for a long time. Farmers needs to pay more attention on challenges of eutrophication from manure land applications and the increased logistics costs associated with the expansion of a single animal farm (Motew et al., 2018).

The cost of manure nutrient recycling is mainly the logistics cost of transportation and land application, while transportation cost accounted for 35-50% of the total operating cost (Christensen, 1995). Especially for intensive animal feeding farms, the expenditures on logistics are even more than moderate farms. In the United States, if all animal farms meet the nutrient standard of manure land application, the cost of livestock and poultry sectors would exceed $2 billion (Ribaudo et al., 2003).

Crop farmers is facing challenge of fertilize crops by animal manure. Only 18% of large swine production farms and 23% of large dairies have enough cropland for applying manure in the United States, which makes large AFOs travel a longer distance and spend more on manure nutrient recycling (Ribaudo et al., 2003). Many European crop farms reject swine manure because they prefer concentrated inorganic fertilizers (Makara and Kowalski, 2018). The research indicates the farmers in Europe would consider using the bio-based fertilizers only if the prices were 65% of the chemical fertilizers' (Tur-Cardona et al., 2018). Encouraging the participation of crop farmers in manure nutrient recycling becomes a global challenge.

Energy production is another alternative way for manure utilization. Anaerobic digestion plants take manure as the carbon source to produce biogas, which is a local renewable source of energy. The anaerobic digestion process also reduces the manure's pathogen and the carbon footprint, and has a positive effect on the environment (Martens and Böhm, 2009; Schievano et al., 2011; Caruana, 2019). However, this process does not reduce the load of manure. The digestate still has a high concentration of nitrogen, phosphorus, and potassium, which must be safely applied to croplands based on nutrient plans. The thermochemical process or hydrothermal process, like hydrothermal liquefaction, converts livestock manure to bio-crude oil. This approach can altogether remove the bioactive CECs and antibiotic-resistant genetic material (Pham et al., 2013b). After the treatment, the aqueous product can be further upgraded into liquid fuels (He et al., 2000). However, this technology is not mature, and the wastewater after HTL is toxic to crops and needs further processing (Pham et al., 2013a).

Because of the reasons mentioned above, the meat and feed markets are very fragile and sensitive to any environmental policies toward manure management. The most direct response is the increase of meat product cost. For example, adopting the crop nutrient plans from nitrogen-based standards to phosphorus-based standards would make livestock and poultry farms in Chesapeake Bay Watershed in the United States travel more than 90 miles for spreading manure to the cropland (Ribaudo et al., 2003). If the restriction of the slope of cropland to which manure can be applied was set from 12% to 18%, the swine farms in Kentucky would pay an additional \$0.35 head^{-1} (Fleming, 1999; Fleming and Long, 2002). There is still a debt between the benefit of low-priced protein products and the benefit of environment quality.

The decisions of management practices, polices and regulations should involve intensive knowledge and scientific proofs according to local conditions (Tilman et al., 2002). It is necessary to understand the dynamics and impacts of a manure management practice, especially for the environment-sensitive area or animal-production intensive regions. For example, the swine production industry of North Carolina has declined due to the increase of manure management cost (Stoddard and Hovorka, 2019). Chinese government designated a similar relocation plan that transferred the swine production from the watercourse region to the southwest and northeast provinces. Such a plan resulted in unexpected air pollution and damage to the local ecological system due to lacking appropriate investments and incentives (Bai et al., 2019a). Many studies indicated the strategy and policy should encourage the large-scale animal farms to adopt their manure practice voluntarily in a sustainable way (Qian et al., 2018b; Long et al., 2018). The professional services, financial assistance, and subsidies help AFOs with their decision-making preferences to reduce their production cost and to achieve the environmental protection target (Hutchings et al., 2013; He et al., 2016).

2.2 The scope of animal manure management

Animal manure management is a combination of agricultural manure management strategies and natural resource conservation practices. From a systems perspective, the animal manure management system (AMMS) includes on-site manure management, manure treatment, logistics, and nutrient utilization (Figure 2.1). A successful AMMS is accomplished by a series of planning, designing, evaluation, and installation to meet sustainable, economic, and engineering needs.

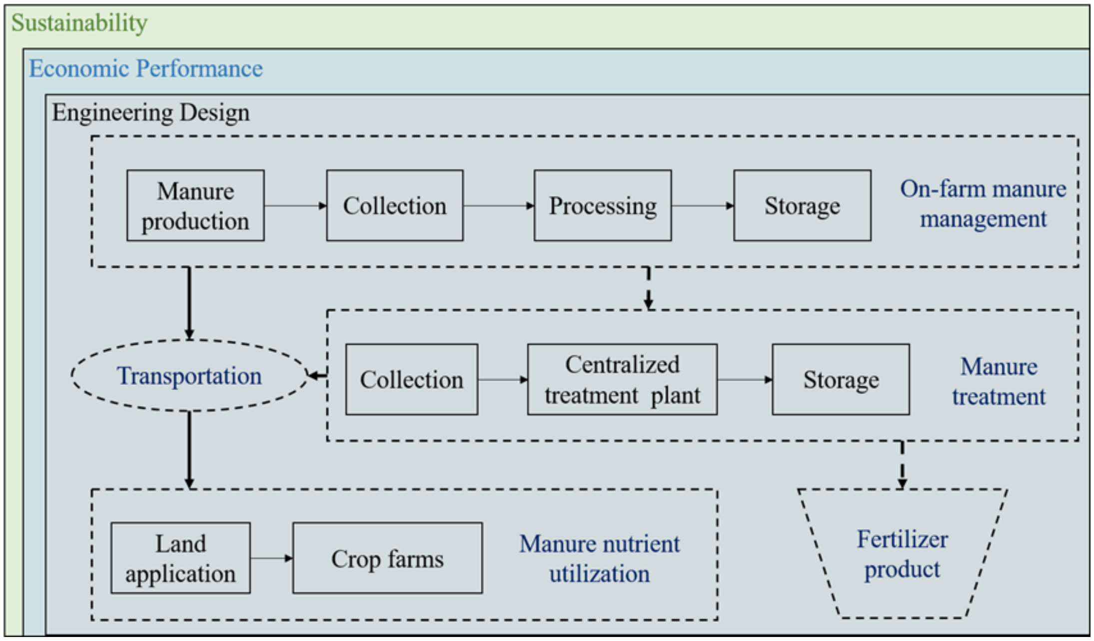


Figure 2.1. The components and evaluation dimensions of livestock manure management

Animal manure composition

Livestock and poultry manure contain abundant nitrogen, phosphorus, and potassium that can support crop production and enhance the fertility of the soil. In general, swine and cattle manure have high moisture contents (>85% as excreted). Poultry, sheep, and goat manure have relatively low moisture contents (~70% excreted) (Barker et al., 2002; MWPS, 2004). The solid manure has higher nutrient density and is much easier for processing, transportation, and utilization. Therefore, the poultry, sheep, and goat manure have higher values compared to swine and cattle manure.

The type and amount of several nutrients and chemicals are considerable in manure management. Chemical oxygen demand (COD) and biological oxygen demand (BOD) are used to indicate the measurable quantity of organic compounds in manure. The anaerobic digestion process prefers manure with high COD and BOD values, which means the high potential of biogas production. Nitrogen (N) compounds in manure is from the protein residues of animal feed. Fresh manure contains the most ammonia nitrogen (TAN = NH_3-N + NH_4-N), which might be emitted to the atmosphere as ammonia. After long time storage, nitrogen content will be further reduced, and the formation of nitrogen compounds will be changed through a series of biological and chemical reactions. Finally, the plant only can absorb inorganic nitrogen compounds (plant-available nitrogen: PAN). The organic nitrogen in manure will be further decomposed by soil bacteria, which cannot be used at once (Jonker et al., 2016).

Phosphorus (P) is an essential element for both plant and animal growth. Plants only take inorganic P and the current diet of livestock, especially for swine, are over-formulated in P (Turner et al., 2002). The indigestible P is not utilized by the animal. It stays in the manure and is utilized by the plants at some rate. There has been a great interest in manure P management, which reduces the diet P or adds phytase to increase the digestible P (Smith et al., 2004). Potassium (K) compounds are an another valuable element for plant growth, which is soluble and nearly not lost in the manure management system (USGA, 2015). Recently, there is a concern of increasing the use of some metal elements (copper, zinc) in feed, which lead to the potential toxic effect on plants (Qian et al., 2018a).

The measurement of animal manure composition is necessary when recycling nutrients to agricultural land. Many organizations and agricultural extension groups recommend a regular analysis of manure samples is necessary to maximize nutrient efficiency and minimize nutrient loss to the environment (Zhu et al., 2004; Marino et al., 2008). However, some planners and AFO owners use reference numbers or the recommendation factors to determine the application rate.

Manure collection, processing and storage

On-farm manure management includes manure collection, processing, and storage. In general, poultry, sheep, and goat farms have relatively simple on-farm manure management than swine and cattle farms. The solid manure is collected from the animal house. Some farms store the solid raw manure, wait for the organic fertilizer makers or centralized manure treatment plant to collect, and other compost the solid manure, and sell it as organic fertilizer by themselves (Martins and Dewes, 1992). Swine and cattle manure are in the form of liquid and slurry (moisture content <10%) that the management has more options and components than poultry, sheep, and goat manure management.

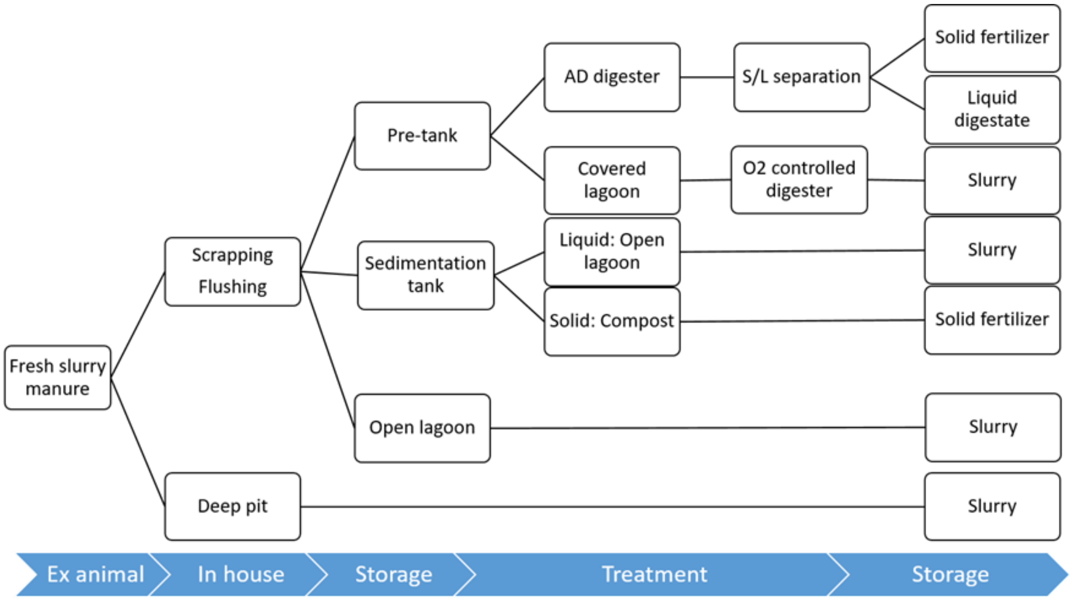


Figure 2.2. The options of a typical on-farm manure management system (slurry manure).

As shown in Figure 2.2, there are many options of slurry manure management. From the engineering perspective, the design standards are the strictest constraints. The selection of an on-farm manure management system requires professional knowledge and experience. For example, the flush system uses a surge of water to remove manure from the gutter to outdoor tanks. The flushing system can remove in-house gases and adapt to the most building structures. However, it generates a larger quantity of wastewater, and the storage lagoons have risks with the rainstorm. Moreover, for some cold regions and dry areas, the flush system is not appropriate, while people use the scraping system or deep pit system instead (Barker and Driggers, 1985). The anaerobic digestion process requires maintaining the digester temperature at the desired level (mesophilic: 35 ^{o}C, thermophilic: 55 ^{o}C) while this process is infeasible in some cold region that the heating cost exceeds the natural gas value (Meegoda et al., 2018). The standard design of manure storage should include the minimum storage period, control of runoff and seepage, design for storm and precipitation (Chastain and Henry, 2002). Relaxing engineering constraints will cause the risks of design failure.

From the environmental perspective, the manure operations are restricted by environmental regulations. Water resources, energy resources, cropland availability, weather, and site condition are the key factors affecting the decisions of manure management selection (NRCS, 2009). The conventional designs shown in Figure 2.2 could be invalid for some exceptional cases. The reasons could be the annoyance of odors from the neighbors, the changes in environmental regulations, and the alteration of land use. For example, ammonia and methane emissions occur during the storage and land application (Zhang et al., 2005). The local community might complain about the manure operations, and many governments published the regulation of setback distance to living area (Lim et al., 2000). The manure management designers can choose to either upgrade the conventional designs or create an innovation plan. The upgrading plans include the manure acidification and covered storage for reducing gas emissions, enhanced solid/liquid separation for reducing the nutrient contents in liquid manure, phosphorus and heavy metal removal for improving the manure land application, etc. (Ford and Fleming, 2002; Moller et al., 2007b; ten Hoeve et al., 2016).

Manure utilization and land application

The actions in AMMS include transportation, manure treatment (optional), and nutrient utilization after the manure leaves the AFOs. For the regions with low pressure of manure, the manure utilization is about the individual farm decisions of crop farm partnership, fleet design, and adequate nutrient management plans (NMP). For the livestock production intensive region, manure utilization involves collective and distributive management. In this case, decisions for region-scale will be network-planning, resource allocation, NMP distribution (Flotats et al., 2009).

The solid manure is transported by trucks, and slurry manure can be carried by pipeline and tank truck. For individual AFO, the transportation cost is composed of hauling cost and manure application cost (Fleming, 1999). For a large-scale manure supply chain, the transportation cost is comprised of manure collection cost, distribution cost and manure application cost (Ghafoori and Flynn, 2007). Any transportation-related cost is the combination of fixed costs and variable distance-dependent costs (Mahmudi and Flynn, 2006).

The storage facility and centralized treatment plants are the transitions in the manure utilization chain. The storage facility serves as a buffer between year-round continuous manure production and a short-time window of crop fertilizing. The centralized treatment plants could be organic fertilizer production plants, agricultural manure treatment plants, and biogas production plants. The decisions on the selection of site location are dependent on the crop nutrient demands, livestock and poultry farm distribution, setback distance to the living area, etc. (Yadav et al., 2016). The design of the storage facility needs to consider the seasonal variation of crop nutrient demands, climate conditions, natural resources, and local social concerns (Flotats et al., 2009; Sharara et al., 2017).

Crops will be the end-users of the processed manure product. The most common NMP are nitrogen-based nutrient management plan (N-NMP) and phosphorus-based nutrient plan (P-NMP). The application rate of nutrients can be calculated from the nutrient removal (N, P, and K) by harvest (Kellogg et al., 2000). Different land application practices will alter the ammonium loss percentage (Moore and Gamroth, 1991). A general assumption of the nitrogen application rate is multiplying nitrogen removal in harvest by 1.43 (Kellogg et al., 2000). Crops cannot use all the nutrients in manure. The suggested approach is to measure the PAN and available P content in manure before calculating the nutrient application rate (Berry et al., 2002).

Engineering design and evaluation

The AMMS designer follows the design criteria and standards that were developed to ensure the design feasibility. The design criteria and standards could be empirical equations, design procedures, design boundaries of the feature, and environmental limits. Then, the planners will formulate alternative plans, evaluate each of them, and choose the best solution.

The manure production and characteristics need to be determined before the design. Many organizations and local universities published the standard values (COD, BOD, N, P, K, production rate, water content) of manure production and characteristics for each type of animal (Barker et al., 2002; ASABE, 2005). Most standards do not have values of heavy metals (copper, zinc, etc.). If the diet of animals contains heavy metals, the designer needs to check the local records of manure’s heavy metal contents. For the region that does not have the standard values, the designer can use the empirical equations to estimate the manure production information from animal production data and diet information (ASABE, 2005).

The on-farm MMP design should follow both engineering design standards (structure, materials, safety, etc.) and environmental conservation standards. The environmental conservation standards include the setback distances to open water and living areas, manure storage design requirements, and runoff control (Iowa). The setback distances to the watershed and living area are different in each state. For example, Illinois requires new facilities (> 50 AU and < 2,000 AU) should not locate within ¼ mile (1,320 ft.) from nearest occupied residence; (2,000 AU to 7,000 AU) should not locate within ¼ mi. (1,320’) + 220 ft. per 1,000 AU above 1st 1,000 from residence; (7,000 AU or greater) should not locate within ½ mile from residence. The design requirements of manure storage include minimum storage period, control of runoff and seepage, design for the storm, and precipitation (Chastain and Henry, 2002). The runoff control is the supplementary design and evaluation for the risks of design failure. Abnormal climate and operating procedures might lead to accidental discharge into the surface water. The on-farm MMP needs to include assessment of location and capacity that minimize the exposure to vulnerability and risks (NRCS, 2009).

The design of a manure supply chain and NMPs is a simple task for farm-scale planning, but it becomes complex at a regional scale. Many factors need to be considered during the design, as shown in Table 2.1. For farm-scale planning, selecting the manure spreading crop farms needs to balance the transportation cost and manure nutrient values (Flotats et al., 2009). The geospatial restrictions of manure spreading include land slope, distance to open water and residential or populated areas. Moreover, the NMP should consider the seasonal changes of crop nutrient and potential risks of runoff in winter (Cronauer, 2010).

Table 2.1. Factors to be considered when designing the manure supply chain and NMPs (Flotats et al., 2009)

• Availability of accessible soils and crops to be fertilized
• Nutritional requirements and productivity of the crops
• Presence of other competitive/synergic organic fertilizers in the area
• Mineral fertilizers price
• Climate factors
• Density and intensity of farming
• Property structure of farms and agricultural lands
• Distances and transportation costs
• Energy prices

2.3 Decision support tools

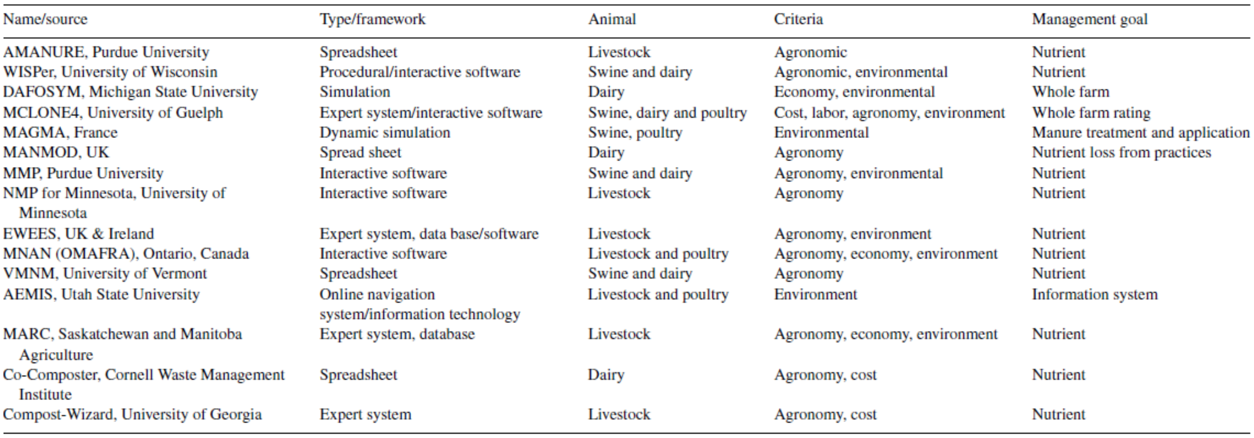
Manure management is becoming more important today for the livestock industry. The aggregative concerns of the environment lengthen the planning horizons and increase the decision variables in manure management (Karmakar et al., 2007). For animal feeding operations, the selection of on-farm manure management and treatment options requires professional consultants to assess economic performance and environmental regulations. For policymakers, the impacts of any rules should be entirely evaluated by experts for reducing the negative consequences to society.

Computer-based tools, software, and program are developed for assisting the users in organizing the necessary information and making decisions on manure management. The most recognized decision support systems aim to help decision-makers to evaluate their manure management options in a systematic approach based on some criteria that are relevant to design, standards, and local policies (NRCS, 2009). However, while these approaches work for evaluating some classic designs, they are unable to help with optimal design and the feasibility analysis regarding complex operations of the innovation system. Optimization modeling methods are applied for complex system designs, while the manure management designs and operations can be adjusted under constraints (de Figueiredo and Mayerle, 2014; Gebrezgabher et al., 2014). For a large-scale supply chain problems or manure utilization networks, the information system is used to evaluate the interactions between different units, which includes data processing models, optimization models, and analysis models (Lin et al., 2014).

Criteria-based decision support tools and their application

Decision support tools typically are interactive computer-based programs or software that have graphical user interfaces (GUI) for decision-makers to select answers from questionnaires or enter the farm information. Through a series of calculations following the empirical equations and analytic models, those tools can give the evaluation results to the users. As shown in Table 2.2, some of the decision support tools are commercialized and adopted for various dimensions (Karmakar et al., 2007).

Table 2.2. Decision support systems (DSS) for manure management (Karmakar et al., 2007).



Name/source	Type/framework	Animal	Criteria	Management goal
AMANURE, Purdue University	Spreadsheet	Livestock	Agronomic	Nutrient
WISPer, University of Wisconsin	Procedural/interactive software	Swine and dairy	Agronomic, environmental	Nutrient
DAFOSYM, Michigan State University	Simulation	Dairy	Economy, environmental	Whole farm
MCLONE4, University of Guelph	Expert system/interactive software	Swine, dairy and poultry	Cost, labor, agronomy, environment	Whole farm rating
MAGMA, France	Dynamic simulation	Swine, poultry	Environmental	Manure treatment and application
MANMOD, UK	Spread sheet	Dairy	Agronomy	Nutrient loss from practices
MMP, Purdue University	Interactive software	Swine and dairy	Agronomy, environmental	Nutrient
NMP for Minnesota, University of Minnesota	Interactive software	Livestock	Agronomy	Nutrient
EWEES, UK & Ireland	Expert system, data base/software	Livestock	Agronomy, environment	Nutrient
MNAN (OMAFRA), Ontario, Canada	Interactive software	Livestock and poultry	Agronomy, economy, environment	Nutrient
VMNM, University of Vermont	Spreadsheet	Swine and dairy	Agronomy	Nutrient
AEMIS, Utah State University	Online navigation system/information technology	Livestock and poultry	Environment	Information system
MARC, Saskatchewan and Manitoba Agriculture	Expert system, database	Livestock	Agronomy, economy, environment	Nutrient
Co-Composter, Cornell Waste Management Institute	Spreadsheet	Dairy	Agronomy, cost	Nutrient
Compost-Wizard, University of Georgia	Expert system	Livestock	Agronomy, cost	Nutrient

The tools for farm-level manure management planning mainly focus on nutrient management that establishes the nutrient balance between nitrogen, phosphorus, potassium content in manure and the quantity of these nutrients needed by crops. Some tools, named "expert system," integrates the manure processing information with the manure nutrient planning (MMP, Purdue University) and the method of manure land application (MARC, Saskatchewan and Manitoba Agriculture). Those tools rank the management options or grade each option with the criteria matrix. The final comparisons can inform the decision-makers the best choice and explain the advantages or drawbacks (Saaty, 2000; Karmakar et al., 2010).

The advanced tools for farm-level manure management planning usually focus on the environmental assessment, such as the estimation of gas greenhouse gas emission and the dispersion of the odor gas (Henry et al., 2010; Sykes et al., 2017). Those tools are not self-guided software but require specialized persons to operate and analyze the results with knowledge. For example, the odor assessment models, such as the AERMOD model that is developed and proved by EPA of the United States, needs meteorological data, terrain data, and facility layout. The programs are executed by running the commands. The results are not readable and need additional process and explanation (Li, 2009; Carbonell et al., 2010). Although those tools are very powerful, only very few farms can apply them for decision-making. Typically, they are used by the government or some organizations for regional planning and creating guidelines for the local farms (Lim et al., 2000; Jacobson et al., 2005).

Optimization modeling and their application

The modeling approaches are widely applied for designing, planning, and evaluating the time-dependent manure handling tactics or operational decisions. The design and planning decisions could be treatment and storage capacity design, logistic design, resource allocation, etc. The optimization models select the best design variables from the feasible sets based on the objective mathematical functions (or evaluation functions). The simulation models (or dynamic models) simulate the nutrient, water, energy, and gas flux in the manure management process for enlightening the operational tactics over time. In general, those models are the deterministic model and constrained by design rules and local parameters.

The optimization models are constructed to find the best possible values for a specific goal. For farm-level manure management design, the goal could be the “minimum management cost,” “shortest transportation distance” or “maximum biogas production of the anaerobic digestion plant,” etc. (de Figueiredo and Mayerle, 2014; Gebrezgabher et al., 2014). For region-level manure management design, the goal could be “minimize total risk,” “maximum profits from livestock and crop enterprises,” “shortest transportation distance,” etc. (Schnitkey and Miranda, 1993; Nema and Gupta, 1999; Ghafoori and Flynn, 2007). The design requirements and environmental requirements are programmed as constraints and parameters. Depends on the types of objective functions and domains, such as linear programming, integer programming, nonlinear programming, we can use different solvers to find the optimal solutions. For example, the logistics and location problems are the mixed-integer linear programming (MILP) problem, which can be solved by CPLEX solver, Gurobi solver, etc. (Jonker et al., 2016; Sampat et al., 2017).

The simulation models are constructed for predicting the process behavior over time, which can best mimic the actual responses in specified local condition. For example, the ammonia volatilization is different if the climate was changed. The dynamic models can simulate the ammonia level of partially slatted floors in different seasons (Aarnink and Elzing, 1998). The results can guide management practices and be used for house design. For region-level research, the simulation models can estimate the long-term effect of manure management practices and test the flux between different agricultural production systems (Feng et al., 2005). For example, the impact of rotation design on N, P, K balances can be simulated by NDICES model that indicates the correlation between cropping system, farm management practices, soil and rainfall (Smith et al., 2016).

Integrated information system and their application

The decision support system for solving large-scale manure management problems, such as the local resource allocations and regional logistics infrastructure, typically integrate several models and subsystems, which have functions of data preparation, data processing, design optimization and result analysis (Hu et al., 2017a). Each subsystem is functionally independent and connected by the data stream. Those tools can optimize strategic decisions and operational decisions simultaneously (Lin et al., 2013).

Regional level manure management planning and evaluation typically requires substantial information and access to the database, including manure production, manure processing, crop fertilizing, geospatial and climate data, and local regulatory constraints. Most of those constraints are the geospatial basis and can be prepared through Geographic Information System (GIS). The decision-makers use GIS to manage the data of watershed, soil, terrain, and land use, then create the proper area with defined criteria and forecast the potential economic and environmental consequences of designed policy and regulations (Jain et al., 1995). The elevation data, terrain data, and meteorological data can be obtained from the public online database, such as National Agricultural Statistics Service (NASS), National Oceanic and Atmospheric Administration (NOAA), and U.S. Geological Survey (USGS). Some location information and distance measurement can be obtained from google map services.

The mathematical formulation of a large-scale optimization problem is also different from a classic optimization problem. Manure management problems encompass many agricultural production units and pair-wise interactions. Depends on the complexity of the problem, the decision variables could be hundreds or thousands. On the other hand, the objective function is not unique for multi-dimension evaluations of the performance. For example, the objective function can be maximizing operating profit or maximizing soil organic matter accumulation for the same manure management (Liang et al., 2018). The early attempts were to keep one objective function and formulate others to constraints (Singh, 2014). The later research applies multi-objective optimization to balance economic, environmental, resource, and social considerations (Yue et al., 2013). The difficulties are not only problem formulation but also solution strategies and computational challenges. For some multi-objective optimization problems, such as the convex mixed-integer quadratic constrained programming (MIQCP) problems, it is nearly impossible to solve them by any optimization solvers (Liang et al., 2018). These large-scale problems with hundreds and thousands of variables are formulated in one function (Lin et al., 2013). It is hard for any developers to collaborate and diagnose errors. Therefore, these advanced decision support systems are not commercialized and only applied to scientific research topics, such as agricultural waste supply chains and regional hazardous waste management systems (Nema and Gupta, 1999; Jonker et al., 2016).

Multidisciplinary design optimization (MDO), a modified method of collaborative optimization (CO), has been applied to solve many large-scale industrial systematic problems, such as aero-elastic optimization, smart grid design (Chell et al., 2019). It is characterized by a distributed, bi-level structure, whereas the problems are decomposed into several naturally independent smaller problems (Yang et al., 2018a). As shown in Figure 2.3, the optimizer takes the responses from the analytic models, optimizes the design variables, then return designs to analytic models for checking the feasibility and calculating responses. The optimizer only uses the results from analytic models. Therefore, the analytic models are not necessary to be revised to the same programming environment. Moreover, depending on your expectations of optimization speed and intermediate outcomes; the analytic models can be formulated to multidisciplinary feasible (MDF) and individual feasible (IDF) structures (Cramer et al., 1994).

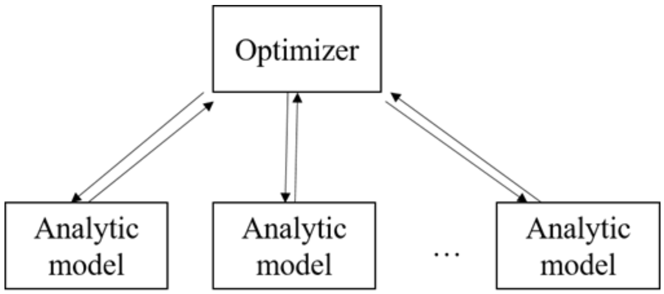


Figure 2.3. Example of multidisciplinary design optimization structure

The large-scale manure management system that showed in Figure 2.1 is naturally separated into three levels. Each level can be formulated to a general optimization model. Although each level influences other levels of the system, the overall target can still be achieved by sequentially re-visiting the rest sub-models in the system, which is a very typical structure of MDO (Kim, 2001). There is no a particular document to consult the collaborative optimization method to solve agricultural production problems. The MDO approach can help us to employ various types of models and tools that were mentioned above to establish an ideal method for solving the large-scale manure management problems.

2.5 Summary of the literature review

The nature of animal manure production in intensive feeding farms can impose a high cost of transportation and land application. Manure nutrient and energy utilization cannot guarantee a sustainable ecological system right now and in the future.

A typical animal manure utilization pathway ranges from manure production, collection, processing, storage, transportation, treatment, or land application. Optimizing this chain can preserve profits for livestock/poultry farmers to support environmental protection practices in local communities. The computer-based tools, software, and models could assist the decision-makers in organizing the necessary information and optimizing decisions on animal manure management. The Criteria-based decision tools focus on the strategic level planning and evaluation, while modeling based tools emphasize the optimization of detailed tactical-level planning. There is a need to develop an integrated information system to integrate different models to understand, evaluate, and optimize both strategic planning and tactical planning decisions for animal manure management.

In this chapter, we discussed the necessary information to design a manure management system. To accelerate the information connection between management design and management evaluation, a cyber-map enabled decision support platform has been developed in MATLAB (Appendix A). This platform integrated the information to confine the proposed management, which helps the user quickly assessing the alternative design by choosing options. We explained that the methodologies of developing integrated strategic and tactical modeling tools for manure management problems. Due to the complexity of mathematical formulation, those modeling approaches are not widely applied for manure management design. From literature regarding multidisciplinary design optimization, we found that there are few or no studies discussing the application of MDO formulation on agriculture problems. The MDO formulation has compatibility with heterogeneous computing environments. Many examples showed that this method is capable of solving large-scale systematic problems. We believe the exploration of an integrated decision support system and MDO approach on manure management problems can overcome the barriers to the implementation of a high-quality decision-making process for complex agricultural production systems.

CHAPTER 3: OPTIMAL DESIGN OF MANURE MANAGEMENT FOR INTENSIVE SWINE FEEDING OPERATION: A MODELING METHOD BASED ON TARGET CASCADING

3.1 Introduction

In the last ten years, intensive swine feeding operations (ISFO) make manure management more costly, difficult to process, and to transport. Moreover, the willingness of crop farm owners to fertilize crops with livestock manure is continuously decreasing (Makara and Kowalski, 2018). For the local community that does not have intensive animal production, manure utilization is mainly about the practices of a single farm. It is always a challenge with risks to select and to design manure management.

The designs and decisions about swine manure management are multi-disciplinary studies while considering both manure processing and utilization from engineering, economic, and environmental perspectives. The manure generated by ISFO is processed through manure treatments at the farm, exported as certain types of fertilizer products, and eventually used for crop growth. Compared to the other kind of livestock manure, swine manure as excreted has a high moisture content (>90%) (Barker et al., 2002). After the manure treatment, solid fertilizer product is recognized as organic fertilizer. However, the liquid portion (digestate), which has large volume and low nutrient density, is not a commercial organic fertilizer but is commonly given to local crop farms for free. As shown in Figure 3.1, a sustainable swine manure management must contain the manure treatment design and the crop-fertilizing plan for liquid fertilizer.

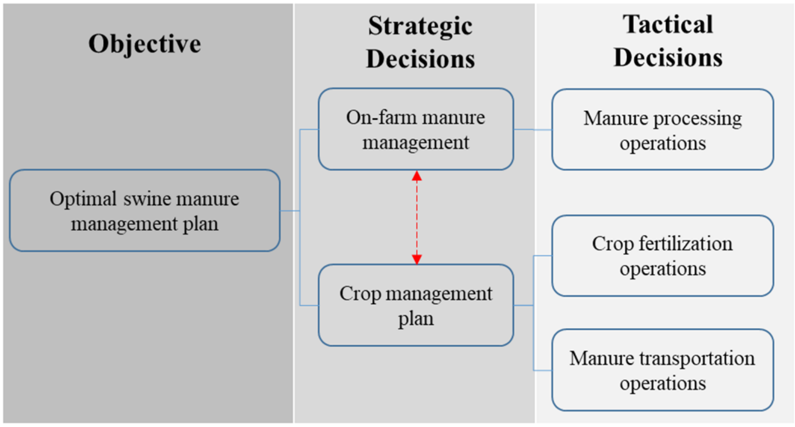


Fig. 3.1. Schematic diagram of the swine manure management system design problem.

The objective of this research is to present a modeling approach for identifying the optimal swine manure management. The proposed methodology applied the target cascading structure that incorporates both optimization analysis models to simultaneously optimize the strategic-level and tactical-level decisions of manure management. An illustrative case design that contains two treatment processes (Anaerobic Digestion process + Ectopic Fermentation process) for the ISFO in Hangzhou, China, is presented. This is done to demonstrate the decisions and the design, i.e., treatment capacity, a configuration of mass flows in the system and the sizes of each process at different seasons under different economic scenarios. This study can assist in overcoming the barrier to implement high-quality analysis tools in optimization models for establishing an ideal approach to use the information and computational science.

3.2 Problem description and formulation

3.2.1 Problem statement

According to the NRCS (2009), the planning process of animal manure management should include nine steps, which can be summarized as problem identification, alternative designs, optimal designs and final evaluation. Based on the local economic and natural conditions, stakeholders and consultants can select several alternative management plans. Then, the conceptual design of the alternatives should be detailed for evaluating their performance. The conceptual design involves the following steps:

- Identify all components in the manure management plan.
- Calculate the possible design capacity ranges of main components based on the manure production and utilization.
- Determine the material flows and identify the property changes in the process.
- Find the related economic parameters, such as the capacity cost of main components, product price and operational cost.
- Construct the descriptive model of the process that addresses the relationship between manure input and fertilizer production output.

This chapter focuses on optimal design and evaluation for the swine manure management that composes of the on-farm manure treatment design and crop-fertilizing planning. The operation of manure treatment depends on the crop fertilizer demands (crop nutrient demands). Meanwhile, the crop management plans are affected by the fertilizer supply limits and nutrient contents. The interactions between two agricultural production systems, such as the processing operations, transportation operations, fertilization operations, are the operational-level decisions. The major decision variables include:

- Capacities of the main components in manure processing;
- The storage capacity of the liquid manure product;
- Operational plans of the treatment in each season;
- Crops, rotation plans, and fertilization plans of cooperated crop farms;

- Total costs and operating profit.

The goal of the proposed modeling approach is to maximize the economic performance of the swine farms, maximize the crop nutrient utilization to improve the local sustainability and reduce the neighbor concerns of the odor gas to the swine productions. Based on the conceptual design and the parameters, the first step is to construct the objective function and constraints. A general approach is to formulate the economic performance into objective functions and add environmental restrictions as constraints. The feasible capacity ranges and operational constraints (such as mass balance, operational limits) can also be formulated into constraints (Liang et al., 2018). However, some environmental assessments, such as odor impact, are conducted by professional models, which are developed in different coding language and the results are based on the whole design plan (Zhu et al., 2000). It is difficult to integrate those functions in optimization models.

Another modeling challenge in manure management problem is the disunity of decision periods. Manure production is continuous. The crop fertilization practices vary in seasons, but the decision of crop growth and rotation is a yearly basis. Unifying the study period will enlarge the number of optimal decisions, and cause the difficult on results analysis, model adaption, and modification.

The major characteristics of manure management design problems are summarized as follows:

- Multiple production systems involved.
- Strategic-level and tactic-level decisions.
- Multi-objective optimization framework; analysis model and assessment module involved.

- Non-uniform study period.

3.2.2 Model formulation

The proposed method uses the Analytic target cascading structure (ATC) to formulate the optimization problem. Analytic target cascading is the system design approach that enabling the top-level design target to be cascaded down to lower levels of the modeling hierarchy (Kim, 2001). As shown in Figure 3.2, all possible capacities of the main components in the feasible range are combined and merged into the design candidate matrix (DC matrix). Then, mathematical models are constructed in ATC structure. Given the design candidate in DC matrix, the operational plans are optimized. Finally, the economical, sustainable, social performance of the proposed candidate and the operational plans will be evaluated (section 3.2.3); the results will form the post-design evaluation matrix (DE matrix).

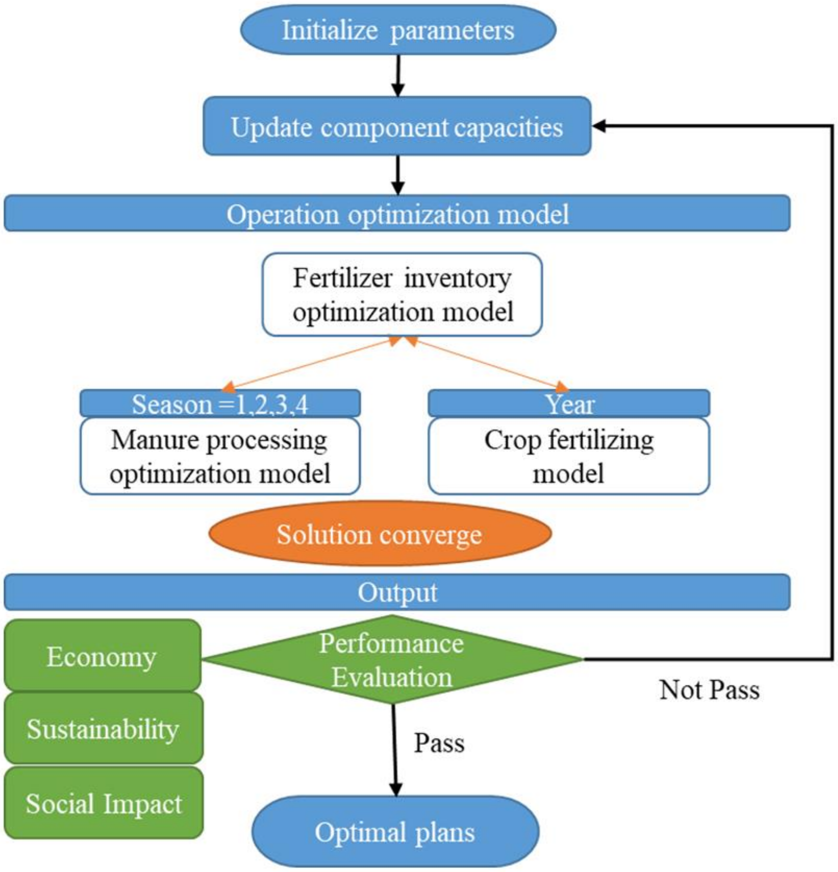


Figure 3.2. Hierarchy-structure for designing a swine manure management plan.

In swine manure management design, the fertilizer inventory capacity is the top-level decision and is optimized with respect to operational plans. Reducing storage can significantly improve farm sanitation, decrease pollution risks and reduce odor emissions. The storage capacity is determined from product inventory, which depends on the responses from the lower-level models (“fertilizer supply”- manure processing optimization model; “fertilizer demand”- crop fertilizing model). At the top-level of hierarchy, the problem is a state as follows: minimize the difference between fertilizer supply and fertilizer demands subject to the results from two lower-level models. Then, the responses from the top-level model will pass to the lower-level models for updating the optimization parameters. The optimal solution is the converged variables that the results of all three models are not changed anymore.

The manure management problem is the non-united decision period problem. Manure production is continuous, but crop fertilization practices vary in seasons. Moreover, the decisions of crop growth and crop rotation is a yearly basis. Unifying the study period will enlarge the number of optimal decisions, and cause the difficult on results analysis, model adaption and modification. The ATC structure can maintain the feasibility of each model and optimize the problem in a collaborative way. Moreover, the ATC structure is flexible for modifications and model extensions. The models are inexpensive at each level. In the development stage, each model can be verified and modified individually. The lower-level model can be further partitioned to smaller problems, while the structure can be further modified to a three-level system.

3.2.3 Post-design evaluation

The performance of the optimal plans can be evaluated in three dimensions: economy, sustainability, and social impact. In this research, annualized profits are used for evaluating economic performance in (Eq. 3.1). The annualized profit includes annualized income and annualized cost. The annualized cost consists of operational cost and annualized capital cost of the process.

$$Annualized\ profit = Revenue - Annualized\ capital\ \mathrm{cost} - Operational\ cost \tag{3.1}$$

The liquid manure holding amount is used for indicating the environmental risks of an annual operational plan (Eq. 3.2), which is equivalent to the holding cost of liquid fertilizer. The holding-amount is to measure the difference between liquid fertilizer supplies (*AccS*) and demands (*AccD*) over time. As shown in Figure 3.3, the storage capacity is the maximum difference between supply and demand. The ideal case is to match the production line with the demand line for minimizing the storage capacity and holding risks.

$$\textit{Liquid manure holding amount (t. Day)} = \sum_{t=1}^{N} (AccS - AccD_t) Ndays_t \tag{3.2}$$

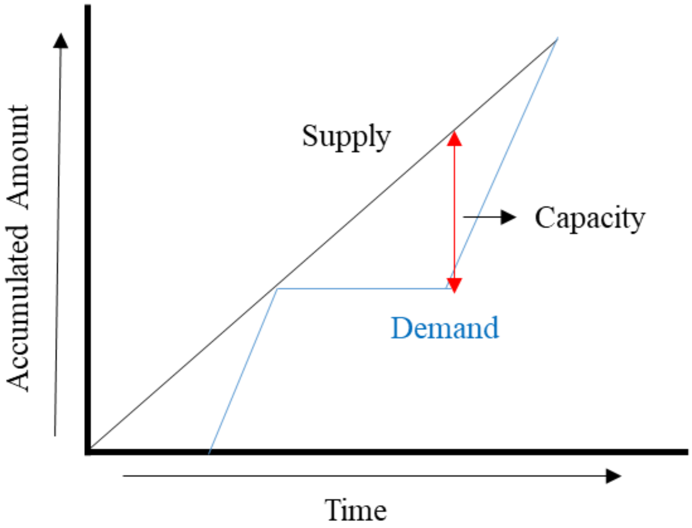


Fig. 3.3. Typical graphic example representing the relationship between supply, demand and capacity

The odor annoyance-free frequency (*Freq_{odor}*) is used for indicating the social impact of the proposed plans as shown in (Eq. 3.3). In this study, we use the AERMOD model to predict the odor concentration ($Conc_{odor}$) in the residential area that is dispersed from the swine farm (Li, 2009). The odor annoyance percentages describe the number of days that the odor concentration exceeds the odor detection threshold over a period. The threshold is the odor intensity considering “faint” to human in a period (Guo et al., 2005).

$$Freq_{odor}\,(\%) = \frac{\sum Ndays \mid (Conc_{odor} \geq Thred_{odor})}{\sum Days} \times 100\% \tag{3.3}$$

3.3 Case study: manure management system for a swine farm in Hangzhou. China

3.3.1 Description of the case study

The methodology for the design of an integrated swine manure management is illustrated through a case study conducted for a swine farm in Hangzhou (an area identified as livestock intensive and an ecosystem sensitive region in China). Specifically, Hangzhou is threatened by ecological issues resulting from the development of large-scale and intensive livestock production. The future livestock development guidance involves a request for proposals and studies as well as an agreement from the government, communities, experts, and businesses (Qiu et al., 2017). The *ecological plan* classified the mountain area as a breeding expansion zone and classified the plain and watershed region as breeding reduction or prohibition zones. Furthermore, the breeding technologies including management were also to be upgraded to satisfy business changes. In Hangzhou, the conventional manure management for swine farms is a storage-based treatment system, such as anaerobic or aerobic storage. However, the arable lands in the mountainous area are limited for using of all manure fertilizer generated from swine farms. Therefore, the storage-based treatment design cannot significantly reduce the amount of slurry manure through evaporation since Hangzhou is in a humid subtropical climate region. To develop the manure management recommendation guidance, research institutions including Zhejiang University, proposed general manure treatments for animal production, such as compost, solid/liquid separation, anaerobic digestion and ectopic fermentation, etc. (ZJAGRI, 2017). In this chapter, we report a pilot study to demonstrate the optimal design in the treatment planning and operation stages under local conditions.

A full-scale demonstration swine farm located in the mountainous area was recognized as a breeding expansion zone. As a typical example of a large-scale swine farm in Hangzhou, this farm can produce 10,000 finishing pigs per year and 11,556 tons of manure. The original manure management of this farm includes two types of manure collection systems (breeding barns: deep pit, finishing barns: scraping system) and lagoon storage. The scraping system splits the manure into a liquid portion and a solid portion. As illustrated in Figure 3.4, there are 6 paddy fields and a greenhouse vegetable farm available to use manure fertilizer. The candidates in general manure treatment recommendation guidance were evaluated in the conceptual design stage. Subsequently, a combination of the anaerobic digestion system (AD) and the ectopic fermentation system (EF) were selected to be further assessed in the optimal design stage.

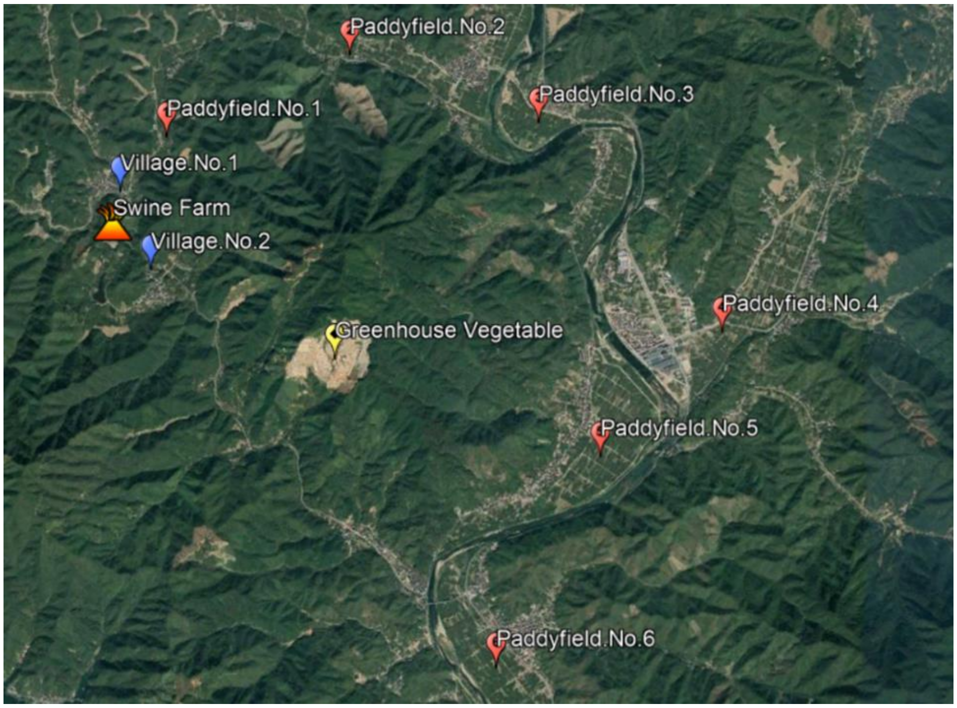


Figure 3.4. Relative geospatial locations of swine farms, residential villages and cultivation fields.

Notably, the AD system ferments manure, inactivates the pathogens, and produces biogas for heating (Heinonen-Tanski et al., 2006). Meanwhile, the AD digestate can be utilized locally or evaporated through the EF system and the solid portion can be treated through the EF system or directly sold to organic fertilizer plants. The EF system feeds animal manure with specific bacteria that is grown in carbon materials and concentrates the nutrients into fermented fertilizers (Wang and Guo, 2009). The raw swine manure was converted into three types of fertilizer products: liquid fertilizer, fermented fertilizer, and raw solid manure. Liquid fertilizer has less nutrient density and is shipped to cooperated crop farms without any charge. Meanwhile, fermented fertilizer and raw solid manure can be sold for profit. Fermented fertilizer can be directly sold to the market, whereas the raw solid manure acts as raw materials for other fertilizer plants or energy plants. Through evaporating partial water and splitting the nutrients to different products, this upgrading plan is considered practical if the system was well-designed.

3.3.2 Mathematical models

The proposed model is formulated as a MILP model that was developed on Python and solved using the Gurobi solver. The assumption and parameters are listed in "Appendix B". A list of set names, decision variables, and parameters used in the model is provided in "Nomenclature." In this example, the strategic decisions are the design variables about the dimension of anaerobic digestion (Cap_{AD}), ectopic fermentation (Cap_{EF}), and storage (Cap_{LS}) for liquid fertilizer. As shown in Figure 3.5, the operational decisions that vary in seasons (t) are the best combination of flow rates to anaerobic digestion and ectopic fermentation [$X_{1.t}$, $X_{2.t}$, $Y_{1.t}$, $Y_{2.t}$, $S_{1.t}$, $S_{2.t}$, $X_{12.t}$, $X_{13.t}$]. The decisions regarding crop farms (Z_{rm}) are farming plans with respect to land (m) and crop rotation plan (r).

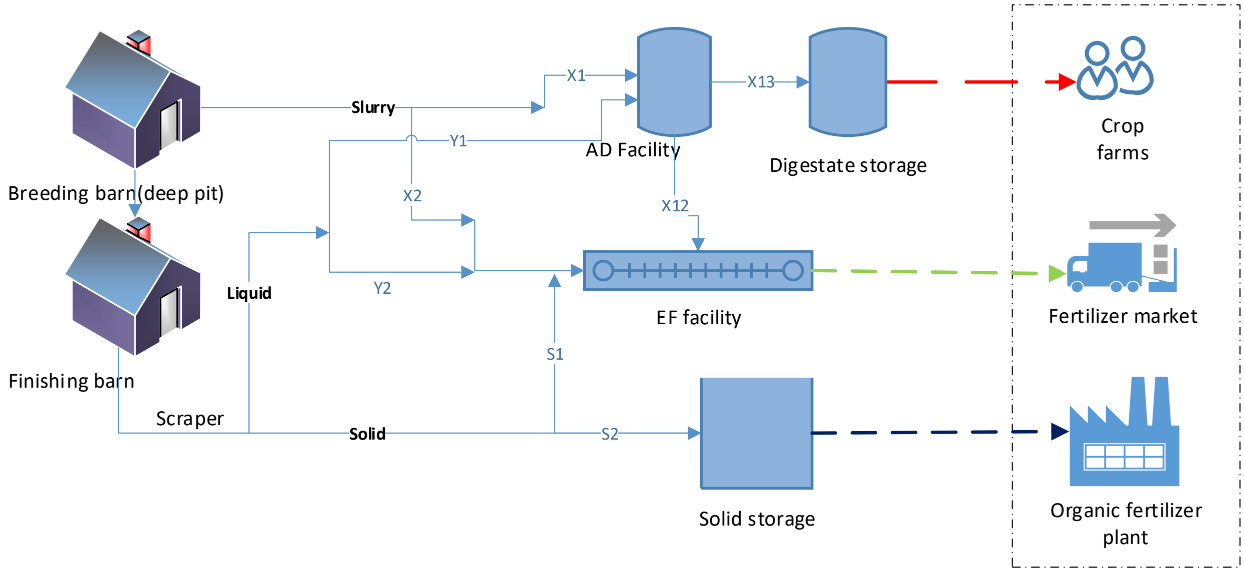


Fig. 3.5. Conceptual design of swine farm manure management in Hangzhou, China.

- Economic optimization

The objective of the economic optimization model (Eq. 3.4) is to maximize annual swine manure management profit that includes three parts: annual operational profit of swine manure treatment (*Po*), the annual operational cost of crop fertilization of liquid fertilizer (*Cf*) and annualized capital cost. The annualized capital cost is the linear combination of unit capital cost (*UC*), capacity (*Cap*) and the capital recovery factors (f_a). The capital cost composed of the main components including anaerobic digestion, ectopic fermentation, liquid fertilizer storage, and scraping system for finishing barn.

$$profit = Po - Cf - f_a \times (UC_{AD}Cap_{AD} + UC_{EF}Cap_{EF} + UC_{LS}Cap_{LS} + UC_{Sep}) \tag{3.4}$$

For manure treatment management, the annual profit (Po, Eq. 3.5) is the summation of individual profit of three production lines in each productive season (t): liquid fertilizer (Po_{AD}), fermented fertilizer (Po_{EF}), raw solid manure (Po_S) and scraping system operational cost.

$$\begin{gathered}
Po = \sum_t Po_t(Cap_{AD}, Cap_{EF}) = \sum_t \underset{X_{1.t}, X_{2.t}, X_{12.t}, X_{13.t} Y_{1.t}, Y_{2.t}, S_{1.t} S_{2.t}}{Max} Po_t^{EF} + Po_t^{AD} + Po_t^{S} + Ndays_t \times \mathrm{co}_{\mathrm{s}craper} \\
where \\
Po_t^{AD} = Ndays_t \times GF_t \times r_{gas} \times (X_{1.t} + Y_{1.t}) - Co_{AD} - Ndays_t \times co_{trans} \times X_{13.t} \\
Po_t^{EF} = (r_{EF} - co_{EF}) \times CF_t \times (X_{12.t} + X_{2.t} + Y_{2.t} + S_{1.t}) \\
Po_t^{S} = Ndays_t \times (r_S - co_S) \times S_{2.t} \\
s.t. \\
h_1 : X_{1.t} + X_{2.t} - \mathrm{M}_A = 0 \\
h_2 : Y_{1.t} + Y_{2.tt} - (1 - \eta_{Sep}) M_B = 0 \\
h_3 : S_{1.t} + S_{2.t} - \eta_{Sep} \times M_B = 0 \\
h_4 : X_{1.t} + Y_{1.t} + X_{13.t} - X_{12.t} = 0 \\
g_1 : X_{1.t} + Y_{1.t} - \frac{Cap_{AD}}{10} \le 0 \\
g_2 : \frac{Cap_{AD}}{40} - X_{1.t} - Y_{1.t} \le 0 \\
g_3 : 1.48 Y_{1.t} - 3.27 X_{1.t} \le 0 \\
g_4 : CF_t \times (X_{12.t} + X_{2.t} + Y_{2.t} + S_{1.t}) - Cap_{EF} \le 0 \\
g_5 : EF_{\min} \times Cap_{EF} \le CF \times (X_{12.t} + X_{2.t} + Y_{2.t} + S_{1.t}) \\
g_6 : DL_t - X_{13.t} \le 0
\end{gathered} \tag{3.5}$$

Given the crop demands of liquid fertilizer (DL_t) and weather information, the operational decisions are altered in each season (*t*). The equality constraints describe the mass balance between each component. Herein, $Nday_t$ is the number of days in each season. The AD system operational profits consist of the revenue of biogas production, the energy cost related to maintaining the operation of the AD system and the transportation cost for shipping liquid fertilizer to crop farms. Liu et al. (2017) described that biogas production factor (*GF*) depends on the volatile solid contents of the mixture and the hydraulic retention time, which is the function of the influents (Eq. B.1, B.2 and B.3). The energy cost (Co_{AD}) related to maintaining the operation of the AD system is estimated from the energy balance (Eq. B.4). The hydraulic retention time constraints (g_1, g_2) ensures the amount of the influents is within a feasible range for anaerobic digestion process. The mixture constraint of the AD system (g_3) ensures the concentration of the influents is above the lower limit. The production constraint of the liquid fertilizer (g_6) recommends the minimum production amount, which is estimated from the crop fertilizing model.

The EF system's operational profit is estimated from the revenue and cost of producing fermented manure as a fertilizer. Liu et al. (2017) indicated the capability of manure treatment in EF system related to the moisture content and the temperature of the fermentation bed. The difference is demonstrated as the capacity factor (CF_t) that varied in different seasons. The operational constraints (g_4, g_5) guarantee the amount of manure is under the capacity of fermentation bed.

For the operational cost of crop fertilization, the total cost (Cf, Eq. 3.6) is the summation of transportation cost with respect to crop rotation decisions (Z_{rm}) and crop fertilizer demand (CD_{rm}) in each productive season (t). The transportation cost is the hauling cost from swine farm to cropland, which contains the fixed cost (cf) and variable cost (cv). The crop rotation decisions are binary variables and constrained by which each land only has one rotation plan per year.

$$\begin{gathered} Cf = \sum_t cf_t(X_{13.t}) = \sum_t \sum_r \sum_m (c_f - c_v D_m) Z_{km} CD_{rm.t} \\ s.t. \\ \sum\nolimits_r Z_{rm} = 1 \\ Z_{rm} \in \{0,1\} \end{gathered} \tag{3.6}$$

- Crop fertilizing analysis

The liquid fertilizer generated by the AD system is shipped to local crop farms. The factors to be considered in liquid fertilizer application rate are characteristics of the fertilizer, crop types, crop rotations, and land spreading method. The nitrogen content of liquid fertilizer is adjusted to plant-available nitrogen (*PAN*, Eq. 3.7) that considers the effect of organic nitrogen mineralization (*mf*) and ammonia loss during the land application ($loss_{NH3}$). The crop farming list summarizes all possible crop rotation and non-rotation plans for the local crop, vegetable, and fruits (Table B.1). The nutrient demand matrixes (Eq. 3.8) for nitrogen and phosphorus (*DN*, *DP*) are estimated based on the crop yield and crop nutrient concentration (*HN*, *HP*). In the end, the total amount of fertilizer demand at season t (DL_t) is the sum of liquid fertilizer demand of each individual field (Eq. 3.9) which can be calculated from farming decisions (Z_{rm}) and the liquid fertilizer demands ($CD_{rm.t}$) for cultivation decision. The liquid fertilizer demands reflect the minimum application rate over nitrogen and phosphorus (Eq. 3.10).

$$PAN_t = f_{OrgN} \times N_t \times mf + \times (1 - f_{OrgN}) \times N_t \times (1 - loss_{NH_3}) \tag{3.7}$$

$$DNu_{km} = Area_m \times Yield_k \times HNu_k \times 100\% \mid Nu = N, P \tag{3.8}$$

$$DL_t = \sum_r \sum_m Z_{rm} D_{rm.t} \tag{3.9}$$

$$CD_{rm.t} = \min\left(\frac{DN_{rm}}{PAN_t}, \frac{DP_{rm}}{P_t}\right) \tag{3.10}$$

- Fertilizer inventory optimization

The nutrient content of liquid fertilizer in each season (Eq. 3.11) is calculated from the mixture of swine manure flows and nutrient loss. The management of liquid fertilizer should consider both AD operations and crop management. Minimizing the inventory of liquid fertilizer can reduce the pollution risks and odor emissions, which is another primary design objective besides economic returns (Eq. 3.12). The equality constraint is to ensure each cropland has only one rotation plan per year. The liquid fertilizer storage capacity is the maximum inventory in a typical year (Eq. 3.2, Figure 3.3). The liquid fertilizer demand of crop farm is adjusted for each season by deducing the leftover from the previous season (Eq. 3.13). The liquid fertilizer transportation cost is also adjusted along with the fertilizing plan changes (Eq. 3.14).

$$Fnu_t = \frac{X_{1.t} \times N\mathrm{u}\% + Y_{1.t} \times Nu\%}{X_{13.t}} \times (1 - \eta_{Nu.loss}) \times 100\% \,|\, Nu = N, P \tag{3.11}$$

$$\begin{gathered} \underset{Z_m \in \{0,1\}}{Min} \sum_{t=1}^{4} \Big(\sum_{r} \sum_{m} Z_{rm} CD_{rm.t} - X_{13.t}\Big)^2 \\ s.t. \\ h_1 : \sum\nolimits_r Z_{rm} = 1 \\ Z_{rm} \in \{0,1\} \end{gathered} \tag{3.12}$$

$$NewDL_t = DL_t - Max(X_{13.t-1} - DL_{t-1}, 0) \tag{3.13}$$

$$co_{trans} = \frac{\sum_{r} \sum_{m} (c_f + c_v D_k) Z_{rm} CD_{rm.t}}{\sum_{t} Ndays_t X_{13.t}} \tag{3.14}$$

- Solution strategies

The computational strategy of this operation optimization model follows the ATC approach. First, we initialize the capacity (Cap_{AD}, Cap_{EF}) and crop fertilizer demand (Z_{rm}=0), then run manure processing optimization model for four seasons to generate initial liquid fertilizer production ($X_{13.t}$). Given the response ($X_{13.t}$), the upper-level model outputs the target of crop fertilizer demand (Z_{rm}) and nutrient content of liquid fertilizer (nu_t | nu=N, P), then pass the results to crop fertilizing analysis model for updating crop fertilizer demand ($CD_{rm.t}$). The summary of crop fertilizer demand (Z_{rm}) will update the liquid fertilizer production target (DL_t) and liquid fertilizer transportation cost (co_{trans}), which are the constraints of the manure processing optimization model. The iteration will stop until to get a converged solution, which is the optimal operational design for the proposed plan (Cap_{AD}, Cap_{EF}). Finally, we calculate the economic performance (Eq. 3.4), liquid fertilizer holding-amount (Eq. 3.2) and odor annoyance-free frequency (Eq. 3.3) for the proposed plan.

- Scenario analyses

Baseline case

To illustrate the viability of the proposed models, we designed manure treatment processes (Anaerobic Digestion process + Ectopic Fermentation process) for a full-scale demonstration swine farm in Hangzhou. As shown in Figure 4, the closest residential communities are approximately 400 meters north and 500 meters southeast of the swine farm. Six paddy fields with total area of 18.3 hectares are available for using liquid fertilizer.

Inputs to the model are drawn from several sources. Swine manure properties and operational treatment parameters that describe the mechanical and processing performance of the equipment are obtained through technical standards and recommendation values in the manure utilization handbook (Moller et al., 2002; ZJAGRI, 2017). The swine manure production and economic parameters, such as the unit costs and prices, are obtained through face-to-face questionnaires to local contractors and farm owners. The local weather information is sourced directly from the local database. The crop agronomic information and fertilizing information were acquired indirectly from local surveys of agronomic practices and ZJAGRI (2017). A detailed summary of assumption and data sources is listed in the supplementary information. The decisions regarding the system capacity (Cap_{AD}, Cap_{EF}) were constrained by the lower-upper bounds (Cap_{AD}: (200,

900) m^3; Cap_{EF}: (400, 1600) m^3). The upper bounds are calculated by assuming the system works only in full capacity to process all manure. The lower bounds are the minimum size reported from contractors.

Design analysis

1. A scenario analysis was conducted to assess how the data inputs affect the performances of manure management business. Scenario F1 investigates the impact of expanding swine farm size, which increases the amount of manure production. Scenario F2 describes the impact of increasing the bedding material prices of the EF treatment. Moreover, scenario F3 analyzes the risks of market closure for solid manure fertilizers while solid raw manure and fermented fertilizers cannot be sold for income. In this scenario, solid raw manure must be treated before leaving swine farms and fermented fertilizers are given to local crop farmers without any charge. Scenario F4 investigates the opportunity benefits if the greenhouse vegetable farm is involved in the liquid fertilizer utilization plan. Scenario F5 investigates the economic benefits of reducing water usage.

2. It is very common for stakeholders to revise the manure treatment design, which is time-consuming in practice for designers to re-evaluate the new design. A scenario analysis was conducted to illustrate an advantage of the proposed modelling structure in model adaption. As shown in Figure 3.6, the alternative design applies a deep-pit system for both breeding barn and finishing barn while the original design uses a scrapping system for finishing barn. All the manure is temporally stored in a tank and then processed through the liquid and solid separator. The data and parameters used at the baseline case were applied for evaluating an alternative design.

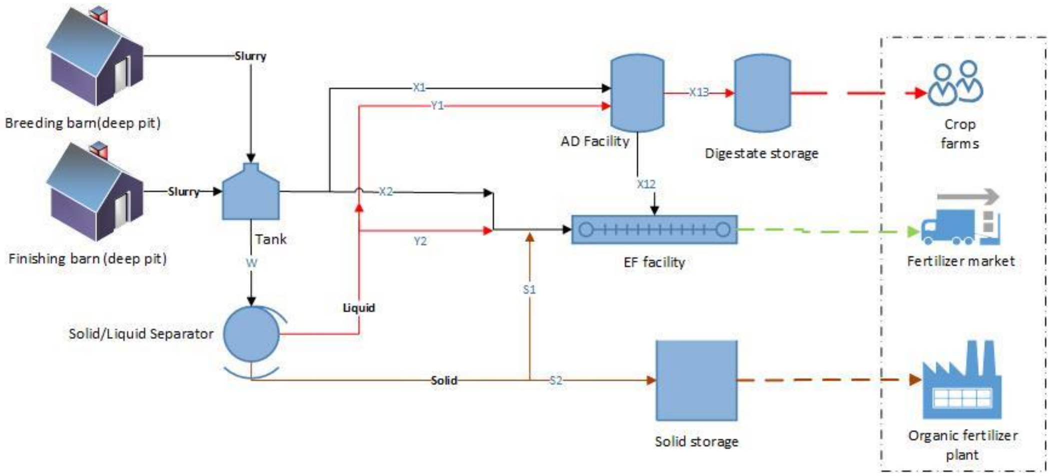


Figure 3.6. Alternative designs of manure processing plan for the proposed farm.

3.4 Results and discussion

3.4.1 Baseline case

The infeasible design options (Cap_{AD} = 200 m^3, Cap_{EF}: [400, 500, 600] m^3) were excluded from the candidate lists by the model since those plans with two systems are not able to process all the generated manure. Among the feasible plans, the net annual expenditures vary from CNY 163,534 to CNY 723,125. The liquid AD fertilizer storage capacity ranges from 48 ton to 5,773 ton. The most profitable design (Cap_{AD} = 200 m^3, Cap_{EF}: 1600 m^3) has the lowest net annual expenditure of CNY 163,534. The optimized storage capacity of liquid AD fertilizer is 88 m^3 in this design plan. The liquid fertilizer holding amount is 3,960 ton.days, while the inventory is zero in winter and spring. The ATC structure is compatible with both built-in environmental constraints and external sustainability assessment models. The odor annoyance-free frequencies for the optimal plan at two residential villages are greater than 98% in 12 months. Liquid fertilizer is transported to six paddy fields with an average transportation cost of CNY 2.7/ton. All the solid raw manure is directly sold to the organic fertilizer makers for profits. As shown in Figure 3.7 and 3.8, the liquid AD fertilizer production (X_{13}) in each season are optimized for matching the crop demands while crop cultivation plans are adjusted simultaneously for reducing the liquid manure holding risks.

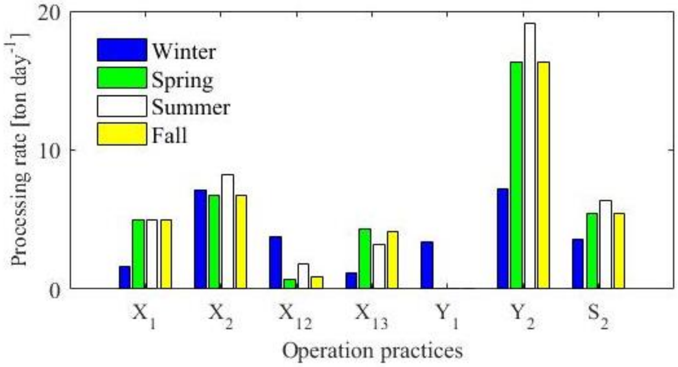


Figure 3.7. Manure processing operational plans based on the parameters made in Table B.1.

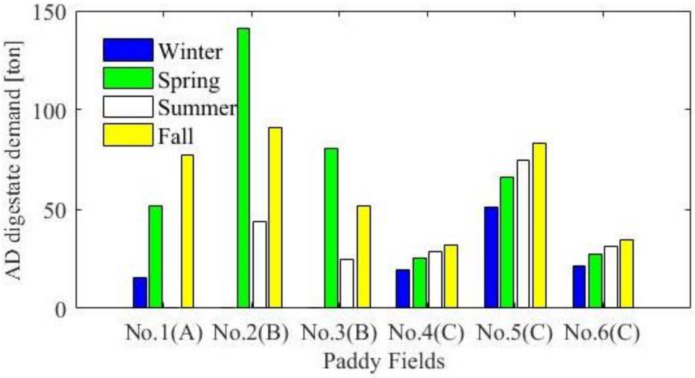


Figure 3.8. Crop cultivation plans and fertilizing operational plans based on the parameters made in Table B.1. (A): Spring grain/Vegetable; (B): Late rice/Vegetable; (C): Oil crop/Late rice.

3.4.2 Design analysis: risks and opportunities

Generally, it was very expensive and ineffective to evaluate whether the manure management plan was feasible or economic in a local region. The proposed model identified the optimal design at given economic and operational conditions. Moreover, this model could quantify changes of parameters on the optimal design through scenario analysis. Five scenarios were discussed for illustrating the common considerations of intensive swine producers that might affect the economic performances of manure management business in Table 3.1. The scenario analysis could quantify the potential risks prior to the real operation. Increasing 10% of swine production as demonstrated in scenario F1 will not change the capacity of AD treatment nor the capacity of EF treatment, and it will only increase total net cost by 4.5%. Adjusting the operational plans and cultivation plans can reduce some manure loads, while excessive manure could cause the increment of holding risks and odor annoyance to neighbors

Table 3.1. Scenarios setting and the optimal results.

	Scenario				
	F1	F2	F3	F4	F5
Description	Manure production +10%	Bedding material cost +20%	No revenue for selling solid manure and solid fertilizer	Cooperate with greenhouse vegetable farm	Reducing water usage in summer by 10%
Parameter changes	Manure production (ton/day) Winter: 25 Spring/Fall: 37 Summer:42	co_{EF}= CNY 260	r_{EF}=0; r_S=0	Add 17 hectares vegetable field	Manure production (ton/day) Winter: 22.5 Spring/Fall: 35 Summer:30.3
Annual net cost (CNY)	171,027	306,972	956,283	172,296	159,650
Capacity of AD system (m^3)	200	200	200	200	200
Capacity of EF system (m^3)	1600	1500	700	1600	1600
Capacity of AD digestate storage (m^3)	340	745	5297	63	0
Liquid digestate holding amount (ton.day)	37,997	161,363	927,505	2848	0
Months of odor annoyance free frequency <= 97%	June	June	June	___	___
Crop cultivation plans in Paddy Field No.1-6[1]	B, C	B, C	B	C, D	A, B, C

[1] Crop rotation plan: (A): Spring grain/Vegetable; (B): Late rice/Vegetable; (C): Oil crop/Late rice; (D): Early rice/late rice

The economic risks from fertilizer markets have significant impacts on this manure management. In general, the EF treatment is sensible to the price of bedding materials and fertilizer prices. If the price of bedding material increases by 20%, the total cost increases by 87% and the optimal capacity of the EF treatment is reduced to minimize the cost. The annual net cost of scenario F3 is the highest and 5.7 times of the base scenario even if the operation plans and crop cultivation plans were optimized. If the market of solid manure fertilizer was closed, swine farmers have to reduce the production of solid raw manure and fermented fertilizer. This is especially since local crop farms cannot take all manure nutrients and excessive manure will be permanently stored.

The liquid fertilizer storage takes 53% of the total annual cost. The risks in scenario F3 not only concern economic loss but also the potential environmental pollution for holding a large quantity of manure. If the EF system is profitable, swine farm owners should produce as much fermented fertilizer as possible. Otherwise, swine farm owners should stop the EF treatment to prevent economic loss.

Furthermore, there are some management opportunities for swine farms to reduce the total cost, holding risks and social concerns. The annual net cost of scenarios F5 is the lowest, even compared to the base scenario. With appropriate cultivation plans, reducing water usage can assist swine farms in utilizing all the produced liquid fertilizer within the season. Additionally, recognizing the nutrient value of liquid fertilizer can promote and improve the economic benefit of the AD system. The operation of the AD system requires a large quantity of energy in maintaining the temperature for anaerobic digestion. However, the biogas produced by AD treatment is insufficient in making AD system profitable. In other words, the AD treatment is performed as a treatment process instead of a fertilizer production process under the assumption that liquid fertilizer is given to crop farms without any charges. In Zhejiang province, the fertilizer market does not recognize liquid fertilizer as a valuable product, while the optimal results could change if this fact was changed in the future.

There are more than 50 residences in these two villages. According to Guo et al. (2005), the odor annoyance-free frequency should be greater than 97%. Scenarios F1, F2 and F3 indicate that there will be odor gas concerns in June for the two closest villages. Since scenarios F4, F5 and the base scenario have no liquid fertilizer storage until the summer, the odor impact is reduced during the worst weather season. Cooperating with greenhouse vegetable farms costs more and increases the holding amounts in general. Greenhouse vegetable farms use liquid fertilizer as a starter before sowing in each season, and swine farms must store some extra liquid fertilizer with extra cost during regular seasons.

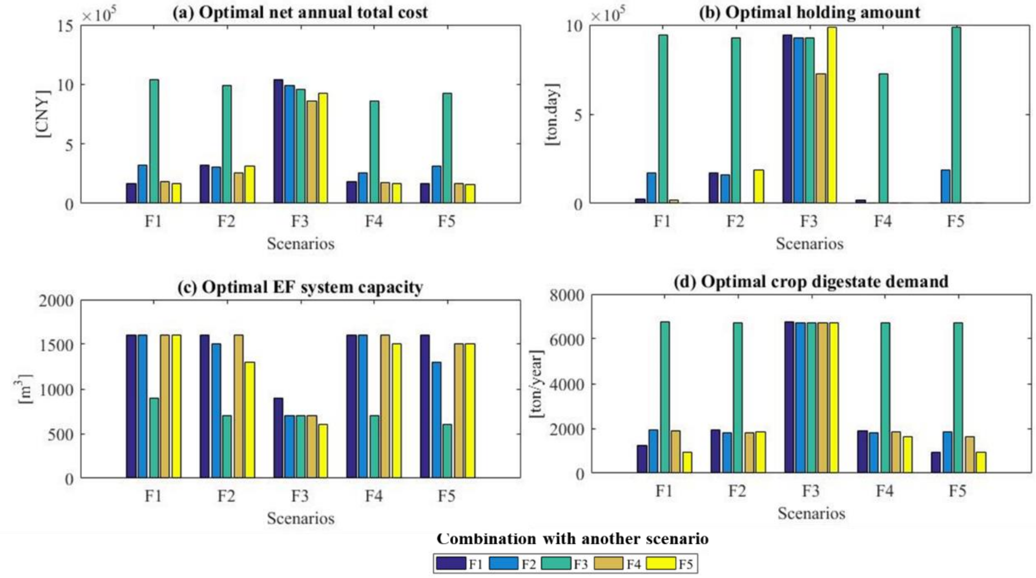


Figure 3.9. Cross evaluation of the optimal results if two scenarios happen at the same time.

The cross-evaluation is shown in Figure 3.9 for discussing the compensation and enhancement effect between different management strategies. The holding risks of increasing swine production (F1) can be reduced with more arable lands (F4) and less water usage (F5). The holding risks of cooperating greenhouse vegetable farms (F4) can be eliminated by reducing water usage (F5). The economic and holding risks of solid fertilizer market closure (F3) and bedding material price increasing (F2) can be compensated if swine farms cooperate with more crop farms (F4) and reduced water usage (F5). Notably, the solid fertilizer market closure (F3) significantly damages the manure management of the proposed swine farm. In Figure 3.8(d), the maximum nutrient demand of 7 crop farms for liquid fertilizer is 6,750 tons/year, but they still cannot take all liquid fertilizers. Due to the high cost of operating the EF treatment and excessive liquid fertilizer storage, farmers could stop the EF treatment. Finally, the economic loss could lead to environmental issues.

3.4.3 Design analysis: model adaptation for design changes

The proposed modeling structure allowed designers to modify and evaluate the design in a flexible manner. The swine farmer's opinions toward this design include relative lower capital cost, simpler manure collection practices and lower operational cost, which requires designers to adapt the original model. In this study, altering the design plan was achieved through modifying the manure processing optimization module. The other two sub-modules were not revised in this process.

Proposition: Suppose alternative design changes the mass flows ($X_{1.t}$, $X_{2.t}$, W_t) before and after the solid-liquid separation ($Y_{1.t}$, $Y_{2.t}$).

1. *The deep-pit system uses more water (~1 ton/day) comparing to scraping system.*
2. *Equation 15 replaced the calculation of scraper system operation cost in Equation 5, and the mass balance equality constraints (h_1, h_2, h_3) were adapted to alternative design (h_{1q}, h_{2q}, h_{3q}).*
3. *The separation efficiency and cost for manure scrapper were replaced to mechanical separator in Table B.1.*

$$\begin{gathered} Co_t^{Sep} = Ndays_t \times co_{Sep} \times (Y_{1.t} + Y_{2.t} + S_{1.t} + S_{2.t}) \\ s.t. \\ h_{1q} : X_{1.t} + X_{2.t} + W_t = M_A + M_B \\ h_{2q} : Y_{1.t} + Y_{2.t} - (1 - \eta_{Sep}) \times W_t = 0 \\ h_{3q} : S_{1.t} + S_{2.t} - \eta_{Sep} \times W_t = 0 \end{gathered} \tag{3.15}$$

The data and parameters used in base scenario analysis at the baseline scenario were applied for evaluating the alternative design. Compared to the base scenario (CNY 163,534, Cap_{AD} = 200 m^3, Cap_{EF}: 1600 m^3), the net annual expenditures increase 60% (CNY 261,654). The liquid fertilizer storage is 840% (830 m^3) and the liquid fertilizer holding amount is 26 times higher than the amount in the base scenario. Comparing the operational plan in Figure 3.6 and 3.10, the inflows of AD treatment was reduced (Y_1=0 for all seasons) and less raw solid fertilizer (S_2) were produced in alternative design. Although the capital cost of the manure collection system of alternative design is lower than the original design, the alternative design has higher liquid fertilizer storage cost and higher holding-amount in spring that causes the odor problem in June. In a systematic perspective, the solid-liquid separator doesn’t effectively reduce the manure load but leave more water to the liquid portion after the separator process, and eventually become the pressure for manure treatment and crop fertilization.

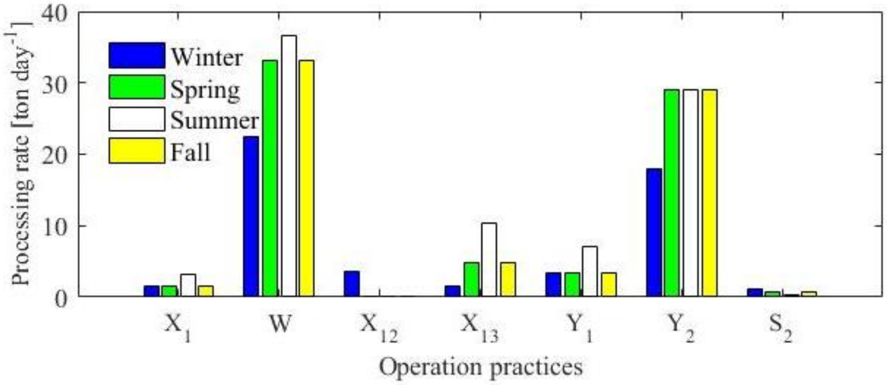


Figure 3.10. Manure processing operational plans of the alternative design.

3.6 Conclusions

Numerous research groups focus on identifying the best manure management method for animal farms. The design criteria not only concern functionality and economy but also focuses more on cleaner production and sustainability. With this in mind, the optimal design is comprised of multiple objectives and multi-level decisions, which makes it difficult for many designers to formulate and solve the problem. This study describes a modeling approach to calculate and optimize the manure management design, which includes the decisions of main component capacities, operation plans in each productive season and cultivation decisions of fertilizing crop farms. A dual treatment system (Anaerobic Digestion/Ectopic Fermentation) was proposed for a swine farm in Hangzhou, China and discussed under different market and strategy scenarios.

The proposed modeling approach simplified the problem formulation and model development. Unlike the classic "all-in-one" formulation, this approach divided the manure management problem into three smaller tasks based on the analytic target cascading (ATC) structure: liquid fertilizer inventory minimization, manure processing optimization and crop fertilizing analysis. Each sub-module implemented one simple objective: minimize inventory, minimize cost, and maximize nutrient utilization. The targets and constraints of three sub-modules were updated in iterations. Notably, the result was the trade-off between operational profit, liquid fertilizer inventory and crop fertilization demands.

In a case study, the model optimizes the swine manure management with crop production system to enhance the local nutrient re-circulation and connections between different agricultural production systems. Through scenario analysis, it is revealed that the AD treatment is not profitable until the liquid fertilizer can be sold for revenue and the design and operational decisions of the EF treatment is very sensible for solid fertilizer prices. Reducing water usage can minimize the total cost and risks from swine production increment and solid fertilizer market fluctuation. Consequently, involving more crop farms that can utilize liquid fertilizer is not always good for the economy and holding risks, but it can reduce management risks. Compared to the alternative setup (deep pits with solid/liquid separator), the scraping system saves more water and achieves better economic and environmental performance.

The modeling structure can be adapted to most agricultural production problems and waste management design projects. After identifying the objective of economy, engineering and sustainability, the problem can be formulated to small tasks and solved sequentially by updating the targets and responses in each iteration. It is possible to integrate some professional assessment models to optimal design, which extends the model functionality in an authoritative but simple way. Our case study highlighted an example of using the ATC structure in swine manure management design. Future research can extend the formulation techniques to more levels of decisions and to handle uncertainty.

CHAPTER 4: OPTIMAL MANURE UTILIZATION CHAIN FOR DISTRIBUTED ANIMAL FARMS: MODEL DEVELOPMENT AND A CASE STUDY IN HANGZHOU, CHINA

4.1 Introduction

In an animal production intensive region, the manure utilization chain is the collective and distributive management that requires network-planning, allocation of limited resources, and optimized nutrient distribution. From a stakeholder's perspective, the economic cost is one of the most critical factors for determining a manure utilization chain. For example, an analysis performed in Wisconsin, USA, estimated the minimum sale price of granulated manure (Sharara et al., 2018). Another research project demonstrated that a random parameter logit model could be used to analyze farmer preferences for animal pollution control policies (Pan et al., 2016). The standard values of most proposed policies, such as setback distance, tax rates, and subsidy, are estimated from a set of parameters and based on the statistical average or median scenario. Few studies have included the interactions and trade-off between animal producers and manure users to the calculation (Sharara et al., 2018). Some studies have also discussed the impacts of environmental policies on individual farm profit, but no research has quantified individual farm responses to regional manure operations (Zheng et al., 2013; Poffenbarger et al., 2017).

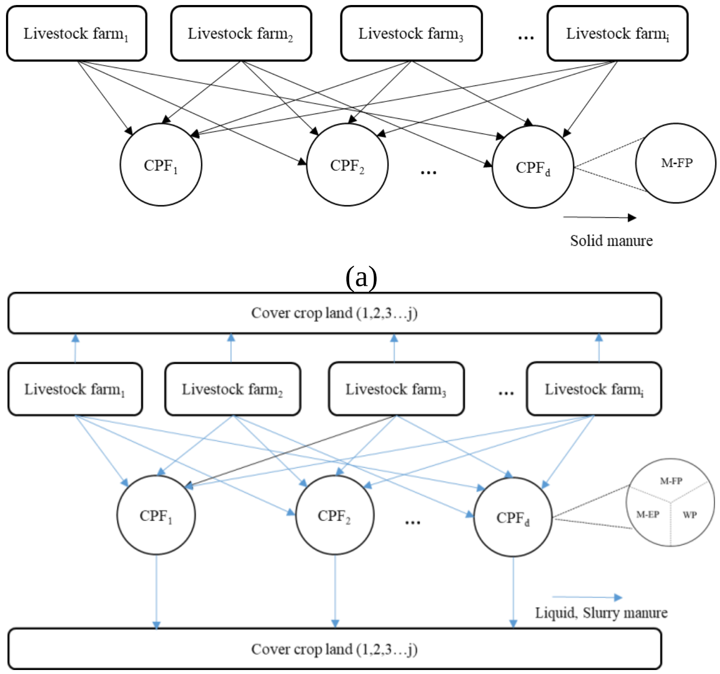
This chapter describes how construct and optimize a regional manure utilization chain that demonstrates the animal manure flows between animal feeding operations (AFOs), centralized processing facilities (CPF), and crop farms under the scope of sustainability. The modeling methodology enables the rapid configuration of the manure utilization chain and supports the evaluation process of various economic, technical, and environmental objectives. The planning and decisions of regional management and resource allocation are subject to the rational agreement of each unit in the manure utilization chain, which balances the sustainability needs and economic outcomes (Ribaudo et al., 2003; Nguyen et al., 2012). Especially for regions with intensive animal production, a decision-support tool can be helpful in many areas, such as distance between manure application areas and sensitive areas, construction of centralized manure processing facility, and the benefits of new technology and strategy (Martens and Böhm, 2009; Qiu et al., 2017; De Menna et al., 2018). This model can be used to inspect configuration (numbers and capacities of facilities, transportation routes, crop farms), quantify the performances (economic returns, available manure application lands, nutrient utilization efficiency), and analyze the synergies and trade-offs among different objectives (Groot et al., 2012; McDonald et al., 2019).

The regional manure utilization chain (RMUC) model enabled the geographical information system (GIS) to estimate the land suitability and nutrient demands for liquid manure land application. The land suitability evaluation allowed for multi-criteria strategies in regional planning and is capable of environmental, economic, and aesthetic constraints for land use (Huang et al., 2010). A case study was performed in Hangzhou, China, demonstrate the present RMUC model functionality. The Hangzhou government was used to evaluate the ecological plan that had both closed breeding operations and setup prohibition zones since 2014. The *ecological plan* has not been complete because the local environmental capacity bears a heavy burden on animal husbandry. In recent years, the increasing demand for meat in urban area challenges the ecological plan. There is an urgent need to improve manure management policies. In addition to prohibition zones, the scenario discussed case study answers proposed by "what-if" questions to analyze how setback distances (distance between manure application areas and sensitive areas) affect the manure utilization configuration and the total cost. The modeling results and scenario discussion can provide evidence to decision-makers and indicate possible future research directions.

4.2 Methodology

4.2.1 Problem formulation

Recognizing the manure utilization mode of an animal operation in the chain is essential before assigning any strategies and decisions. The animal manure utilization chain includes two stages or four stages depending on the manure utilization mode and the commercial value of manure as shown in Figure 4.1. The fertilizer facility prefers solid manure and processes solid manure to organic fertilizer (M-FP) for profit (Figure 4.1(a)). The reliable solid manure sources, lower procurement, and transportation costs are the key factors for a successful organic fertilizer business (Kunz et al., 2009; Sharara et al., 2018).



(a)

(b)

Figure 4.1. Animal feeding operations (AFOs), centralized processing facility (CPFs), cover crop lands and fertilizer markets make up a manure utilization chain. The solid manure utilization chain (a) involves a two-stage utilization chain and slurry manure utilization chain (b) involves a four-stage utilization chain.

The slurry manure produced by swine and cattle has high moisture contents (>85% as excreted) and low nutrient density, which can be either concentrated with higher nutrient contents or separated into the liquid phase with lower solid content depending on the manure process technology of AFOs (Moller et al., 2007a). As shown in Figure 4.1(b), slurry manure can be stored at the animal farms and used by local crop farms. The unused portion is shipped to centralized processing facilities for further manure to energy processing (M-EP), manure to fertilizer processing (M-FP), or wastewater processing (WP). The processing treats manure to irrigation water at a very high cost. The effluents from M-EP and M-FP are utilized as liquid fertilizer. Compared to solid manure processing, the slurry manure utilization chain is more complex because of the profitability that is related to nutrient concentration, cropland availability, application cost and transportation cost (Mayerle and de Figueiredo, 2016).

From the concept point of sustainability, the scope of this chapter is to depict such a system that animal manure is either processed or used by different facilities or the end-users but not to be disposed of without being utilized. The optimization modules identify the optimal mass and nutrient flow between AFOs, CPFs, and crop farms as shown in Figure 4.1. For a solid manure utilization chain, the RMUC model is to minimize the regional manure utilization cost for all units in solid manure treatment. For the slurry manure utilization chain, this study focuses on solving one particular problem formulation: the units in the slurry manure utilization chain, such as AFOs and CPFs, decide their flow patterns based on their local objectives (minimization of manure operational cost) but don’t focus on the minimization cost of the whole chain. This formulation guarantees the operational-level decisions for AFOs and CPFs are made independently based on their benefits, as described above. This design ensures the various stakeholders make the decision for sustainability goals and face the consequences from that decision but not the irrational global optimal results (Klotz et al., 2018). In this sense, the RMUC model can depict the co-benefits and trade-offs between units in different stages at possible configuration schemes.

The scope of this paper is to depict a system where animal manure is either processed or used by different facilities or the end-users, but it is not to be disposed of without being utilized. The manure utilization chain is segregated into two chains: (i) the manure collection chain for organic fertilizer and (ii) the manure utilization chain for the slurry and liquid-portion of manure. An efficient manure collection chain involves the CPFs at optimal locations with enough capacity to reduce the manure collection cost for solid manure. A sufficient manure utilization chain allocates the manure nutrients to the crop farms and excessive manure to CPFs at a relative lower cost, as shown in Figure 4.2. Other CPF products, such as solid fertilizer, treated water, and sludge, can be sold in the organic market to be used as irrigation water and treated by other treatment plants. The fates of these products would not affect the decision of local manure utilization.

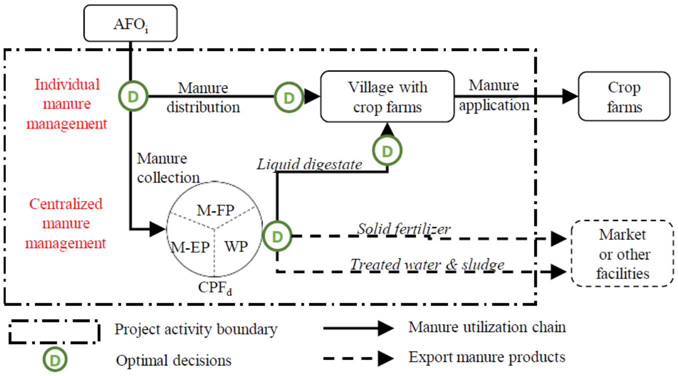


Figure 4.2: System boundaries.

With the information from manure supply (AFOs), manure demand (crop farms), and logistic networks, RMUC models could construct an optimal logistics configuration for manure and manure-based products under certain constraints. For a solid manure utilization chain, the objective is to minimize the regional manure utilization cost for all units in solid manure treatment. For the slurry manure utilization chain, this study focuses on solving one particular problem formulation: the units in the slurry manure utilization chain, such as AFOs and CPFs, decide their flow patterns based on their local objectives (minimization of manure operational cost but do not focus on the minimization cost of the whole chain). This formulation guarantees the operational-level decisions for AFOs and CPFs are made independently based on their benefits, as described above. This design ensures the various stakeholders decide on sustainability goals and face the consequences from that decision but not the irrational global optimal results (Klotz et al., 2018). In this sense, the RMUC model can depict the co-benefits and trade-offs between units in different stages for possible configuration schemes.

4.2.2 Overview of the RMUC model

The RMUC model integrated information analysis and optimization tools to provide optimal mass and nutrient flows in the animal manure utilization chain. The integration of data processing models, optimization models, and analysis models could effectively address the issues of a large production system (Lin et al., 2014). In this study, the Animal Husbandry and Veterinary Bureau of Hangzhou provided information from AFOs and CPFs in Hangzhou. The information from AFOs includes physical addresses, animal types, animal inventory, manure handing system, solid-liquid separation system, annual manure production, annual solid-portion manure production, and annual liquid-portion manure production. The information from CPFs used in this study include physical addresses, solid manure processing capacity, and liquid manure process capacity. The spatial-related data was provided by the Urban Planning and Land Resources Bureau of Hangzhou.

There were three sub-modules to prepare the necessary information: land application module, transportation distance module, and manure characteristic module (Figure 4.3). The land application module summarizes the land-use information from crop farm polygons to village-level units (crop-farming village: the smallest unit in manure utilization chain) through geographical information system (GIS), and it calculates the nutrient demands (nitrogen and phosphorus) by average crop yield, land area, and the reference value for nutrients removed by the harvest of agricultural crops. The average crop yields are obtained from the 2019 Hangzhou Agricultural Census (Zhejiang Bureau of Statistics, 2019). The land area can be estimated from land suitability analysis in GIS by user-defined parameters, such as setback distances to living space, rivers, and roads. The reference value for nutrients removed by the harvest of crops was derived from the plant database of the Natural Resource and Conservation Service of the United States Department of Agriculture (NRCS-USDA).

The transportation distance module estimated the shortest route and distance through the application programming interface (API) that connected the address of units in the manure utilization chain to online map-service providers. As shown in Figure 4.3, the physical address of each unit in the manure utilization chain (AFOs, CPFs, crop-farming village) is converted to a geospatial location. The geospatial locations of starting and ending points were then sent to the online map-service providers (google map) to estimate the shortest route and distance.

The manure characteristics module estimated the nutrient contents (nitrogen and phosphorus) and total solid content of manure and manure products. The fresh manure excreta parameters and nutrient contents of different animals are the standard values in China (Wang et al., 2006). The total solids content and nutrient contents of animal manure were scaled from reference values by assuming the manure nutrients could be diluted with the dilution ratio of fresh manure weight to the reported manure weight. The manure composition might vary substantially. However, due to the comparative nature of this study, it was deemed reasonable to assume a deterministic value for this parameter. Table C.2 presents the values for the operational parameters to calculate the manure nutrient flows and losses, which are documented in the references.

Subject to user-defined scenarios, the required information for input data was prepared through the models described above and stored in a spreadsheet file format. The GIS data sources, and processing assumptions are listed in Appendix C. A list of set names, decision variables, and parameters used in the model is provided in the “Nomenclature” section. All capital cost and operational cost values of CPFs were obtained from local contractors and standardized to the annualized costs. Table C.2 presents the values of the economic parameters used in computational experiments. The optimization module (RMUC-OPT) could read spreadsheet files to initialize parameters and constraints. The RMUC-OPT models were formulated as mixed-integer linear programming (MILP) that included two optimization models: solid manure RMUC-OPT model and slurry manure RMUC-OPT model. The MILP is solved using the Gurobi solvers. The results were stored in the Excel spreadsheet for further visualization of the maps through ArcGIS.

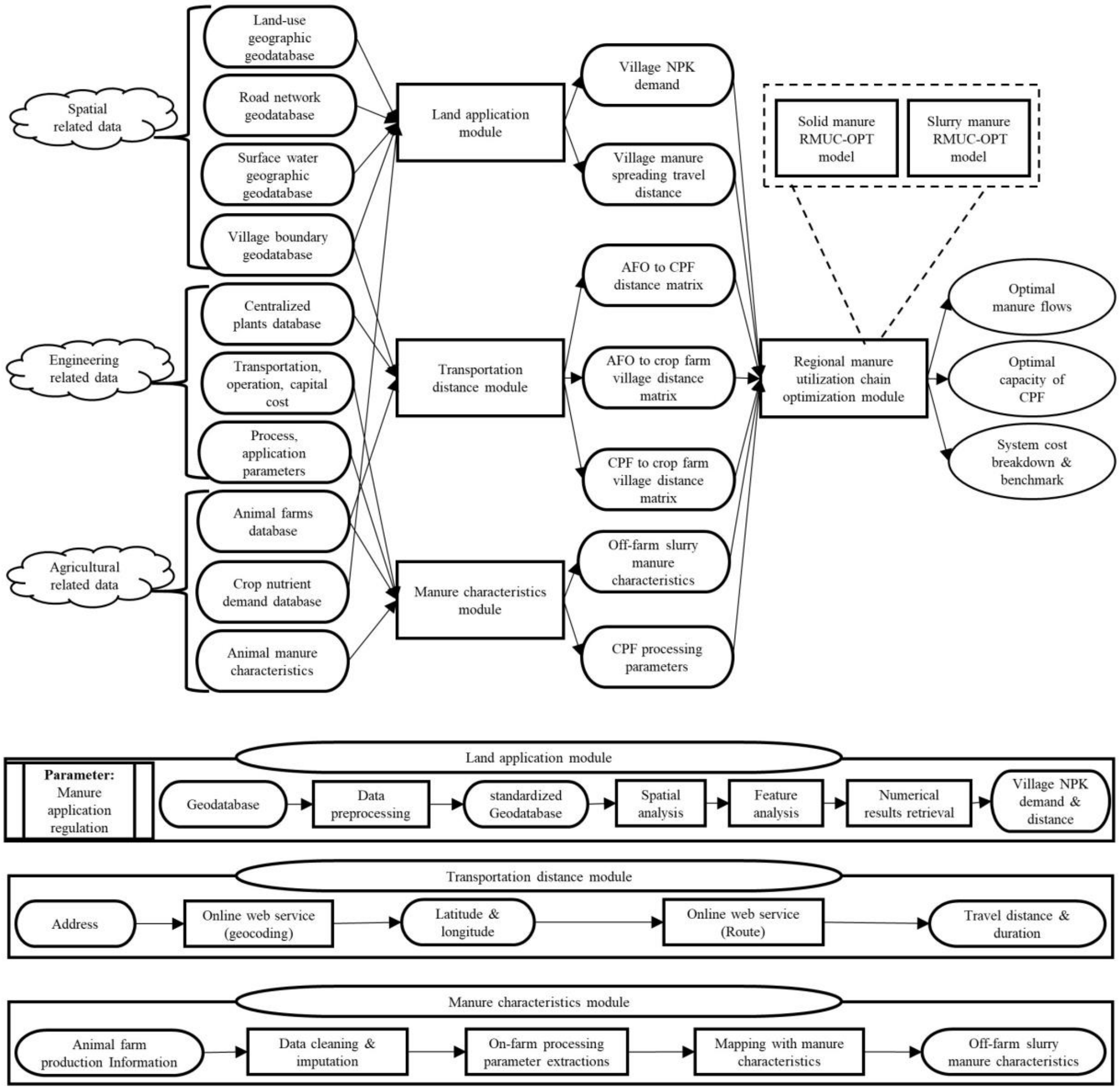


Figure 4.3. The components of the regional manure utilization chain (RMUC) model and the data flow.

4.2.3 Solid manure RMUC-OPT model

The optimization model objective is to minimize the total cost composed of solid manure logistics, solid manure processing, excessive solid manure penalty, and opportunity costs (Equation 4.1). The decision variable related to the objective function is the amount of solid manure flow from AFOs to CPFs (XDs) and the processing capacity of solid manure at candidate

CPF sites (*CAPs*). The inputs determined by the users include AFO solid manure (*ASs*), current solid manure processing capacities at candidate CPF sites (*caps*), and distance matrices from AFOs to CPFs (*DMSP*). Transportation costs are a function of both variable and fixed costs. Variable costs reflect transportation costs associated with distances, which are a function of unit variable cost (*Ctvs*), the amount of manure, and the transportation distance. Fixed cost does not vary with transportation distance and is a function of unit fixed cost (*Ctfs*) and amount of manure, which includes loading and unloading costs. The solid manure processing cost is linearly dependent on unit operational cost (*Cops*) and solid manure processing capacity. Two equality constraints (h_1 and h_2) guarantee all solid manure from AFOs is adequately collected by CPFs.

Moreover, the decisions associated with expanding or reducing the processing capacity at each facility site will result in penalty cost or opportunity cost (f_d, Equation 4.4). The excessive manure penalty cost is the additional annualized capital cost for the manure exceeding the current capacity (*Ccs*: annualized unit capital cost). The opportunity cost is the loss of potential gain if the optimal solid manure processing capacity is lower than the current capacity. This value is estimated from unit revenue (*Rs*), unit operational cost (*Cops*), and the difference between the optimal solid manure process capacity and current manure processing capacity.

$$\begin{gathered}
\underset{i,d}{Min} \sum_i \sum_d (Ctfs + Ctvs \times DMSP_{id}) XDs_{id} + \sum_d CopsCAPs_d \\
+ \sum_d f_d (CAPs_d, caps_d) \\
s.t. \\
h_1 : \sum_d XDs_{id} = ASs_i \\
h_2 : \sum_i XDs_{id} = CAPs_d \\
g_1 : CAPs_d \geq 0 \\
g_2 : XDs_d \geq 0
\end{gathered} \tag{4.1}$$

$$Rs = r_{OF} CF_{OF} \tag{4.2}$$

$$Copps = Rs - Cops \tag{4.3}$$

$$f_d = Ccs\max(CAPs_d - caps_d, 0) - Copps\min(CAPs_d - caps_d, 0) \tag{4.4}$$

4.2.3 Slurry manure RMUC-OPT model

The optimization of the slurry manure utilization chain uses the sequential optimization approach based on the analytic target cascading structure (ATC), which includes three modules as shown in Figure 4.4. The CPF location module is the upper-level module, which simulates CPF locations and capacities in the decision-making process. The AFO logistics optimization module is a lower-level module and optimizes the optimal slurry manure flows for each AFO. The CPF logistics optimization module is a lower-level module and simulates the optimal flows of liquid effluents. The analysis module summarizes the characteristics of the influent slurry manure for each CPF and calculates operational parameters and economic parameters for each CPF based on the collected influents. Given the input data sets and parameters, the first step is to run the AFO optimization logistics modules without capacity constraints. The crop nutrient demands, available croplands, and manure collection costs are updated to the upper-level module (CPF location module). Slurry manure processing amounts are sent to the upper-level modules (CPF logistics optimization module). The CPF logistics optimization module optimizes liquid fertilizer distributions and sends the cost factors to the upper-level module. The CPF location module takes the lower-level module responses and optimizes the locations and capacities of all given CPF sites. Then, the optimal decisions serve as the capacity constraints of the AFO logistics module for another iteration. The iterations continue until convergence is reached, which is the optimal capacities for all given CPF sites.

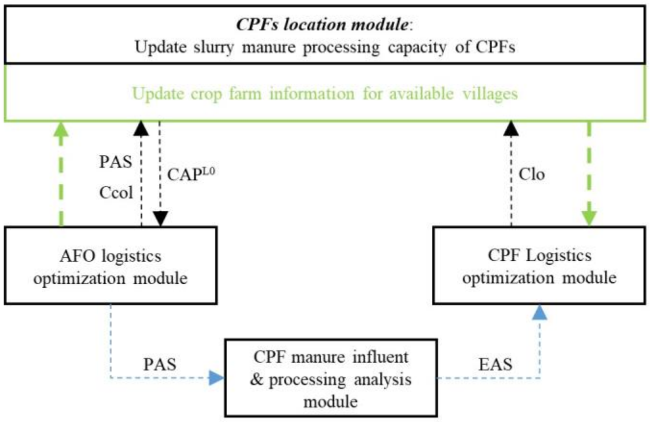


Figure 4.4. Analytic target cascading (ATC) structure of Slurry manure RMUC-OPT model.

The ATC was used to build a slurry manure RMUC-OPT model, which is the system design approach that enables a top-level design target to be cascaded down to lower levels of the modeling hierarchy (Kim, 2001). The ATC structure can simulate the decision-making process regarding the strategic-level and tactic-level decisions. Meanwhile, this structure maintains the feasibility of each submodule and optimizes the problem in a collaborative way. The multilevel optimization methods have been well studied and are applied in many large-scale industrial systematic optimization problems, such as aero-elastic optimization and smart grid design (Chell et al., 2019).

- CPF location module

The CPF location model is the upper-level module. The objective is to minimize the total facility cost composed of operational, manure collection, waste treatment, and liquid fertilizer distribution costs. Slurry manure availability (*PAS*) and unit collection cost (*Ccol*) are the responses of the AFO logistics optimization module. Unit CPF distribution cost (*Clo*), unit processing cost (*Copl*), and unit opportunity cost (*Coppl*) are the responses from the CPF logistics optimization module. The decision variables (CAP^{L0}) associated with expanding or reducing current capacities (*capl*) at each facility site result in a penalty charge or opportunity cost. The excessive manure penalty cost is the additional cost of the manure exceeding the current capacity (*Ccl*: the unit cost of processing excessive slurry manure). The opportunity cost is the loss of potential gain if the optimal slurry manure processing capacity is lower than the current capacity.

$$
\begin{gathered}
\underset{d}{Min} \sum_{d} [(Clo_d + Copl_d + Ccol_d) CAP_d^{L0} + Ccl \max(CAP_d^{L0} - capl_d, 0) - Coppl_d \min(CAP_d^{L0} - capl_d, 0)] \\
s.t. \\
h_1 : CAP_d^{LB} = \min(PAS_d, capl_d) \\
h_2 : CAP_d^{UB} = \max(PAS_d, capl_d) \\
g_1 : CAP_d^{LB} \leq CAP_d^{L0} \leq CAP_d^{UB} \\
g_2 : \sum\nolimits_d CAP_d^{L0} \leq \sum\nolimits_d PAS_d
\end{gathered}
\tag{4.5}
$$

- AFO logistics optimization module

The AFO logistics optimization model objective is to minimize the logistics cost of slurry manure from AFOs to crop farm villages and to CPFs. The decision variables related to AFO slurry manure transportation costs are the amount of slurry manure going to the crop-farming village (*XJ*) and to CPFs (*XD*). Slurry manure availability (*AS*), the transportation distance matrix (*DMSC* and *DMSP*), distance for manure spreading in the crop-farming village (*DS*), and the nutrient demands of crop farms (*CND*, *CPD*) are the inputs of the module. The equality constraints (h_1) guarantees that all slurry manure from AFOs is adequately shipped to CPFs or crop-farming villages. The control constraint (g_1) ensures the slurry manure shipped to CPFs is less than the capacity that is optimized at the upper-level module (CAP^{L0}). Since nutrient requirements at each crop-farming village are different, the nutrients supply (N and P) to the crop-farming villages should be limited to the nutrient demands (g_2 and g_3). The parameters of nutrient loss during manure application (ε_N, ε_P) are the values from a reference (Hutchings et al., 2013). The unit manure collection cost (*Ccol*) of each CPF equals the total manure collection cost divided by the amount of collected manure.

$$\begin{gathered}
\underset{i,k,d,j}{Min}\sum_{i}\sum_{j}\sum_{k=1,2}[Ctfl+Ctvl\times(DMSC_{ij}+DS_{j})]XJ_{kij}+\sum_{i}\sum_{d}\sum_{k=1,2}(Ctfl+Ctvl\times DMSP_{id})XD_{kid}\\
s.t.\\
h_{1}:\sum_{j}XJ_{kij}+\sum_{d}XD_{kid}=AS_{ik}\\
g_{1}:\sum_{k}\sum_{i}XD_{kid}\leq CAP_{d}^{L0}\\
g_{2}:0.01\times(1-\varepsilon_{N})\sum_{i}\sum_{k}NC_{ik}XJ_{kij}\leq CND_{j}\\
g_{3}:0.01\times(1-\varepsilon_{p})\sum_{i}\sum_{k}PC_{ik}XJ_{kij}\leq CPD_{j}
\end{gathered}\tag{4.6}$$

$$Ccol_{d}=\frac{\sum_{i}\sum_{k=1,2}(Ctfl+Ctvl\times DMSP_{id})XD_{kid}}{\sum_{i}\sum_{k=1,2}XD_{kid}}\tag{4.7}$$

- CPF manure influent & processing analysis module

The CPFs were expected to store, handle, and process manure for pre-determined fertilizer or energy products in order to provide a consistent format and reduce logistics challenges. A classic CPF treatment, as shown in Figure C.1, was used in this study. The component flows from AFOs to CPFs, such as mass flows (*PAS*), total solid content (*PSTC*), total volatile solid content (*PSVC*), total nitrogen content (*PNC*), and total phosphorus content (*PPC*) will be calculated by analysis module (Equations C.1 to C.6). A biogas production factor (*GF*) and effluent nutrient contents (*EAS, ENC, EPC*) were estimated based on the operational parameters and nutrient partitions (Figure C.2), which were described in the literature (Moller et al., 2007a; Suresh et al., 2009; Hutchings et al., 2013). The local crop farms will use the liquid effluent of CPFs. The unit processing cost and the opportunity cost of CPFs (*Ccopl*, *Coppl*) are calculated by equations C.11 to C.13.

- CPF logistics optimization module

Similar to the AFO logistics optimization module, the decision variables related to liquid effluents of CPFs are the amount of liquid fertilizer to crop farm village (*XJD*) and the amount of slurry manure processed by the waste treatment plant (*XPD*). Model inputs include the transportation distance matrix (*DMPC*), manure spreading distance matrix (*DS*), and the nutrient demands of crop farms (*CND*, *CPD*). The equality constraint (h_1) guarantees all liquid digestate from CPFs are adequately used by crops, and unused portions presenting certain pollution risks will be treated at the wastewater treatment process. Since nutrient requirements at each crop-farming village are different, the supply of the nutrients to the crop-farming villages should be limited to the nutrient demands based on the agronomic standards (g_1 and g_2). Unit CPF distribution costs (*Clo*) of each CPF equals to the total manure utilization cost divided by the effluents.

$$\begin{gathered}
\underset{d,j}{Min}\sum_d\sum_j[Ctfl+Ctvl(DMPC_{dj}+DS_j)]XJD_{jd}+\sum_d Co_{waste}XPD_d \\
s.t. \\
h_1:\sum_j XJD_{jd}+XPD_d=DAS_d \\
g_1:0.01\times(1-\varepsilon_N)\sum_d DNC_d XJD_{jd}\le CND_j \\
g_2:0.01\times(1-\varepsilon_P)\sum_d DPC_d XJD_{jd}\le CPD_j
\end{gathered} \tag{4.8}$$

$$Clo_d=\frac{\sum_j[Ctfl+Ctvl(DMPC_{dj}+DS_j)]XJD_{jd}+Co_{waste}XPD_d}{EAS_d} \tag{4.9}$$

4.2.4 Case study in Hangzhou, China

The Hangzhou metropolitan area, the capital of Zhejiang province in China, is about 16,596 km^2 and has a population of over 20 million, as shown in Figure 4.5. The landscape of Hangzhou is characterized by mountainous topography, where over 65% of the total area is hills and mountains, 8% of the area is water bodies, and plains account for 26.4% (Qiu et al., 2017). An overlay analysis between the standard criteria maps in Table A.1 indicated that the village with arable lands and forest lands account for 63% of all towns in the Hangzhou metropolitan area, and all of them have surface waters, such as river, lakes, and wells. The major crops in this area are rice, corn, wheat, tubers, and soybean, which account for 16% of the total area. Hangzhou also has a large production of fruit and tea. The common fruits are citrus, pears, peaches, red bayberry, persimmons, and grapes that accounts for 2.5% of the total area. Some other agricultural products, such as vegetables, bamboo, and mulberry, take up 0.8% of the whole area (Zhejiang Bureau of Statistics, 2019). The available area for manure application is only a small portion of total lands because of the geological conditions, environment, and social concerns. Most arable lands that are along the river or lakes were developed for agriculture purposes, such as rice farming and fishery. The arable lands have easier access to the water source, and the nutrients are more likely to pollute the Qiantang river system, which is the largest river in Zhejiang province and passes through Hangzhou metropolitan area (Huang et al., 2010)

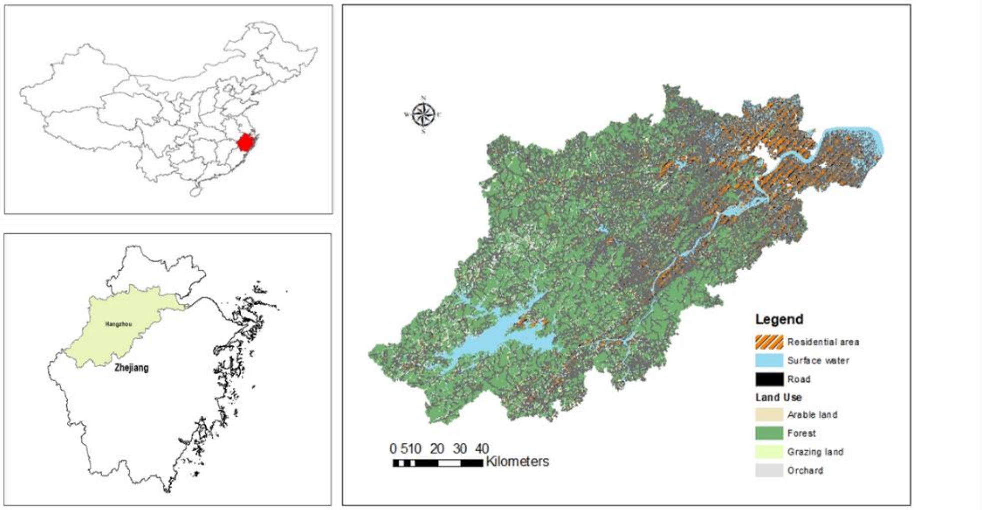


Figure 4.5. Location map of the study area.

Based on the information from the Animal Husbandry and Veterinary Bureau of Hangzhou, there are 822 AFOs and 32 CPFs in the Hangzhou metropolitan area. Over the past few decades, the animal production industry in Hangzhou has significantly increased due to market growth and the improvement of nutrients, housing, and mechanics in animal husbandry. As shown in Figure 4.6, most livestock farms, especially for swine, sheep, and cattle farms, are still small-scale or medium-scale. Poultry industry grows rapidly, and some farms have changed to large-scale. The livestock and poultry farms are sparsely distributed in Hangzhou. The annual manure production is 3.2 million tons (liquid and slurry: 2.4 million tons; solid manure: 0.75 million tons). The slurry manure production from swine and dairy farms accounts for 89% of total slurry manure production in Hangzhou, as shown in Figure C3.

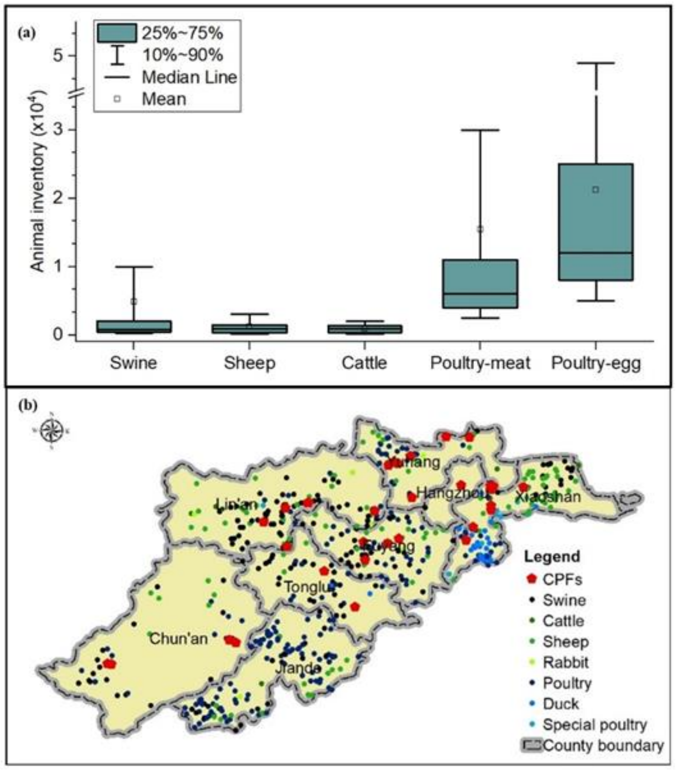


Figure 4.6. Animal inventory statistics (a) and location of animal farms and centralized manure processing facilities (b) in Hangzhou, China.

Hangzhou has 30 certified manure specific CPFs and two waste treatment facilities. Among 32 certified CPFs, 19 CPFs that can convert solid manure into organic fertilizer, and 18 CPFs that could process slurry manure. The current manure processing capacity of CPFs is 1.46 million tons (M-FP: 0.75 million tons, M-EP: 0.71 million tons). 5 CPFs have processing capacity for both solid manure and slurry manure. 2 CPFs have the waste treatment capacity to annually process a total of 95 million tons of liquid manure for irrigation water. The solid manure processing capacities of CPFs are commensurate with the solid manure production of animal farms. However, only 30% of slurry manure can be processed by CPFs (Hangzhou Bureau of Agriculture, 2018). The local regulation prohibits the direct land-application of raw manure. Slurry manure generated from AFOs in Hangzhou is produced, collected, processed, and stored at their farms for a period. In most cases, the procurement cost of slurry manure is zero or negligible. If the land application cost and logistics cost exceed the nutrient values for slurry manure, slurry manure would be recognized as a costly waste instead of a valuable fertilizer for both AFOs and CPFs.

4.3 Scenario analyses

To illustrate the use of the RMUC model, a manure utilization chain in Hangzhou was chosen as a baseline scenario. In Hangzhou, the available lands for manure fertilizer application are classified and summarized (unit: administrative village) into four classes: arable land, forest land, grazing land, and orchards. Most villages are distributed between the valley of mountains and hills. Currently, manure application practices suggest that tank trucks carry the liquid manure fertilizer, get to the target arable lands or orchards, and spread liquid fertilizer by pressurized guns along the roads and trails. Commercial orchards can store liquid manure fertilizer. Only the arable lands on the roadside can use liquid manure products because of a lack of infrastructure and no large equipment access. The baseline case was to analyze the manure utilization infrastructures and calculate the utilization cost for current solid manure utilization and slurry manure utilization. In addition to the baseline, the sensitivity analysis was conducted to illustrate how manure utilization cost changed with the economic parameters.

The RMUC model was also applied to evaluate the current manure utilization chain in Hangzhou. A scenario analysis was conducted to allow the solid manure from AFOs to be shipped to the closest CPFs without capacity constraints. A scenario analysis was also conducted to assess the impact of a setback policy change on the configuration of slurry manure utilization chain. The manure application setbacks of Illinois (USA) were compared as the initial trial for policymaking.

4.4 Results and discussion

4.4.1 Baseline scenario in Hangzhou, China

To understand the manure utilization chain configuration, the logistics of both solid manure and slurry manure utilization were optimized by the RMUC model. The solid manure processing capacities range from 7,000 tons/year to 140,000 tons/year. The optimal logistics cost was CNY 20/ton, and the average transportation distance was 40 km for solid manure. The solid manure collection distance for CPFs varies from 5 km to 89 km. As shown in Figure 4.7(a), some CPFs with high procurement demands had to collect the solid manure across the district boundary for the CPFs. The logistics expenditure accounts for up to 12% of the total cost. Especially in the Jiande district, many AFOs were generating solid manure, but none of the CPFs were in this district or close to the district border, thus requiring allocation of the CPFs to reduce the logistics cost.

Slurry manure utilization involves land application stages. In theory, any lands covered by crops can utilize manure fertilizers. However, the available area for manure application is only a small portion of total lands because of the geological conditions, environment, and social concerns. For slurry manure, the optimal utilization cost was CNY 25.4/ton, and the average travel distance (from supply to end-users) was 15.7 km. The results indicated that 11 CPFs should reduce their capacity, 3 CPFs needed waste treatment process, and the manure processing capacity ranged from 778 tons/year to 301,000 tons/year. As shown in Figure 6(b), 82% of AFOs applied 68% of manure fertilizer in nearby villages. Among 2,050 villages with different crop growth, 78% of villages followed the phosphorus-limited manure applications, and 22% of villages followed the nitrogen-limited manure application. The average liquid fertilizer and CPF effluent usage for a single village was 1089 tons.

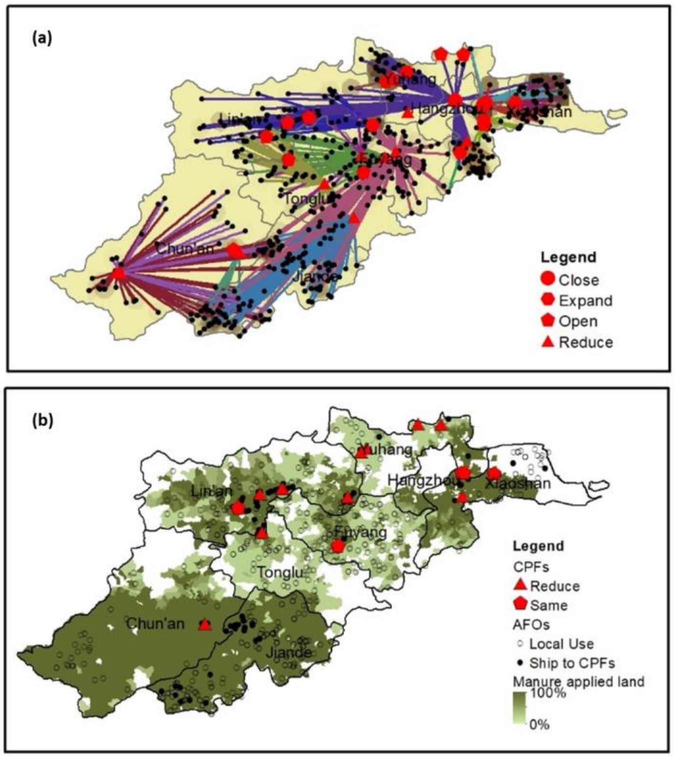


Figure 4.7. The optimal manure supply-chain configuration with (a) solid manure business (Background color represents the solid manure production density) (b) liquid manure business.

4.4.2 Sensitivity analysis of economic parameters

The sensitivity analysis results quantify changes in each economic parameter based on the optimal manure utilization cost while others are kept at the same constant level. The results indicate that the variable transportation cost had the most significant impact on solid and slurry manure utilization costs. Increasing or decreasing 10% of variable transportation costs would increase or decrease the solid manure logistics costs by 8%. As shown in Figure 4.8, a 10%

increase in variable transportation cost would increase unit utilization cost by 4%. The processing cost of slurry manure ($Cops$, Co_{AD}) had much more impact on unit utilization cost. However, the results showed that a 10% variation in processing cost would not affect the slurry manure utilization chain configuration. The optimal results are more sensitive to some parameters, such as variable transportation cost, capital costs, and treatment costs. For example, increasing or decreasing the treatment cost by 10% would result in 3% less or more slurry manure be processed by treatment instead of shipping to the crop fields.

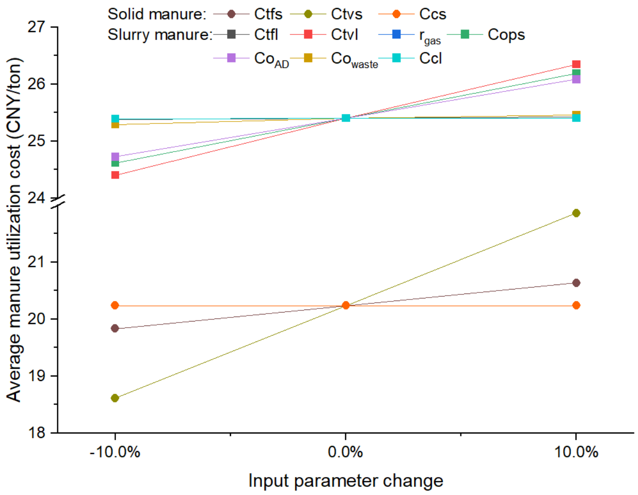


Figure 4.8. Global sensitivity analysis of slurry manure utilization chain optimization at baseline scenario.

4.3.3 Scenario analysis of CPF solid manure capacity

The candidate locations of CPFs were fixed while the solid manure processing capacity limit was relaxed compared with the baseline scenario. There were 30 CPFs involved in solid manure utilization, and their capacities ranged from 240 tons/year to 214,000 tons/year. Solid manure was shipped to the nearest CPFs. The average transportation cost of solid manure was CNY 8/ton, and the average manure collection distance was 20 km. As shown in Figure 4.9, compared to CPF capacities in the baseline scenario, 5 CPFs were selected for expanding processing capacities; 12 CPFs were selected for reducing processing capacities; 2 CPFs that didn't have location advantages should be closed; 11 CPFs that didn’t have solid manure processing operations in the past were selected for servicing the neighbor animal farms.

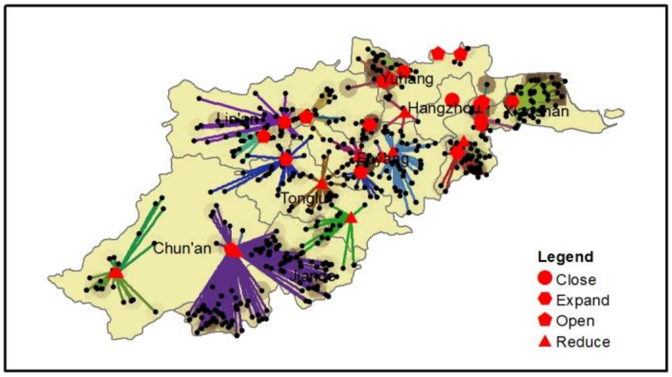


Figure 4.9. The optimal solid-manure supply-chain configuration with relaxed solid processing capacity constant capd=0 at Eq. 4.1. Colored lines represent the AFOs that are severed by CPFs. Background color represents the solid manure production density.

4.4.4 Scenario analysis of the manure application setbacks on slurry manure utilization

Hangzhou has policies for AFO locations but lacks land application restrictions. Regarding the environmental concerns, over 50% of arable lands are within range of surface water boundary less than 90 m away. To quantify the impact of land application, the impact of the manure application setbacks of Illinois (USA) was evaluated, which restricts the distance for land application of manure to down-gradient surface water is 200 feet (~60m); Within a quarter mile (400 m) of a residence, fertilizer must be injected or incorporated (Illinois Environmental Protection Agency, 2003). In this study, we assumed the setback distance to the residential area (400 m) and to the surface water (60 m) with current manure application practices (Illinois Environmental Protection Agency, 2003). The land suitability analysis indicates only 7.4% of arable lands and 24.5% of operated orchards are available for manure application under this restriction.

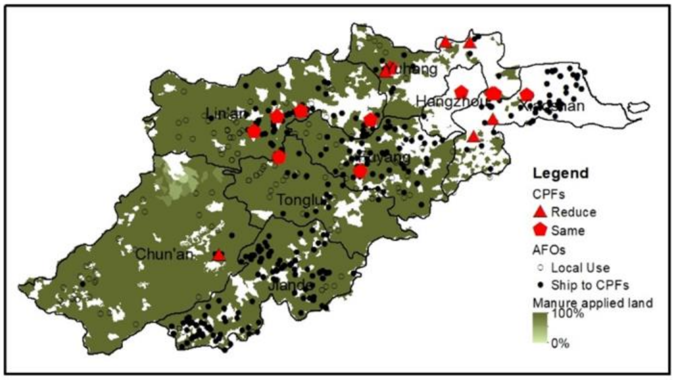


Figure 4.10. The optimal configuration of slurry manure utilization chain at Illinois manure application setbacks.

In general, land application restrictions suggest that less land is available for manure application, and more farming villages and CPFs would become involved in slurry manure utilization. As shown in Figure 4.11, the percentages of slurry manure applied to the villages nearby AFOs were reduced from 68% to 14%, and the percentage of slurry manure that was processed by CPFs increased from 32% to 86%. With land application restriction, 7 CPFs should reduce their capacity, all CPFs need a treatment process, and the manure processing capacity ranged from 621 tons/year to 1,250,000 tons/year. The optimal results suggested that the application policy significantly impacted slurry utilization patterns in the southeast districts. Over 98% of villages that had available lands were full capacity. The treatment process processed around 80% of the manure. The optimal results suggested more and larger CPFs process the excessive manure under the Illinois land application policies. In the Xiaoshan district, most arable lands were not suitable due to open water setback restrictions. Most of the slurry manure was converted to irrigation water instead of liquid fertilizer.

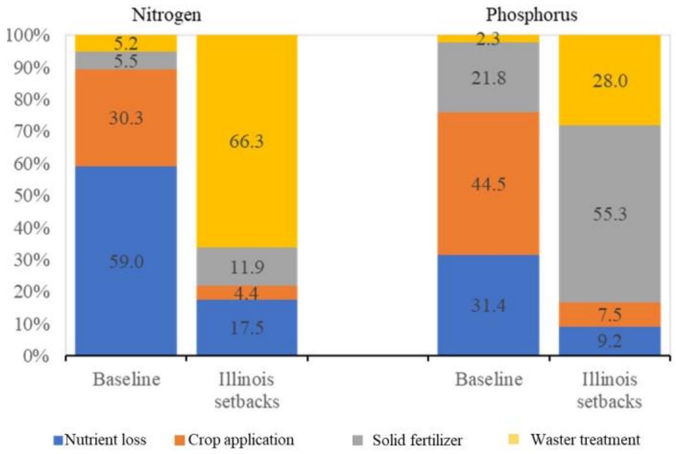


Figure 4.11. The fate of animal manure nitrogen and phosphorus input.

The manure nutrient utilization pattern for the scenario using Illinois land application policy was very different from the baseline scenario utilization pattern. The nitrogen and phosphorus losses included gas emissions during manure utilization and runoff during the land application, respectively (Oenema et al., 2007; Hutchings et al., 2013). Considering the Illinois land application policy, less nitrogen and phosphorus were released to the environment because of reduced land application practices. The baseline scenario had better nitrogen and phosphorous efficiency when compared to the scenario with the Illinois land application policy. As shown in Table 1, the baseline scenario's nutrient value was 60% higher than the value of the scenario with the Illinois land application policy. More nitrogen was removed by treatment, and more phosphorous was exported to other agricultural production systems as solid fertilizer in the scenario with Illinois land application setbacks. The land application setbacks reduced the environmental capacity of nitrogen and phosphorus. The treatment process removed the excess nitrogen and phosphorus from the local agricultural production system. In other words, the deterministic factor for the manure management to be effective "nutrient utilization" or to be "waste treatment" was not the intensive manure production criteria but rather the manure land application.

Table 4.1. A breakdown of slurry manure utilization costs with and without land application setbacks.

	Baseline scenario		With land application policy	
	Total cost (Million CNY)	Average (CNY per ton)	Total cost (Million CNY)	Average (CNY per ton)
CAFO local use	11.3	6.9	4.8	14.2
CAFO to CPFs	6.5	8.4	32	15.4
CPFs processing	35.3	49.6	87.2	45.5
CPFs local use	6.2	10.2	0.0085	7.8
CPFs treatment	2	18	34.5	18
Average utilization cost	61.3	25.4	158.5	65.8
NP utilization value*	13.7	-	8.5	-

* Nitrogen (P_N) and phosphorus (P_P) that is used by crops or concentrated into a solid fertilizer.

The total utilization cost of applying manure land application policy was 2.59 times greater than the total cost at the baseline. The optimal results (Table 4.1) showed that the average cost for AFO local manure utilization was increased from CNY 6.9/ton to CNY 14.2/ton. The average cost for CPFs collection was increased from CNY 8.4/ton to CNY 15.4/ton. The average travel distance (from supply to end-users) for slurry manure was decreased from 15.7 km/ton to 4.3 km/ton. The savings of total CPF expenditure outweighed the increased transportation cost, which suggested the utilization pattern that was mainly a "centralized strategy" instead of an "individual-farm strategy."

4.4 Conclusions

A regional manure utilization chain (RMUC) model was developed to minimize the animal manure utilization cost by selecting the optimal decisions of manure transported between animal feeding operations (AFOs), centralized manure processing facilities (CPFs), and crop farming villages. This research assumed that the essential nutrients (N, P) for such a system will be either utilized or treated, but they will not be disposed of without utilization. A case study for Hangzhou China was presented, which intended to demonstrate how this approach benefits decision-making with a modeling strategy for assessing current configuration and analyzing the impact of policy changes to the regional agricultural production.

he baseline case was set to the current economic parameters, animal production levels, and manure utilization configurations. The optimal results indicated that the average solid manure logistics cost was CNY 20/ton, and the average transportation distance was 40 km. The average slurry manure utilization cost was CNY 25.4/ton, CPFs process and reallocate 32 % of slurry manure, and the average travel distance was 15.7 km. The total slurry manure utilization cost for Hangzhou was CNY 61.3 million.

The scenario analysis indicated that the current solid manure CPF configuration had the potential to be improved. Optimizing the solid manure processing capacities of CPFs could reduce 70% of the transportation cost. Optimal solid manure supply chain suggested an increased number of smaller CPFs. The scenario analysis indicated that the current slurry manure utilization pattern could be significantly changed if the manure land application policy was implemented. Considering Illinois manure fertilizer land application restrictions, the total utilization cost of slurry manure would be 2.59 times the total cost for the baseline scenario. Around 53% of AFOs will change from individual manure management patterns to centralized manure management patterns. The regional slurry manure management should be better described as "waste management" instead of "nutrient management".

Based on the analysis results mentioned above, the Hangzhou *Ecological Plan* with respect to manure management can be adapted to present more precise strategies that can balance the development of animal husbandry and environmental protection at a lower cost. In fact, the production cost of organic fertilizer in Hangzhou is relatively high compared to the average cost in China. The government is providing subsidies to some CPFs to collect and process the slurry manure. In the RMUC models, the constraints guaranteed that the application of both nitrogen and phosphorus be less than the nutrient requirement of crops. The estimation of manure utilization cost can be used as evidence to determine the economic support that would help AFOs and CPFs use manure in a sustainable way.

CHAPTER 5: QUANTIFY THE IMPACTS OF POTENTIAL STRATEGIES TO SUSTAINABLE ANIMAL MANURE UTILIZATION CHAIN IN HANGZHOU, CHINA

5.1 Introduction

The sustainability of animal manure production and utilization has been receiving a growing attention in recent years. However, most stakeholders still prefer cost-effective or operation-simple improvement practices. Large AFOs could either increase the lands to apply manure, or improve manure treatment to reduce the pollution risks, or ship the excessive manure to other facilities when they violate the environment regulations (Keplinger and Hauck, 2006; Wesnæs et al., 2009). This manner might solve the single farm problem but could not work between different units of manure utilization chain. The operational research and logistics optimization communicate different units and propagates the changes to upstream and downstream units in a supply chain. This method was used to find optimal strategic and operational decisions on biomass production, bioenergy production, and management supply chains (Mayerle and de Figueiredo, 2016; Huang et al., 2019; Díaz-Trujillo and Nápoles-Rivera, 2019). We, therefore, reason that some systematic frameworks can guide practitioners and enhance the sustainability trajectories, such as adjusting the diet formula, optimizing manure utilization networks, changing the crop combination (Hutchings et al., 2013; Zhang et al., 2020).

This research proposes an optimization approach to estimate the animal manure utilization chain's optimal configuration under given objectives and conditions. This approach can expose the trade-off and enhancement effects between different units and quantify the impact of the management under a certain level of decisions and constraints. The slurry manure utilization chain optimization (RMUC-OPT) model, including animal farm sites (AFOs), centralized processing facility (CPFs), and crop farms, was developed to minimize the total utilization cost of animal manure in Chapter 4. In this research, greenhouse gas emission has also been incorporated to the manure utilization analysis. The objectives of this study are to (1) develop a multi-objective optimization model to evaluate the regional manure utilization chain configurations by considering both economic and environmental impacts (2) quantify the impacts of some manure management options, and (3) propose the strategies to improve the regional manure management.

5.2 Methodology

5.2.1 Overview of the RMUC-OPT model: Widening the scope

The model used in this study is modified from the slurry-manure RMUC model, which was initially designed for minimizing the total costs of AFOs and CPFs with the analytic target cascading structure(ATC), which enables the top-level design target to be cascaded down to lower levels of the modeling hierarchy (Kim, 2001). This formulation guaranteed the operational-level decisions for AFOs and CPFs are made independent in lower-level modules based on their benefits. The model is extended to optimize both total cost and greenhouse gas emission of regional slurry manure utilization. Unlike the original economic optimization model, the modified slurry-manure RMUC model does not only explore the interactions between individual stakeholders in their pursuit for lower cost but aim at capturing the dynamic of decision changes under the upper-level requirement. As shown in Figure 5.1, The scope of a slurry manure utilization chain to be analyzed includes four major steps: AFO manure distribution, village manure application, CPF manure collection, and CPF manure distribution. This study focuses on manure utilization, which includes both individual farm manure management and centralized manure management in a region. AFOs and CPFs decide their manure utilization patterns based on their local objectives (minimization of manure operational cost) while their decisions are constrained by the greenhouse gas emission target.

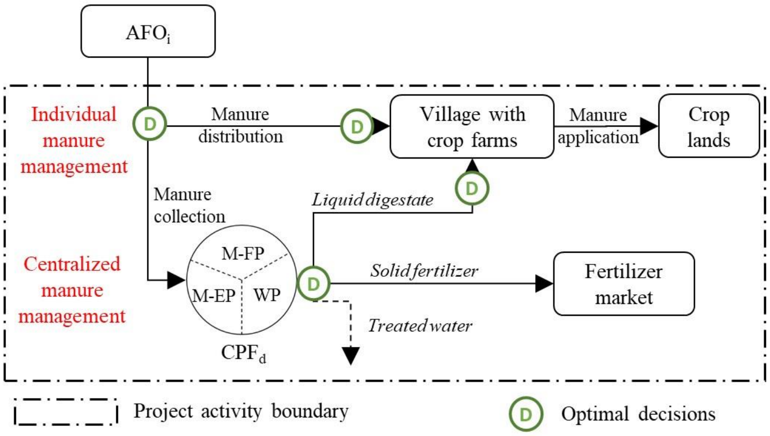


Figure 5.1. System boundaries.

The objective of the upper-level module is updated to minimize the total utilization cost and the total deviation tolerances. Total utilization cost is composed of both slurry manure logistics cost, processing cost, land application cost, and the capital cost to expend CPFs' processing capacity of slurry manure (Eq 5.1). The decision variable related to the upper-level objective function is the amount of slurry manure flow from each AFO (Xc^{L0}) and the slurry manure processing capacity at candidate CPF location (CAP^{L0}). Three lower-level modules (AFO logistics optimization module, CPF manure influent & processing analysis module, CPF logistics optimization module) was used to calculate and update the economic parameters and constraint factors from optimal operation decisions in each iteration.

$$
\begin{gathered}
\underset{i,d}{Min} \sum_i Cuc_i Xc_i^{L0} + \sum_d (Clo_d + Copl_d + Ccol_d) CAP_d^{L0} + \sum_i \varepsilon x_i + \sum_d \varepsilon p_d \\
w.r.t \\
h_1 : \sum_i Xc_i^{L0} + \sum_d CAP_d^{L0} = \sum_i \sum_k AS_{ik} \\
g_1 : Xc_i^{L0} \le \sum_k AS_{ik} \\
g_2 : (Xc_i^{L0} - Xc_i)^2 \le \varepsilon x_i \\
g_3 : (Cap_d^{L0} - PAS_d)^2 \le \varepsilon p_d \\
Xc_i = \sum_j \sum_{k=1,2} XJ_{kij} \\
Cuc_i = \frac{\sum_j \sum_{k=1,2} [Ctfl + Ctvl \times (DMSC_{ij} + DS_j)] XJ_{kij}}{Xc_i}
\end{gathered} \tag{5.1}
$$

The economic parameters from lower-level modules include the unit AFO crop utilization cost (*Cuc*), unit CPF manure collection cost at (*Ccol*), unit CPF manure processing cost (*Copl*), and unit CPF effluent distribution cost (*Clo*). The operational responses from lower-level modules include the amount of slurry manure transported from AFOs to local crop farms (*Xc*) and the amount of slurry manure transported to CPFs from AFOs (*PAS*). The target deviation to tolerance (εx, εp) links the decision variables to the responses from lower-level modules as shown in g_2 and g_3.

5.2.2 Environmental Objective: Minimizing greenhouse gas emissions

The environmental objective is to minimize the total annual CO_2-equivalent GHG emission from the operations of animal manure utilization. The formulation of this objective is based on the life cycle analysis from animal farms, transportation, manure treatment, and land application, which considers the following life cycle:

- Transportation from AFO locations to crop farms (E_{AC}, Eq 5.2)
- Animal manure-fertilizer land application (E_{CF}, Eq 5.9)
- Transportation from AFO locations to CPF locations (E_{AF}, Eq 5.3)

- Emissions from biogas combustion in CPFs (E_B, Eq 5.8)
- Emissions from treatment process in CPFs (E_P, Eq 5.5)
- Emissions from centralized processing and treatment facility (E_W, Eq 5.6)
- Transportation of liquid products from CPFs to crop farms (E_{FC}, Eq 5.4)
- The land application of liquid products from centralized processing facilities (E_{CL}, Eq 5.7)

Transportation-related GHG emissions are a function of unit transportation GHG emissions (*EFt*), the amount of biomass being transported (XJ_{kij}, XD_{kid}, XJD_{jd}), and the transportation distance ($DMSC_{ij}$, $DMSP_{id}$, $DMPC_{dj}$). Transportation from AFO locations to crop farms includes hauling transportation ($DMSC_{ij}$) and the travel of manure applications in the field (DS_j). Unit emission data of the medium-duty vehicle and pipeline transportation are taken from the experiment results and GREET model from literature (You and Wang, 2011; Yang et al., 2018b).

$$E_{AC.i} = \sum_k \sum_j EFt \times DMSC_{ij} \times XJ_{kij} + EFt \times DS_j \times XJ_{kij} \tag{5.2}$$

$$E_{AF.d} = \sum_k \sum_i EFt \times DMSP_{id} \times XD_{kid} \tag{5.3}$$

$$E_{FC.d} = \sum_j EFt \times DMPC_{dj} \times XJD_{jd} \tag{5.4}$$

Manure treatment related to GHG emissions are a function of unit management GHG emissions (*EFp*, *EFpw*, *EFcl*) and the amount of biomass being processed (XPD_d, XJD_{jd}). Given the manure treatment options, the emissions of methane (CH_4), nitrous oxide (N_2O^-), ammonia (NH_3) and nitrate (NO_3^-) from manure treatment, manure storage, and digestate land application contribute to global warming potential were summarized to the function unit of digestate (Rehl and Müller, 2011). The GHG emission of biogas combustion is measured as the emission of CO_2, as shown in Eq. 5.8.

$$E_{P.d} = \sum_j EFp \times XJD_{jd} \tag{5.5}$$

$$E_{W.d} = EFpw \times XPD_d \tag{5.6}$$

$$E_{CL.d} = \sum_j EFcl \times XJD_{jd} \tag{5.7}$$

$$E_{\mathrm{B.d}} = 0.717 \times HRT \times GF_{\mathrm{d}} \times PAS_d \tag{5.8}$$

The GHG emission of manure fertilizer application from animal farms is a function of unit GHG emissions of manure applications from different animal manure ($EFcf_i$) and the amount of biomass being applied (XJ_{kij}). The GHG emissions of animal manure applications were scaled to the functional unit by dividing the total amount of manure. The GHG emissions include emissions of CH_4, direct and indirect emission of N_2O, which were estimated using the standard equations in IPCC version 6 (IPCC, 2006).

$$E_{CF.i} = \sum_k \sum_j EFcf_i \times XJ_{kij} \tag{5.9}$$

$$EFcf_i = \frac{L_i(CH_4) + L_i(N_2O)}{\sum_k AS_{ik}} \tag{5.10}$$

$$L_i(CH_4) = 25 \times N_i \times VS_i \times (Bo_i \times 0.67 \times \frac{MCF_{land}}{100}) \tag{5.11}$$

$$L_i(N_2O) = 298 \times N_i \times \frac{44}{28} \times Nex_i \times (\frac{Os_{leach}}{100} \times EF_{leach} + \frac{Os_{gas}}{100} \times EF_{dep}) \tag{5.12}$$

Where methane emissions depend on the number of livestock inventory (N_i), amount of nitrogen extraction (Nex_i), volatile solids excreted (VS_i), the maximum methane-producing capacity (BO_i), and the methane conversion factor (MCF_{land}) as shown in Table D.1. Direct and indirect N_2O emissions from cropland account the direct emission of N_2O-N (EF_3 = 0 for manure spreading), amount of N_2O-N from atmospheric deposition of nitrogen volatilization, the amount of N_2O-N from nitrogen leaching and runoff. The global warming potential (GWP) conversion parameter CH_4 is 25, and N_2O is 298 over 100 years.

The economic and GHG emission benefits were calculated from the nitrogen, phosphorus, and potassium intake by crops to show the value of the manure fertilizer and AD digestate in terms of the synthetic chemical fertilizers. The unit prices of synthetic chemical fertilizers are taken from a local survey. The unit GHG emissions of synthetic chemical fertilizers included manufacture, storage, transport, and application and were obtained from the Chinese Life Cycle Database (Wang et al., 2017b).

$$\begin{aligned} B_{value} &= \sum_k \sum_i \sum_j [p_N(1-\varepsilon_N)NC_{ik} + p_P(1-\varepsilon_P)PC_{ik} + p_K(1-\varepsilon_K)KC_{ik}]XJ_{kij} \\ &+ \sum_d \sum_j [p_N(1-\varepsilon_N)ENC_d + p_P(1-\varepsilon_P)EPC_d + p_K(1-\varepsilon_K)EKC_d]XJD_{jd} \end{aligned} \tag{5.13}$$

$$\begin{aligned} B_{GHG} &= \sum_k \sum_i \sum_j [credit_N(1-\varepsilon_N)NC_{ik} + credit_P(1-\varepsilon_P)PC_{ik} + credit_K(1-\varepsilon_K)KC_{ik}]XJ_{kij} \\ &+ \sum_d \sum_j [credit_N(1-\varepsilon_N)ENC_d + credit_P(1-\varepsilon_P)EPC_d + credit_K(1-\varepsilon_K)EKC_d]XJD_{jd} \end{aligned} \tag{5.14}$$

5.2.3 Multi-objective optimization

The ε-constraint method is used to optimize the economic and environmental performance of the manure utilization chain. The first step of the ε-constraint method is to determine the optimal lower and upper bounds of the annual CO_2-equivalent GHG emission. The upper bound is obtained by solving the single economic optimization model (Eq. 5.15). The lower bound is obtained by replacing the economic objective function with the GHG emission objective functions.

$$\underset{i,d}{Min} \sum_i Euc_i Xc_i^{L0} + \sum_d Euf_d CAP_d^{L0} \tag{5.15}$$

$$Euc_i = \frac{E_{AC.i} + E_{CF.i}}{\sum_j \sum_k XJ_{kij}} \tag{5.16}$$

$$Euf_d = \frac{E_{AF.d} + E_{P.d} + E_{W.d} + E_{CL.d} + E_{B.d}}{PAS_d} \tag{5.17}$$

The GHG emission parameters include the unit AFO crop utilization emission (*Euc*), unit CPF manure utilization emission (*Euf*), which are derived from the estimation of lower-level modules regarding the operational plans. Then, the range between the upper and lower bound is divided into 19 identical intervals (20 breakpoints). The total economic cost is minimized under additional constraint (g_4) that the GHG emission should not exceed the breakpoint (ε_{GHG}). A set of Pareto optimal solutions are generated to evaluate the degree of optimality.

$$g_4 : \sum_i Euc_i Xc_i^{L0} + \sum_d Euf_d CAP_d^{L0} \le \varepsilon_{GHG} \tag{5.18}$$

5.3 Case study of manure utilization in Hangzhou

5.3.1 Baseline case

In the past few decades, the animal production industry has significantly increased in Hangzhou, China, due to market growth and breeding technology improvement. The structure of animal farms is changing from family-scale to large-scale. Since 2014, a large number of existing large-scale livestock farms located at the breeding reduction or prohibition zone were closed for environmental protection purposes (Qiu et al., 2017). However, the policy reduced the self-sufficiency in food animal production. Many scientists suggested that the trade-offs between food security and environmental protection could be optimized through holistic planning and integrated manner considering different constraints (Bai et al., 2019b).

A base case was implemented with 666 AFOs and 32 CPFs in Hangzhou metropolitan area. As shown in Figure 5.2(a), the annual slurry manure production is 2.4 million tons. The current slurry manure processing capacity of CPFs is 1.46 million tons (additional waste treatment: 95 million tons). The applicable manure lands in Hangzhou are classified and summarized (unit:

administrative village) into four classes: arable land, forest, grazing land, and orchard. As shown in Figure 5.2(b), 63% of villages have arable lands and forest lands, but all of them have surface waters, such as rivers, lakes, and wells. Currently, manure application practice is that tank trucks carry the liquid manure fertilizer, get to the target arable lands and orchards, then spread liquid fertilizer to the lands along with roads and trails by pressuring guns. This method was not unsustainable due to eutrophication, odor problem, and sanitation issues. In chapter 4, using the manure application policy like the setback distance restriction, will tremendously increase the utilization cost and reduce the land resources for manure application. The base case proposes an improved setback policy for manure land application that the slurry manure is incorporated into the arable land and orchard instead of surface spreading and is constrained to the land within 60 m of surface water. Such a method can reduce gas emission and nutrient loss.

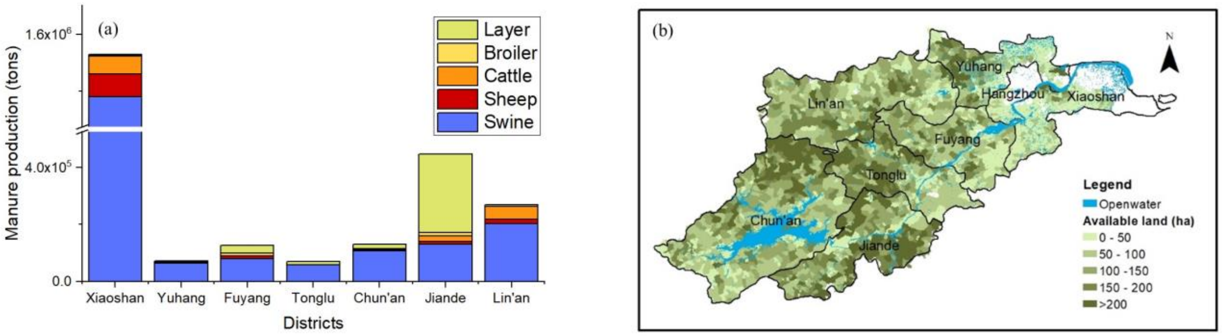


Figure 5.2. The statistic of manure production (a) and land available map (b) in Hangzhou.

5.3.2 Animal production improvement

The structure of livestock farms is changing from family-scale to confined and specialized animal feed operations. As shown in Table 5.1, the production levels of AFOs vary greatly, and the top 10% of livestock farms are on a large scale and have good productivity. Most of the livestock farms, especially for swine farms, goat farms, and dairy farms, are still small-scale with relatively low productivity.

Table 5.1. Summary of animal farm records from Animal Husbandry and Veterinary Bureau of Hangzhou.

Animal Farms	Farm inventory statistics (herds, 10%/median/mean/ 90%)	Sale to inventory ratio statistics (10%/median/mean/ 90%)	Manure production statistics (t/animal, 10%/median/mean/ 90%)	Installation rate of Scraper system/ SL separation (%)
Swine	250/800/5592/10000	1.5/1.75/1.72/2	0.7/1.08/1.12/1.59	81.8/84.4
Sheep	215/1,000/1428/3000	0.4/0.0.8/0.8/1.3	0.22/0.47/0.74/1.5	50.0/53.3
Dairy cow	170/900/913/1580	0.13/0.5/0.49/0.95	17.6/22.5/22.4/26.5	89.0/75.0
Broiler	3000/8000/17636/38000	2/2.7/2.7/4.0	0.006/0.047/0.03/0.047	42.1/42.1
Layer	5000/13500/21867/49100	-/-/-/0.25	0.04/0.07/0.06/0.09	92.7/8.5

The on-farm manure management also varies from farms to farm. The slurry manure production of swine and dairy farms account for 89% of total slurry manure production. Some animal farms prefer to use flushing water to clean the animal barns and remove the manure from the animal area that results in an extra load of manure. The worst 10% of broiler farms generate 7.8 times manure than the median level farms, and the worst 10% of sheep farms produce 6.8 times manure than the median level farms. The failure of water management in those farms caused additional expenditures on manure management.

AFO owners have different opinions about separating solid portion from the slurry manure. Some farms insist that solid/liquid separation is costly and useless in manure utilization. Other AFOs prefer the scraper system and solid/liquid separator to split the nutrient into the liquid and solid portions. An advantage of solid/liquid separation is to make organize fertilizer from solid portion of manure and used elsewhere. The liquid portion of manure has lower nutrient content and can be applied to the crop land. The scenario analyses were conducted to quantify the economic and environmental benefits of manure management improvement.

- A scenario analysis was conducted to assess the impact of solid/liquid separation on manure utilization chain configuration by assuming the slurry manure was not separated into the liquid portion and solid portion.

- A scenario analysis was conducted to quantify the economic and environmental benefits if on-farm wastewater was controlled, and the manure load was reduced to the median level. The manure production level of the AFOs above the median level of the same species was corrected to the median level.

5.3.3 Animal manure composition measurement

A lack of information about manure nutrient contents is one barrier of recycling nutrients to agricultural land. Many organizations and agricultural extension groups recommend a regular analysis of manure samples is necessary to maximize nutrient efficiency and minimize nutrient losses to the environment (Zhu et al., 2004; Marino et al., 2008). However, most planners and AFO owners in Hangzhou use reference numbers or the recommendation factors to determine the application rate. The laboratory tests are not widely recognized by local governments and AFO owners. A scenario analysis was conducted to allow the manure nutrient content from each AFO to vary within specific ranges (10%, 30%, 50%) respectively, while the manure application rate is calculated from the reference numbers. The normal distribution was assumed for each level of variation, and 100 statistic samples (N%, P%) were generated.

5.3.4 Transportation alternatives

The distribution of manure and manure fertilizer involves large logistics activities. The two major modes of transportation are truck and pipeline. The distribution of manure by truck transportation is mainly at low-speed for a long time condition, resulting in lower fuel economy and lower-labor efficiency (Yang et al., 2018b). Many organizations believe electric trucks are more suitable than diesel trucks for local distribution. Another alternative transportation method is portable pipeline pumping, which was used by some farms for short-distance transportation. A scenario analysis was conducted to study how these transportation alternatives affect the GHG emissions and operational cost in the manure utilization chain. Yang et al. (2018b) estimated the total cost and GHG emission factors of commercial diesel trucks and electric trucks in China. In this chapter, we specifically refer to the operational cost and GHG emissions including use of energy (grid-electricity and petroleum diesel), maintenance, labor and battery replacement (electric vehicle only). The plug-in electric vehicle is selected since the manure transportation is not time-sensitive and the vacant time at night can be utilized to charge plug-in electric trucks. There are many studies discussing the pipeline transportation of animal manure (Chen and Hashimoto, 1976; Chen, 1986; Ghafoori and Flynn, 2006) . The operational cost includes pipeline operational cost, pump operational cost, and booster station operation cost (Marufuzzaman et al., 2015). In addition, we assume the operational activities include maintenance and operation of pipeline and pumps since the short-distance transportation of a portable pipeline does not need booster station. Wang et al. (2019) estimated the electricity cost and GHG emission factors of pump operations in China. Ghafoori and Flynn (2006) summarized the breakdown of the operational cost. We assume the portable pipeline pumping is used for the manure and manure fertilizer distribution within a village. The long-distance transportation between AFOs to villages and AFOs to CPFs are operated by diesel vehicles or electric vehicles. The transportation cost is the function of the unit variable transportation cost and unit fix transportation cost. Variable transportation cost is directly proportional to the amount of manure and the transportation distance. Fixed transportation cost is independent of distance traveled, including the loading, and unloading activities. A list of unit costs, emission factors, and parameters were provided in Table D.2.

5.4 Results and discussion

5.4.1 Scenario analysis of baseline case

The Pareto-optimal curves are provided by solving the multi-objective optimization problem at 20 constraint levels of GHG emissions. As shown in Figure 5.3(a), GHG emission objective has conflict with the AFO-related cost and CPF-related cost. Restricted GHG emission constraint (ε_{GHG}) increases the penalty of violating GHG emission constraint (Eq. 5.18), reduces the impacts of target deviation to tolerance (εx, εp), and forces AFO-based decision-making to match the upper-level objectives. In the restricted GHG emission scenario, some AFOs may ship manure to the farther crop-farming villages instead of the closer CPFs since that decision benefits the entire chain as the upper-level module proposed. However, the stricter GHG emissions constraint does not tend to increase the averaged total cost. As shown in Figure 5.3(b), CPFs processed more manure with the relaxed GHG emission constraints. Compared with individual manure management, centralized manure management has higher processing costs and GHG emissions. Without GHG emission constraints, the regional average cost is CNY 23/ton, and the regional average GHG emission is 21.7 kg CO_2 e/ton. CPF-related cost account for a significant portion of the total cost. Although relaxing the GHG emissions constraint (ε_{GHG}) reduced the cost for each AFO and CPF, the utilization cost of the whole chain is higher because of the large quantity of manure processed by CPFs. Target deviations to tolerance (εx, εp) have large impacts on upper-level optimization module. The optimal manure utilization configuration is decided by the AFOs' logistics decision at lower-level module. Such a formulation illustrates how decision-making is shifting from individual interests to regional benefits under GHG emission constraints. Without superior target, the manure management cost is the lowest for each stakeholder. But the global optimal point of entire chain cannot be reached.

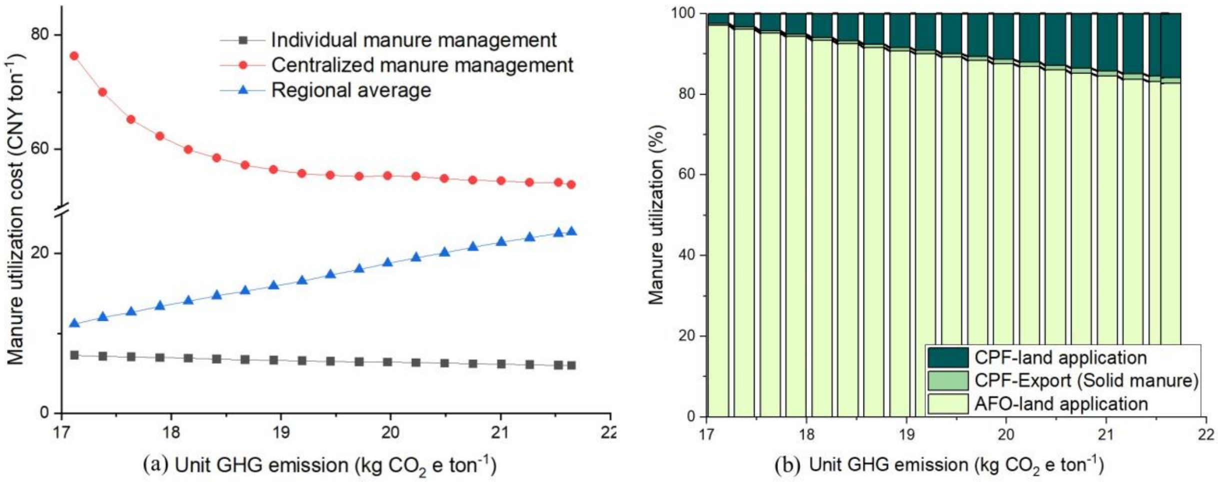


Figure 5.3. Pareto-optimal curves under 20 GHG emissions levels (a) utilization cost (b) breakdown of manure utilization pathways.

The optimal results also indicate the available land in Hangzhou for manure land application is sufficient for current AFOs at proposed setback policy. As shown in Figure 5.3(b), 90% of manure is applied to the crops directly from AFOs when the GHG emission constraints are less than 19 kg CO$_2$ e/ton. The economic benefits (Average: CNY 22/ton) and GHG credits (Average: 3.75 kg CO$_2$ e/ton) for land application remain relatively stable. The percentage of manure applicable land takes around 11% to 12% of the total available lands in different GHG emission scenarios. As shown in Figure 5.3, the northeast district of Hangzhou has various water networks and less available croplands to use manure. The central districts have many villages involved in manure utilization. The southwest districts of Hangzhou are recognized as mountain areas with enough land resources for AFO development. The logistics behaviors change a lot in central districts and northeast districts under relaxed GHG emission constraint ($\varepsilon_{GHG.max}$). The results indicate that some AFOs are very sensitive to transportation distance. The manure in Lin'an district travels around 6 km in restricted GHG emission scenario while travels 3 km in relaxed GHG emission scenario. In other words, the land resources are still not enough in some local communities, which force AFOs to decide further crop farms or nearby CPFs. Among all exist

CPFs under relaxed GHG emission constraints ($\varepsilon_{GHG.max}$), 2 CPFs in the Xiaoshan district process excessive manure and are essential to prevent environmental pollution. 13 CPFs serve for AFOs with lower logistics costs and reduce the risk of pollutions

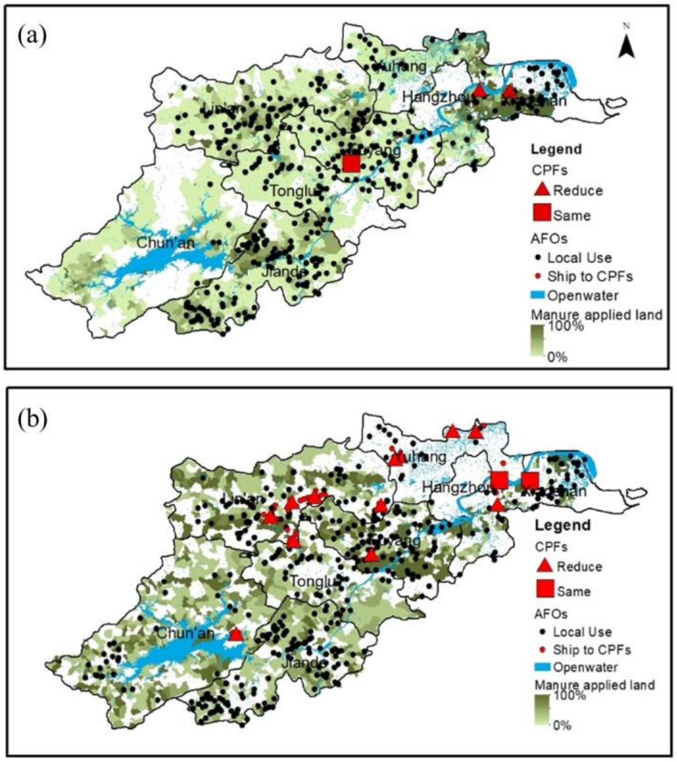


Figure 5.4. The optimal slurry manure supply-chain configuration at (a) $\varepsilon_{GHG.min}$ (b) $\varepsilon_{GHG.max}$.

5.4.2 Scenario analysis of animal production improvement

The large AFOs often use automatic manure handling systems, such as the scraper system and solid/liquid separators, to reduce the pollution risks and other environmental concerns. Compared with some convention systems, like deep pits, flushing-gutters, and bedding, the investment and operational costs are relatively high, especially for small and medium-sized AFOs. To quantify the impact of solid/liquid separation on the manure utilization, the slurry manure produced from each AFO was assumed non-separated into a solid portion and liquid portion. In other words, 0.55 million tons of solid manure that was processed and sold elsewhere will be used locally under this assumption. The optimal configuration of manure utilization chain was changed (Figure D.1), including the capacity of CPFs and manure utilization patterns. Especially for the Jiande district, the cropland usage increased with higher transportation costs, while most of the villages are full of their capacity to use animal manure. As shown in Table 5.2, utilization cost and manure applied land increase significantly. The nutrient values increase 114%, and twice croplands were required to compensate the excessive nutrients from solid manure. Under both GHG emission relaxed and restricted constraints, using the solid portion of manure locally will not benefit the local economy and GHG emission. The solid manure in the baseline scenario has high nutrient density and creates revenue for CPFs but becomes a part of slurry manure that increases the transportation and manure application costs.

Table 5.2. Summary of economic, operational, and GHG emission performances considering no S/L separation and manure load reduction for high manure production farms.

	Baseline	No S/L separation	Reduction of manure production
Solid portion of manure (million ton)	0.55	0	0.5
Slurry & liquid portion of manure (million ton)	2.4	2.97	2.0
Nutrient value of solid portion (million CNY)	44.6	0	42.8
Total GHG emission credit of solid portion (Gg CO2 e)	11.3	0	10.8
Utilization cost of slurry & liquid manure (million CNY)	*20.1/37.3*	*30.6/69.7*	*16.1/32.9*
Nutrient value of land application manure (million CNY)	*53.0/50.9*	*82.1/76.2*	*48.3/46.2*
Total CPFs processing capacity (ton)	*22,318/427,584*	*40,275/542,023*	*38,942/390,446*
Number of CPFs in manure utilization chain	*3/16*	*1/18*	*2/16*
Manure applied land (%)	*12.8/11.9*	*32.3/28*	*11.7/10.8*
Total GHG emission of slurry & liquid manure utilization (Gg CO2 e)	*40/52.5*	*53/77.5*	*37.0/49.9*
Total GHG emission credit of land application manure (Gg CO2 e)	*9.0/8.44*	*15.6/14.1*	*8.2/7.6*

(Value under $\varepsilon_{GHG.min}$*/ Value under* $\varepsilon_{GHG.max}$*).*

The manure production level of the AFOs above the median level of the same species was corrected to the median level to quantify the impact of manure reduction strategies on manure utilization. This scenario can refer to management strategies such as reducing cleaning water usage, improving animal drinking systems, reducing the cooling system water usage. Compared with the baseline scenario, 15% (0.45 million tons) manure will be reduced with the manure reduction strategies. The manure application percentages of cropland were decreased notably for central and west districts (Figure D.2). There will be 41 and 70 villages (~1% prime land for manure application) quit the manure application business under relaxed and restricted constraints, respectively. As shown in Table 5.2, utilization cost and GHG emission are also decreased with less manure load and transportation distances. The wastewater reduction will save CNY 4 to 4.4 million and reduce 2.6 to 3 Gg CO_2 e in different GHG emission constraints.

5.4.3 Scenario analysis of manure composition measurement

The composition of animal manure has wide variation due to the difference in animal diet, housing system, and manure management for any animal (Marino et al., 2008). However, no research has quantified the impact of manure composition measurement on nutrient recirculation. This analysis represents the practice of using manure nutrients that the manure composition varies by farms, but manure application amounts are calculated from the standard values. As shown in Figure 5.5, the variance of nitrogen and phosphorus results in a certain level of economic and environmental loss. In GHG emission scenarios, the nutrient surplus land ranges from 110 to 140 km^2, where 54.6 tons to 347.6 tons nitrogen and 9.2 tons to 49.2 tons phosphorus will be over-supplied if the nutrient variance increased from 10% to 50% . The mismatched nutrient allocation also causes the direct loss for both nutrient surplus and nutrient deficit. In general, relaxing GHG emission constraint reduces land application area, the economic loss and GHG emission. The economic loss and GHG emission increased from CNY 0.6 million to CNY 3 million and 0.2 Gg CO_2 e. to 1.1 Gg CO_2 e. if the nutrient variance increased from 10% to 50% under restricted GHG emission constraint ($\varepsilon_{GHG.min}$). These numbers can be considered as the benefits of accurate measurement of animal manure composition. If each facility (AFOs and CPFs) measured animal manure composition per year, the average economic credit and GHG emission credit (nutrient variance: 10% to 50%, $\varepsilon_{GHG.max}$) are CNY 773 to CNY 3,976 and 269 kg CO_2 e. to 1,386 kg CO_2 e. In other words, the economic and GHG emission credit for each measurement will be CNY 3,203 and 1,117 CO_2 e if the animal manure composition measurement can reduce the nutrient variance to from 50% to 10%. The results conceptually approved with the benefits of accurate measurement of nutrient composition in manure management and suggested further research on the measurement method, cost, and related policies.

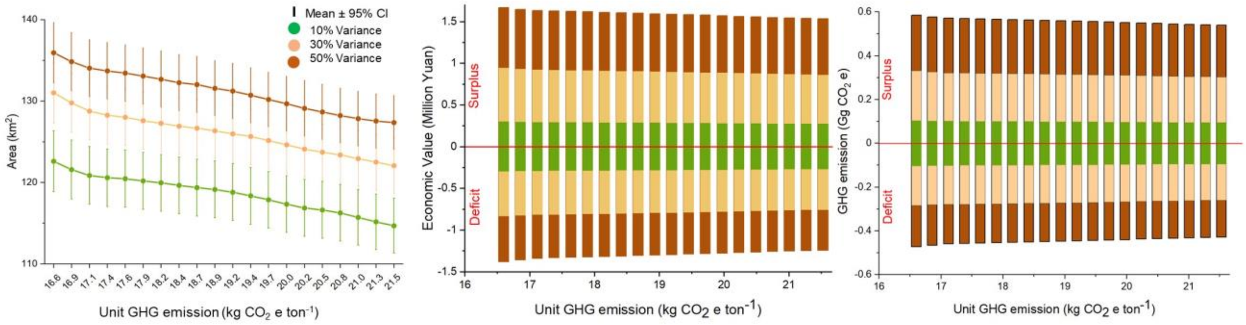


Figure 5.5. Pareto-optimal curves of manure surplus land, economic values and GHG emission credits under 20 GHG emissions levels for 10%, 30%, 50% variance of nitrogen and phosphorus.

5.4.4 Scenario analysis of transportation alternatives

The summary of operational cost and GHG emission with four transportation modes is shown in Table 5.3. Replacing the diesel trucks by electric trucks does not affect the logistics configurations but reduces the total transportation cost and GHG emission are reduced by 28% and 14% respectively. The main contributors are the AFO manure distribution and the village manure application. The transportation distance from AFO to local crop farm villages is typically greater than 10 km and the average travel distance of manure application is around 5 km in restricted and relaxed GHG emission scenarios. Such a fact shows the importance of “last-mile” distribution process in animal manure utilization and indicates that improving the agricultural infrastructure of villages might reduce the total utilization cost.

Table 5.3. Summary of transportation operational cost and greenhouse gas emission with different transportation modes.

	Diesel trucks only	Electric trucks only	Diesel trucks with portable pipeline	Electric trucks with portable pipeline
Average travel distance (km)*	**16.9/16.9**	**16.9/16.9**	**18.2/18.1**	**17.6/17.3**
AFOs manure distribution (km)*	11.6/10.7	11.5/10.7	9.3/8.9	9.7/9.6
CPFs manure collection(km)*	19/8.6	20.9/8.6	4.8/5.8	15.9/6.9
CPFs fertilizer distribution (km)*	7.3/10.6	9.1/10.6	7.5/8.4	9.3/9.1
Village manure application (km)*	5.3/4.9	5.2/4.9	8.8/8.5	7/6.8
Total transportation cost (Million CNY)	**18.9/18.3**	**13.1 /13.2**	**15.1/15.2**	**11.9/11.8**
AFOs manure distribution (%)	68.3/52.5	68/51.0	63.3/55.8	61/53.4
CPFs manure collection (%)	1/9.2	1.5/9.0	3.5/7.4	6.2/8.2
CPFs fertilizer distribution (%)	0.4/10.4	0.6/10.0	4.9/9.7	3.3/9.8
Village manure application (%)	30.2/27.9	29.8/30.0	28.3/27.1	29.3/28.4
Total transportation GHG emission (Gg CO_2 e)	**9.4/9.4**	**8.1/8.1**	**6.2/6.3**	**5.9/5.9**
AFOs manure distribution (%)	67.5/52	66.9/52	74.5/65.2	74.7/65.3
CPFs manure collection (%)	1/9.3	1.5/9	3.9/8.4	7.8/9.8
CPFs fertilizer distribution (%)	0.4/10.2	0.6/10.2	5.7/11.3	4.1/12
Village manure application (%)	31/28.8	31/28.8	15.8/27.1	13.4/12.9

**Average travel distance =sum(weight*distance) / sum(weight)*
(Value under $\varepsilon_{GHG.min}$/ Value under $\varepsilon_{GHG.max}$).

The portable pipeline pumping is also discussed for comparison. Trucks carry manure fertilizer to the crop-farming village, then unload manure fertilizer to the secondary station. crop farm-owners use pump and portable pipelines for land application. The logistics configurations are different with portable pipeline pumping by analyzing the component of the average travel distances. In general, the manure fertilizer travels farther in a village instead of being shipped to farther villages. Distributing manure and manure fertilizer using pipeline will increase the average travel distance. However, transportation distance from AFOs to either crop villages or CPFs can be reduced with pipeline transportation. The total transportation cost and GHG emission are reduced by 21% and 34% respectively if portable pipeline pumping replaces the diesel trucks for manure application. The total transportation cost and GHG emission are reduced by 10% and 27% respectively if portable pipeline pumping replaces the diesel trucks for manure application. Compared to truck transportation only, using pipeline transportation in the villages will introduce additional expenditures on transition. However, the results show the operational cost and GHG emission can be reduced significantly, which recommends adding a secondary storage station in each village to improve the animal manure utilization.

5.5 Conclusions

In this study, the slurry-manure RMUC model was modified to analyze the operational cost and operational greenhouse gas emission of the slurry manure utilization chain in Hangzhou, China. By comparative scenario analysis, the model could be used to assess and quantify the economic and GHG emission values of sustainable trajectories on animal manure utilization chain. The optimal results can support the strategical actions of industries and governments to recycle animal manure nutrients in crop farming systems. However, the uncertainty analysis and improved data-acquisition are required to implement such a method in accurate calculation of economic costs and regular supervision of regional manure utilization behaviors.

The Pareto-optimal results of the baseline scenario demonstrate how GHG emissions affect the decision-making process of each stakeholders within the manure utilization chain. The GHG emission constraints increase the individual AFO-related cost and CPF-related cost but reduce the total cost and GHG emission of the whole manure utilization chain. The scenario analysis of animal production improvement discussed the economic and environmental benefits of implementing solid-liquid separation and water usage reduction practices on manure management. The results indicated the improvement of those practice could change the manure utilization configuration, increase nutrient recirculation, and reduce the overall cost and GHG emission.

A scenario analysis was conducted to allow the manure nutrient content from each AFO to vary within specific ranges. The results show the measurable benefits of regular measurement of manure nutrient composition and suggest further research on the measurement method, cost, and related policies. Finally, we compared four different transportation modes, diesel truck only, electric truck only, diesel trucks with portable pipeline manure application, and electric truck with portable pipeline manure application. The optimal results highlight the economic and environmental potentials of electric vehicles on local manure transportation and recommend a secondary storage station in each village to improve the animal manure utilization.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

6.1 Summaries

The management of manure utilization is a set of actions that control manure from its source to the end-users that need manure nutrients. The overall goal of my dissertation research is develop systematic decision-support models and methods to enhance AFO manure management in sustainable and profitable ways. Two comprehensive optimization models were developed to optimize both single-farm manure management and regional manure utilization chains for animal production. A graphical user interface was developed to bridge existing information gaps between AFO manure production, local conditions, and available technologies.

1. A modeling approach was implemented to optimize the manure management design, including the decisions regarding main component capacities, operation plans in each production season, and cultivation decisions regarding fertilizing crops. This model was used to assess a dual treatment system (Anaerobic Digestion/Ectopic Fermentation) for a swine farm in Hangzhou, China. Unlike the classic "all-in-one" formulation, this approach divided the manure management problem into three smaller tasks based on the analytic target cascading (ATC) structure: liquid fertilizer inventory minimization, manure processing optimization and crop fertilizing analysis. This structure allowed designers to modify and evaluate the design in a flexible manner. The case study and scenario analysis showed the functionality of the model and exposed the potential risks and opportunities for the proposed manure treatment design.
2. We proposed protocols (RMUC models) to demonstrate the decisions of stakeholders of the manure utilization chain in a region. This research assumed that in such a system that

the essential nutrients would be either utilized or treated but not disposed of without being utilized. The RMUC models are a precise calculation method for estimating the regional manure utilization costs with respect to the optimal and practical logistics decisions. A case study for Hangzhou China was presented and demonstrated how this approach benefits the decision-making with a modeling strategy for assessing current configuration and analyzing how setback distance affects the total cost of manure utilization.

3. The slurry-manure RMUC model was modified to analyze the operational cost and operational greenhouse gas emission of the slurry manure utilization chain in Hangzhou, China. Four scenarios were discussed to assess and quantify how policy, management, and technology affect the configuration, operational cost, and GHG emission of the local animal manure utilization chain. The Pareto-optimal results of the baseline scenario demonstrated how the GHG emission constraints affect the optimal manure utilization configuration. The scenario analysis of animal production improvement indicated how the improvement of those practices (water-usage reduction, solid liquid separation, accurate measurement of animal manure composition) could change the manure utilization cost, increase nutrient utilization, and reduce the overall cost and GHG emission. A scenario analysis was conducted to allow the manure nutrient content from each AFO to vary within specific ranges. The results conceptually demonstrated the benefits of accurate measurement of nutrient composition in manure management and suggest that further research is needed on the measurement method, cost, and related policies. Finally, we compared four different transportation modes, and the results

recommended adding a secondary storage station in each village to improve the animal manure utilization.

6.2 Future work

The long-term goal of animal manure management is to enhance manure nutrient recirculation and control pollution on a sustainable and profitable basis. The integrated information system developed in this dissertation can provide professional recommendations and support by communicating the critical information among AFO owners, crop farmers, and policymakers. This dissertation provides a protocol of RMUC model, nutrient utilization, and the possible application to the current manure utilization chain. Proposed future work targets a comprehensive study on the pollution control and decision recommendation for future manure utilization chain.

1. Heavy metal analysis and constraints: It is anticipated that environmental regulation of heavy metal contents in diet additives will affect the decision of on-farm manure processing technology, and the configuration of manure utilization chain. Thus, analyzing the heavy metal flows and the RMUC model's constraints is necessary to improve the reliability and the scope of the information system.

2. Data and information: Data drive the modeling results. The data used in this dissertation are from the regional statistical surveys and databases. A cellphone-based application platform that directly serves both AFO owners and crop farmers would be beneficial. Critical data, such as treatment details, water usage, and crop yields, could be directly obtained, and the modeling results directly verified. Meanwhile, the data can be further used for operational-level designs, such as fleet design.

3. Future animal production planning: Animal protein operations will continue to increase in Hangzhou due to the consumption market growth and the technology development of animal husbandry. It is crucial to evaluate the impact of a new farm on the overall manure utilization chain, which can be a useful indicator of agricultural services. We can use a statistical method to analyze manure utilization chains' future configuration based on different assumptions of market growth. We can analyze the transportation routes and propose the infrastructure of manure utilization in future urban planning.

APPENDIX A: INTEGRATED DECISION SUPPORT PLATFORM FOR SWINE MANURE MANAGEMENT

Developing the decision criteria for selection and design of manure management utilized a knowledge-based approach to incorporate information, including manure production, manure processing, crop fertilizing, geospatial and climate data, and local regulatory constraints. Some of the information is specified by user input, such as animal production plans, animal feed compositions, and location information. General information, such as manure properties, manure processing options, and regulations, are the constants, standards, and regulations which can be summarized in the built-in database. For some climate-based analyses, meteorological data is acquired from public web services. It is essential to identify a reliable data source (Table A.1).

Table A.1 Data sources and models for selecting swine manure processing design and crop fertilizing plans.

Meteorological data	
Data name	*Data source*
Upper-Air Meteorological Data	National Oceanic and Atmospheric Administration/ Earth System Research Laboratory (NOAA-ESRL)
Hourly-Surface Meteorological	National Climatic Data Center/ National Oceanic and Atmospheric Administration (NCDC/NOAA)
One Minute Sound Data	National Climatic Data Center/ Automated Surface Observing System (NCDC/ASOS)
Terrain Data	
Data name	*Data source*
Location/map	Google Earth
Elevation map	Digital elevation map (30m-RAS)
Crop data	
Data name	*Data source*
Crop nutrient intake	Natural Resources Conservation Service (NRCS)/ Agricultural Waste Management Handbook
Land use map	United States Department of Agriculture (USDA)/ National Agricultural Statistics Service (NASS)
Environment Constraints	
Data name	*Data source*
Setback distances to open water and flood planes	Illinois Livestock Management Facilities Act, Section 900.803
Nitrogen, phosphorus and potassium price	Illinois livestock extension handbook
Assessment model	
Data name	*Data source*
Air dispersion model (AERMOD/AERMET model)	United States Environmental Protection Agency (EPA)
Manure nutrient assessment model	University of Illinois Certified Livestock Manager Training workshop

In summary, the static built-in database includes:

- Reference table and equations for animal manure characteristics.
- Empirical equations and technical parameters for manure processing options.
- Crop nutrient demand database; correction table for manure application practices.

The pre-defined data files are:

- Animal dietary information and animal performance.
- Manure application maps that excludes restricted areas for manure operations and land applications based on local regulations.
- Terrain data and meteorological data of proposal location.

The pre-defined input data includes:

- Proposed animal production plans.
- Local economic parameters.
- Location information and crop farming information.

A.1 Platform structure

A user-friendly computer program is developed for assisting the user in adding all the information on manure management selection and design, as shown in Figure A.1. Firstly, the user gives essential information such as location, swine production plans, and common crops, etc. Then, the user selects manure processing designs and defines crop fertilizing strategies with their preferences using the tools of the platform. Users can cross-compare the combination of manure processing designs.

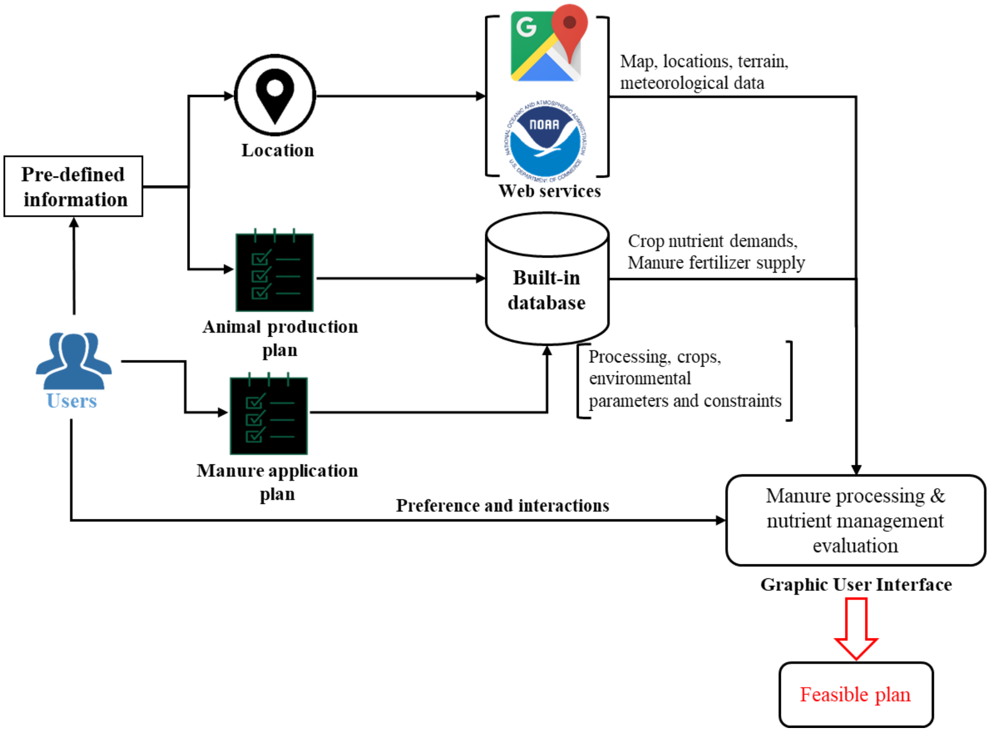


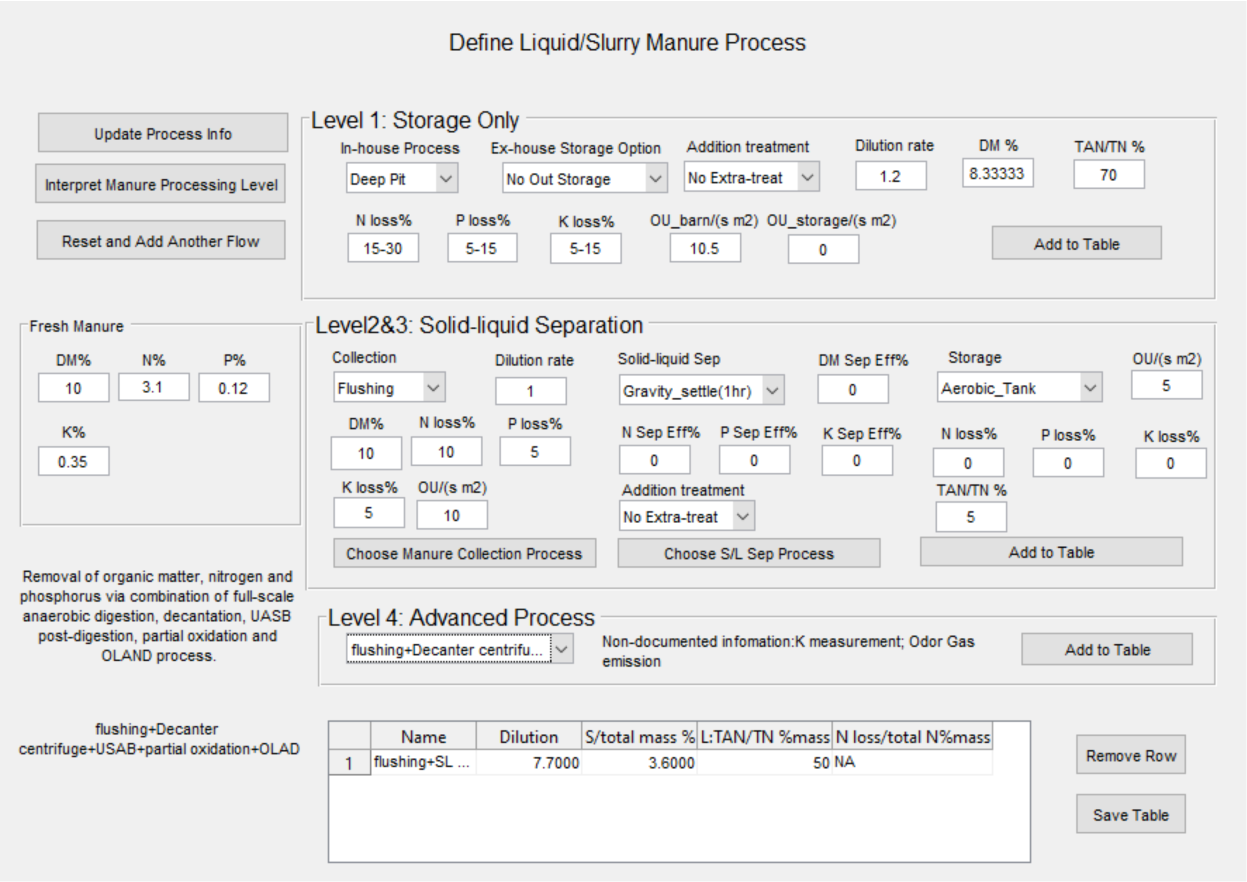
Figure A.1 System structure is composed of user interactions, web services, and built-in database.

A.2 Manure processing module

The manure-processing module is used to analyze the effluent characteristics after the on-farm manure processing stages. Raw manure is processed at the farm, and the nutrient content changes in each processing stage, including manure collection, manure treatment, and storage. In general, if there is insufficient crop land for spreading manure, the user should select some advanced manure treatment designs that can separate the excessive nutrients from the effluents as shown in Figure A.2. We classified the most common on-farm manure management designs into four levels. The first level includes the basic manure collection methods (flushing, deep pits, and pull-plug) and storage options (aerobic storage and anaerobic storage). The second and third levels incorporate additional single-stage and multi-stage solid/liquid separation into manure management design. The fourth level design is an advanced example, which can further reduce gas and odor emissions or remove the nutrients. The prediction of effluent nutrient contents is calculated from the mass balance and empirical equations described in the literature, as shown in Table A.2. Users can select multiple designs for comparisons.

Table A.2 Reference of the mass balance and empirical equations in manure processing module.

Design at level 1	
Design	*Data source*
Deep-pit system; flushing-lagoon; gutter-pond	(Moore and Gamroth, 1991); (Jacobson et al., 2000); (Chastain and Henry, 2002); (Vanotti et al., 2009); (Wesnæs et al., 2009);(García-González et al., 2016)
Anaerobic and aerobic storage	
Slurry acidification	(ten Hoeve et al., 2016)
N-strip	(Lim et al., 2000)
Enhanced aeration of storage	(Karakashev et al., 2008)
Coagulant/sedimentation addictive	(Moller et al., 2007b)
Design at level 2 & 3	
Design	*Data source*
Scraping, gutters, flushing system	(Pork Industry Hanbook, Purdue Extension, 2010)
Anaerobic, aerobic and lagoon storage	(NRCS, 2009); (Chastain and Henry, 2002)
Solid and liquid separation (Decanting centrifuge)	(Moller et al., 2007a)
Solid and liquid separation (Gravity settle, Screw press)	(Chastain and Henry, 2002)
Solid and liquid separation (Vibrating screen)	(NRCS, 2009)
Design at level 4	
Design	*Data source*
Flushing/Solid & Liquid separation(flocculants) With denitrification-nitrification/P separation	(Vanotti et al., 2007; Vanotti et al., 2008; Vanotti et al., 2009)
Flushing/Decanter centrifuge/USAB/partial oxidation/OLAD	(Karakashev et al., 2008)
Solid & Liquid separation (screen)/Energy plant/liquid storage/solid storage	(Wesnæs et al., 2009)
Screw press/Rotatory sieve/Aeration treatment/Composting	(Sáez et al., 2017)



Define Liquid/Slurry Manure Process

Level 1: Storage Only

In-house Process: Deep Pit
Ex-house Storage Option: No Out Storage
Addition treatment: No Extra-treat
Dilution rate: 1.2
DM %: 8.33333
TAN/TN %: 70
N loss%: 15-30
P loss%: 5-15
K loss%: 5-15
OU_barn/(s m2): 10.5
OU_storage/(s m2): 0

Fresh Manure

DM%: 10
N%: 3.1
P%: 0.12
K%: 0.35

Level2&3: Solid-liquid Separation

Collection: Flushing
Dilution rate: 1
Solid-liquid Sep: Gravity_settle(1hr)
DM Sep Eff%: 0
Storage: Aerobic_Tank
OU/(s m2): 5
DM%: 10
N loss%: 10
P loss%: 5
N Sep Eff%: 0
P Sep Eff%: 0
K Sep Eff%: 0
N loss%: 0
P loss%: 0
K loss%: 0
K loss%: 5
OU/(s m2): 10
Addition treatment: No Extra-treat
TAN/TN %: 5

Removal of organic matter, nitrogen and phosphorus via combination of full-scale anaerobic digestion, decantation, UASB post-digestion, partial oxidation and OLAND process.

Level 4: Advanced Process

flushing+Decanter centrifu...

Non-documented infomation:K measurement; Odor Gas emission

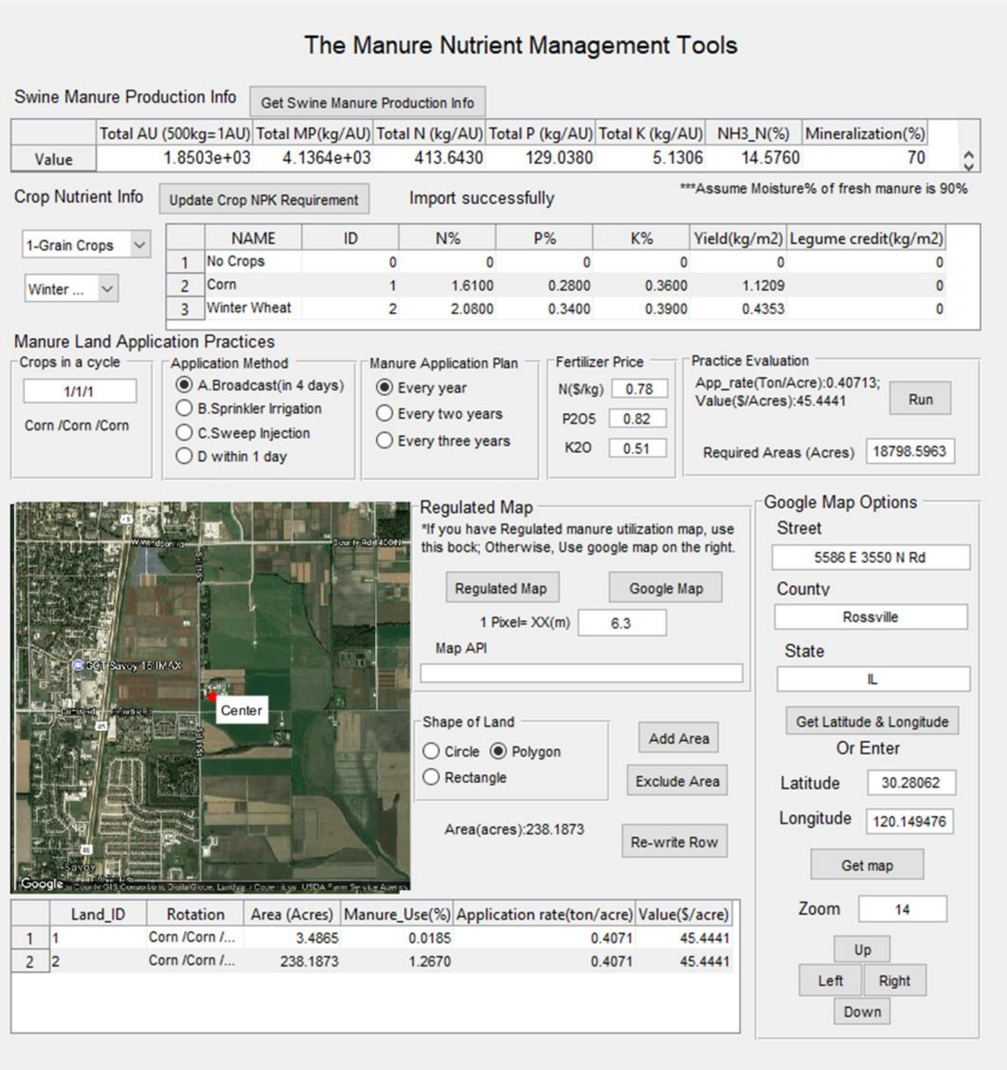
flushing+Decanter centrifuge+USAB+partial oxidation+OLAD

	Name	Dilution	S/total mass %	L:TAN/TN %mass	N loss/total N%mass
1	flushing+SL ...	7.7000	3.6000	50	NA

Figure A.2. Manure processing module.

A.3 Manure nutrient management module

The manure nutrient management module is the platform that integrates the necessary information for users to plan manure land applications. As shown in Figure A.3, the pre-defined manure properties and built-in database of commonly grown crops, separately stored in Excel sheets, can be imported into the module in the “swine manure production info” section and “crop nutrient info” sections. After selecting the crops and rotation plans, the manure and required lands for manure application are calculated considering the state of Illinois manure handling standards and the nutrient credits. The nitrogen content and costs are estimated considering the plant-available nitrogen (PAN), which accounts for the impact of ammonia loss and mineralization of organic nitrogen using different application methods. Users can draw the field with select crop rotation and manure application methods on the map, and the tool calculates the nutrient demands and the percentage of manure used in the chosen field. The map is a Google map that is incorporated in the tools. The actual area and distance are estimated from the projection of latitude and longitude to image pixels at given zoom levels. Users can also prepare the regulatory map that contains the residential area and flood plains around the farm. The manure nutrient management module can lead the user to evaluate their manure application plans, considering the constraints and benefits.



The Manure Nutrient Management Tools

Swine Manure Production Info

	Total AU (500kg=1AU)	Total MP(kg/AU)	Total N (kg/AU)	Total P (kg/AU)	Total K (kg/AU)	NH3_N(%)	Mineralization(%)
Value	1.8503e+03	4.1364e+03	413.6430	129.0380	5.1306	14.5760	70

Crop Nutrient Info

Import successfully

***Assume Moisture% of fresh manure is 90%

1-Grain Crops

Winter ...

	NAME	ID	N%	P%	K%	Yield(kg/m2)	Legume credit(kg/m2)
1	No Crops	0	0	0	0	0	0
2	Corn	1	1.6100	0.2800	0.3600	1.1209	0
3	Winter Wheat	2	2.0800	0.3400	0.3900	0.4353	0

Manure Land Application Practices

Crops in a cycle
1/1/1
Corn /Corn /Corn

Application Method
● A.Broadcast(in 4 days)
○ B.Sprinkler Irrigation
○ C.Sweep Injection
○ D within 1 day

Manure Application Plan
● Every year
○ Every two years
○ Every three years

Fertilizer Price
N($/kg) 0.78
P2O5 0.82
K2O 0.51

Practice Evaluation
App_rate(Ton/Acre):0.40713;
Value($/Acres):45.4441
Required Areas (Acres) 18798.5963

Regulated Map
*If you have Regulated manure utilization map, use this bock; Otherwise, Use google map on the right.
1 Pixel= XX(m) 6.3
Map API

Shape of Land
○ Circle ● Polygon
○ Rectangle

Area(acres):238.1873

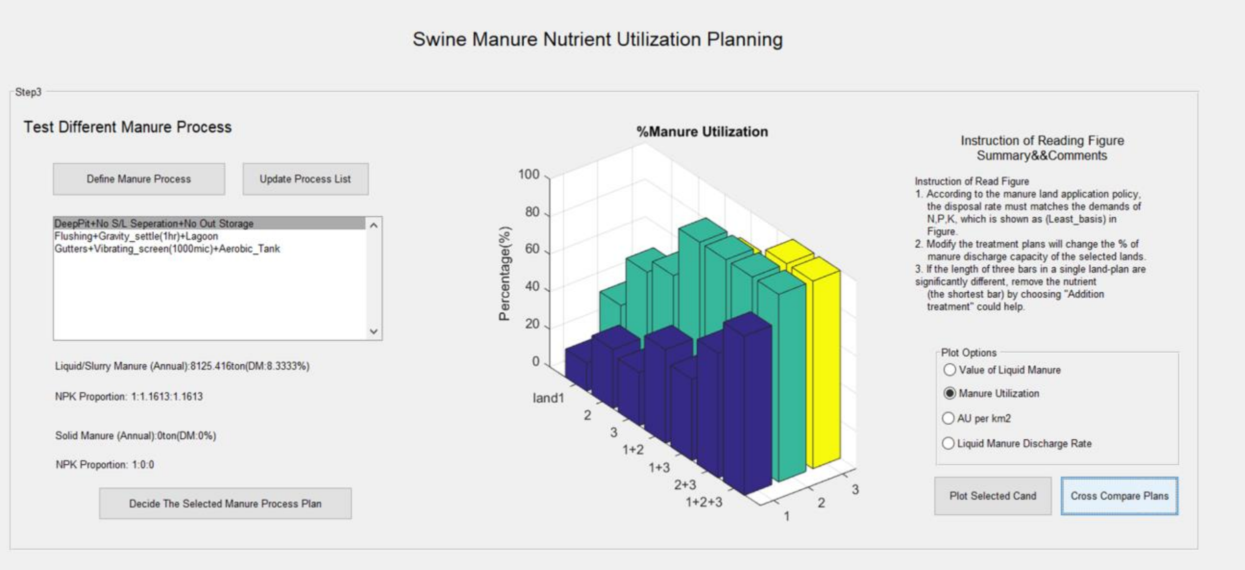
Google Map Options
Street 5586 E 3550 N Rd
County Rossville
State IL
Or Enter
Latitude 30.28062
Longitude 120.149476
Zoom 14

	Land_ID	Rotation	Area (Acres)	Manure_Use(%)	Application rate(ton/acre)	Value($/acre)
1	1	Corn /Corn /...	3.4865	0.0185	0.4071	45.4441
2	2	Corn /Corn /...	238.1873	1.2670	0.4071	45.4441

Figure A.3. Manure nutrient management module.

A.4 Manure management evaluation module

The management evaluation module is an interactive program that allows the user to evaluate the selected manure management designs with manure nutrient management plans. All the chosen manure management designs are coupled with manure nutrient management plans. The users can check performances of a single manure management design and cross-compare all chosen manure management design at one evaluation dimension. The evaluation dimensions are economic values of manure applied, the percentage of manure that can be used, animal unit (AU) per km^2 and the liquid manure discharge rate to the field (metric ton/km^2). This provision provides the required information from different environmental regulations and economic considerations for which the relative importance of the decision criteria is different in different regions and can be re-defined and explained w the instruction section.



DeepPit+No S/L Seperation+No Out Storage
Flushing+Gravity_settle(1hr)+Lagoon
Gutters+Vibrating_screen(1000mic)+Aerobic_Tank

Liquid/Slurry Manure (Annual):8125.416ton(DM:8.3333%)

NPK Proportion: 1:1.1613:1.1613

Solid Manure (Annual):0ton(DM:0%)

NPK Proportion: 1:0:0

Instruction of Read Figure
1. According to the manure land application policy, the disposal rate must matches the demands of N,P,K, which is shown as (Least_basis) in Figure.
2. Modify the treatment plans will change the % of manure discharge capacity of the selected lands.
3. If the length of three bars in a single land-plan are significantly different, remove the nutrient (the shortest bar) by choosing "Addition treatment" could help.

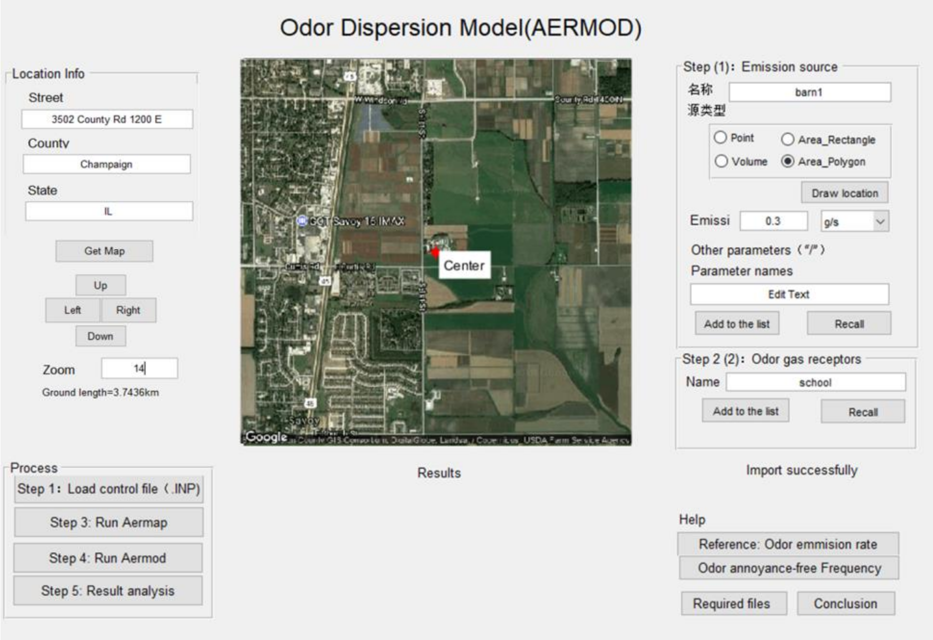
○ Value of Liquid Manure
● Manure Utilization
○ AU per km2
○ Liquid Manure Discharge Rate

Figure A.4. Manure management evaluation module

A.5 Odor annoyance evaluation module

The odor annoyance-free frequency is used for indicating the social impact of the proposed design (Eq. A.1). In this study, we use the AERMOD model to predict the odor concentration ($\text{Conc}_{\text{odor}}$) in the residential area that is dispersed from the swine farm (Li, 2009). The odor annoyance-free frequency describes the number of days that the odor concentration do not exceed the threshold over a period. The threshold is the odor intensity considered “faint” to humans in a sampling period (Guo et al., 2005). The use of the AERMOD model often requires professional knowledge, an extensive quantity of data and programming skills. It is nearly impossible for most users to evaluate their design with the AERMOD model. As shown in Figure A.5, the odor annoyance evaluation module connects the AERMOD model and other related models in a simple way that allows the users to define the odor emissions and odor sensitive receptors by directly drawing on the map. The results would be interpreted and displayed on the interface.

$$\text{Odor annoyance free frequency (\%)} = \frac{\sum Days \mid (Conc_{odor} \geq Threshold_{odor})}{\sum Days} \times 100\% \tag{A.1}$$



Street: 3502 County Rd 1200 E

County: Champaign

State: IL

Zoom: 14

Ground length=3.7436km

名称: barn1

源类型:
○ Point ○ Area_Rectangle
○ Volume ● Area_Polygon

Emissi: 0.3 g/s

Parameter names: Edit Text

Name: school

Import successfully

Figure A.5. The odor annoyance evaluation module

APPENDIX B: SUPPLEMENT MATERIALS OF SWINE FARM MANURE MANAGEMENT OPTIMIZATION MODEL

The major given parameters are:

- Swine manure production data, including raw manure production rate, properties (moisture content, nutrient content). The information was estimated from animal productivity and diet details, based on ASABE model (add reference);
- Local crop agronomic information including the common crop types and rotation combinations, yields, the nutrient requirement of crops, fertilizing practice references (fertilizing frequency, ammonia loss factors, and organic nitrogen mineralization factor;
- Meteorological data that os required for odor dispersion assessment (AERMOD model);
- Economic data associated with the energy cost, capital cost, transportation cost, labor cost, interest and depreciation rates;
- Design constraints and operational details about proposed treatment decision, such as operation conditions, minimum/maximum design capacities, etc.

Key assumptions include:

- The storage design only focuses on the liquid fraction since the cost and environmental concerns of solid fertilizer product is relatively insignificant;
- The manure production of a swine farm is continuous. The crop fertilizing decisions are constant for each crop field on a seasonal basis. Therefore, the inventory calculations of fertilizer product are also on a seasonal basis;

- Crops are fertilized twice during the growing season: prior to seeding (70% of total amount), and middle of growing period (30% of total amount). For vegetable growth, fertilizer is applied to soil as starter in each season for reducing the biological contamination risks.
- The climate information used for the AERMOD model are the data in 2017 from the Hangzhou ground weather station, which represent the most recent climate year.

Chen and Hashimoto (1980) modified the Contoi's kinetic equation for anaerobic treatment of organic waste (Eq. B.1). Equation B.1 provides an estimation of the methane production rate from fermentation process (*GF*, m^3 of CH_4/m^3 volume per day), where B_0 is the maximum rate of methane production (m^3 of CH_4/kg volatile solids); S_0 is the concentration of volatile solids of the manure (kg/m^3), which is estimated from the total solid contents (Suresh et al., 2009); *HTR* is the hydraulic retention rate (in days); K is the kinetic coefficient (Eq. B.3).

$$GF(X_{1.t},Y_{1.t},Cap_{AD})=\frac{B_0S_0(X_{1.t},Y_{1.t1})}{HRT}(1-\frac{K}{HRT(0.013T_{digester}-0.129)-1+K}) \tag{B.1}$$

$$S_0(X_{1.t},Y_{1.t})=8.006\frac{5X_{1.t}+0.35Y_{1.t}}{X_{1.t}+Y_{1.t}}-3.873 \tag{B.2}$$

$$K=0.6+0.0206e^{0.051S_0(X_{1.t},Y_{1.t})} \tag{B.3}$$

The major operational cost for thermophilic anaerobic digestion is the heating cost to maintain reactor temperature. To simplify the heat transfer process model, a control volume approach is applied. Several assumptions are set forth to simplify the calculation of energy consumption:

1. The digester is well-mixed, the temperature is homogenous throughout the digester.
2. The digester set-point temperature ($T_{digester}$) is 35 ^oC.

3. Influent feedstock temperature (T_{in}) is 5°C when the ambient temperature is lower than 5 °C; the influent feedstock is equal to ambient temperature when the temperature is higher than 5 °C.
4. The heat production during the anaerobic digestion process is negligible.

The static energy balance is shown in Equation B.4. The energy balance includes the heat loss through digester envelope of the slurry portion (Q_w) and the gas portion (Q_g), heat loss through inlet manure (Q_{in}) and heat gain from heat exchange (the portion of heat added to the system with heater efficiency). The ambient temperature is the daily average temperature, and the heat is assumed to be generated from methane with the same price of biogas produced by the anaerobic digestion.

$$\begin{aligned} Co_{AD}(X_{1.t}, Y_{1.t}) = r_{gas}\frac{Q_w + Q_g - Q_{in}}{h_{biogas} efficiency_{heater}} = \frac{3600 r_{gas}}{h_{biogas} efficiency_{heater}}[U_s A_s (T_{digester} - T_a) + \\ U_g A_g (T_{digester} - T_a) - \tfrac{1000}{24\times 3600}(X_{1.t} + Y_{1.t}) C_p (T_{in} - T_{digester})] \end{aligned} \tag{B.4}$$

Table B.1. Summary of model parameters.

Item	Unit	Value	Reference
Operational parameters			
Manure production rate (Breeding barn, M_A)	ton/day	Winter:8.7 Spring/Fall:11.7 Summer:13.2	Site -specific values
Manure production rate (Finishing barn, M_B)	ton/day	Winter:14.2 Spring/Fall:21.7 Summer:25.5	Site -specific values
Volume of the fermentation bed per unit of manure (CF)	(m^3/ton day)	Cold: 67 Warm 55	Reference value [1]
Minimum influent percentage for ectopic fermentation (CF_{max})	(m^3/ton day)	Cold: 145	Reference value [1]
Set point temperature of the digester ($T_{digester}$)	°C	35 °C	Reference value [1]
Liquid-solid separation efficiency (η_{Sep} , Scraper)		0.25	Reference value [1]
Liquid-solid separation efficiency (η_{Sep} , Mechanical separator)		0.01-0.05	Reference value [2]
Heater efficiency (η_{heater})		0.7	Reference value [3]
Heating value of biogas (h_{gas})	MJ/m^3	23	Reference value [3]
Heat capacity of liquid manure (Cp)	kJ/kg	4.186	Reference value [3]
Heat transfer coefficient for slurry (U_s)	$W/(m^2 \cdot K)$	0.218	Reference value [3]
Heat transfer coefficient for biogas (U_g)	$W/(m^2 \cdot K)$	0.212	Reference value [3]

Economic parameters			
Unit capital cost of anaerobic digestion (UC_{AD})	CNY/m^3	144	Site -specific values
Unit capital cost of ectopic fermentation (UC_{EF})	CNY/m^3	74	Site -specific values
Unit capital cost of liquid fertilizer storage tank (UC_{LS})	CNY	86	Site -specific values
Capital cost for liquid and solid separation (C_{Sep})	CNY	110,000 (SL) 150,000(Scraper)	Site -specific values
Capital recovery factors(f_a)		0.096 (10 years) 0..23 (5 years)	
Unit revenue for selling biogas(r_{gas})	CNY/m^3	1.3	Site -specific values
Unit revenue for EF fertilizer (r_{EF})	CNY/m^3	250	Site -specific values
Unit revenue for selling solid manure(r_S)	CNY/ton	50	Site -specific values
Unit operational cost for ectopic fermentation (co_{EF})	CNY/ (m^3 for 6 months)	226.1	Site -specific values
Unit operational cost for processing solid manure fertilizer (co_{SF})	CNY/ton	42	Site -specific values
Unit operational cost for raw solid manure (co_S)	CNY/ton	2	Site -specific values
Unit operational cost for Scraper (co_{SL})	CNY/day	2.17	Site -specific values
Unit operational cost for mechanical separator (co_{SL})	CNY/ton	0.14	Site -specific values
Transportation fixed cost(c_f)	CNY/ton	2.23	Site -specific values
Transportation variable cost(c_v)	CNY/(ton km)	0.44	Site -specific values
Crop fertilizing parameters			
Organic nitrogen to total nitrogen (f_{OrgN})		0.25	Reference value [4]
Organic nitrogen mineralization factor (mf)		0.35	Reference value [4]
Ammonia loss in land application ($loss_{NH3}$)		0.05	Reference value [4]

[1] Zhejiang Environmental Protection Bureau, (2017).
[2] Møller, H. B., Lund, I., & Sommer, S. G., (2000).
[3] Yang, S. J., (2015).
[4] MWPS-18, (1993).

Table B.2. Plant nutrient uptake by specific crop and removed in the harvested part of the crop (NRCS, 2009); agronomic practice.

name	Typical Yield (kg/ha)	Average concentration of nutrients			Field type	Sowing season	Harvest season
		N (%)	P (%)	K (%)			
Early Rice	6017	1.39	0.24	0.23	Flat	Spring	Fall
Spring grain	4442	2.08	0.62	0.52	Flat	Spring	Fall
Late Rice	7486	1.39	0.24	0.23	Flat	Early Summer	Winter
Tubers	5351	0.43	0.19	0.52	Flat	Late Summer	Winter
Corn	4532	1.61	0.28	0.36	Flat	Spring	Fall
Soybeans	2926	0	0.54	1.63	Flat	Spring	Fall
oil	2852	3.6	0.79	0.76	Flat	Winter	Early Summer
vegetable	47085.941	0.4	0.19	0.27	Greenhouse	Yearly	

APPENDIX C: SUPPLEMENT MATERIALS OF REGIONAL ANIMAL MANURE UTILIZATION CHAIN MODEL

Table C.1 GIS maps for land availability analysis.

Criteria	Data source	Format
Village border (2017)	Bureau of Urban Planning of Hangzhou	Polygon
Surface water (2017)	Bureau of Land Resources of Hangzhou	Polygon
Residential area (2017)	Bureau of Urban Planning of Hangzhou	Polygon
Transportation road (2017)	Bureau of Urban Planning of Hangzhou	Polygon
Land use (2017)	Bureau of Land Resources of Hangzhou	Polygon

Table C.2 Summary of model parameters.

Item	**Unit**	**Value**	**Reference**
Economic parameters			
Annualized capital cost for solid manure processing (*Ccs*)	CNY/ton	15	Site -specific values
Annualized capital cost for slurry manure processing (*Ccl*)	CNY/ton	25	Site -specific values
Fixed transportation cost for solid manure (*Ctfs*)	CNY/ton	4	Site -specific values
Fixed transportation cost for liquid and slurry manure (*Ctfl*)	CNY/ton	0.2	Site -specific values
Variable transportation cost for solid manure (*Ctvs*)	CNY/ton km	0.4	Site -specific values
Variable transportation cost for liquid and slurry manure (*Ctvl*)	CNY/ton km	0.45	Site -specific values
Unit operational cost of the anaerobic digestion process (Co_{AD})	CNY/ton	21	Site -specific values
Unit operational cost of waste treatment (Co_{waste})	CNY/ton	18	Site -specific values
Unit processing cost of solid manure (*Cops*)	CNY/ton	281	Site -specific values
Unit price of natural gas (r_{gas})	CNY/m^3	1.3	Site -specific values
Unit price of organic fertilizer (r_{OF})	CNY/ton	600	Site -specific values
Operational parameters			
The maximum rate of biogas production (*Bo*)	CH_4/kg SV	0.481	Chen and Hashimoto (1980)
Mass conversion factor for solid livestock manure to organic fertilizer (CF_{OF})	ton/ton	0.72	Site-specific values
Separation efficiency for solid, nitrogen, and phosphorus (*SE*)	%	-	Moller et al., (2007)
Hydraulic retention time (*HRT*)	days	30	Site-specific values
Crop fertilizing parameters			
Nitrogen loss (ε_N)	%	Figure A.2	Hutchings et al. (2013)
Phosphorus loss (ε_P)	%	Figure A.2	Hutchings et al. (2013)

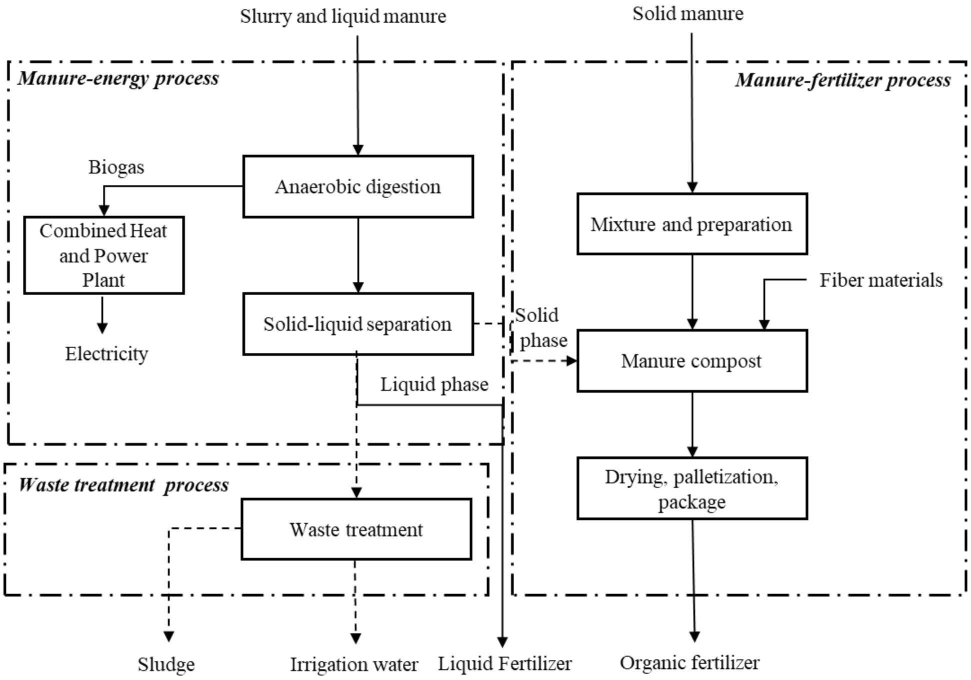


Figure C.1. Proposed treatment of centralized manure-processing facility.

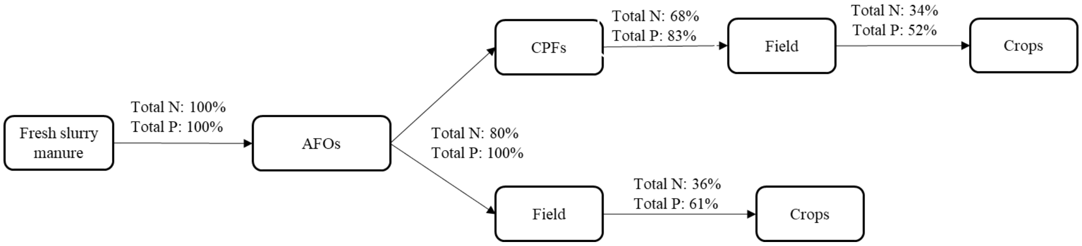


Figure C.2. The summary of nitrogen and phosphorus flows of Livestock slurry manure (Hutchings et al. 2013).

CPF manure influent & processing analysis module

The influent characteristics of CPF are analyzed through summarizing the characteristics of slurry manure from the AFOs that are collected to each CPF. The characteristics include total amount (*PAS*), total solid content (*PSTC*), total volatile solid content (*PSVC*), total nitrogen content (*PNC*), phosphorus content (*PPC*), and biogas production factor (*GF*). The estimation of the biogas production rate from fermentation process (m^3 of CH_4/m^3 per day), where B_0 is the maximum rate of methane production (m^3 of CH$_4$/kg volatile solids). S$_0$ is the concentration of volatile solids of the manure (kg/m^3), which is estimated from the total solid contents (Suresh et al., 2009); HTR is the hydraulic retention rate (in days); K is the kinetic coefficient.

.

$$PAS_d = \sum_k \sum_i XD_{kid} \tag{C.1}$$

$$PSTC_d = \frac{\sum_i \sum_k STC_{ik} XD_{kid}}{PAS_d} \tag{C.2}$$

$$PSVC_d = \frac{\sum_i \sum_k SVC_{ik} XD_{kid}}{PAS_d} \tag{C.3}$$

$$PNC_d = \frac{\sum_i \sum_k NC_{ik} XD_{kid}}{PAS_d} \tag{C.4}$$

$$PPC_d = \frac{\sum_i \sum_k PC_{ik} XD_{kid}}{PAS_d} \tag{C.5}$$

$$K = 0.6 + 0.0206 e^{0.051 PSVC_d} \tag{C.6}$$

$$GF_d = B_o PSVC_d (1 - \frac{K}{HRT(0.013T_{digester} - 0.129) - 1 + K}) \tag{C.7}$$

Based on the analysis of the influent characteristics of CPF, the operational parameters and economic parameters of CPF can be estimated. The slurry manure is mixed before processing, and the mixture goes through the anaerobic digestion plant. After 30 days, the mixture is separated into the liquid portion and solid portion. Knowing the total solid content (*PSTC*) of influent and separation efficiency (*SE*), the CFP effluent nutrient content can be estimated: effluent nitrogen content (*PNC*), and effluent phosphorus content (*PPC*). The operational, economic parameters (*Rl, Copl, Coppl*) can be calculated for further analysis.

$$EAS_d = (1 - SE_M) \times PAS_d \tag{C.8}$$

$$ENC_d = (1 - SE_N) \times \frac{PAS_d PNC_d}{EAS_d} \tag{C.9}$$

$$EPC_d = (1 - SE_P) \times \frac{PAS_d PPC_d}{EAS_d} \tag{C.10}$$

$$Rl_d = r_{gas} GF_d + r_{OF} CF_{OF} SE_M \tag{C.11}$$

$$Copl_d = Co_{AD} + Cops \times SE_M \tag{C.12}$$

$$Coppl_d = Rl_d - Copl_d \tag{C.13}$$

APPENDIX D: SUPPLEMENT MATERIALS OF SUSTAINABLE ANIMAL MANURE UTILIZATION CHIAN OPTIMIZATION MODEL

Table D.1. Parameters of GHG emission factor calculation (IPCC, 2006; Wolf et al., 2017).

Animal	N_{ex}	VS	Bo
Swine	0.42	0.3	0.29
Sheep	1.17	0.32	0.13
Chicken	0.82	0.02	0.24
Dairy cow	0.47	**4.4**	0.13
Rabbit	8.1	0.1	0.32
Special poultry	0.6	0.02	0.24
Duck	0.83	0.02	0.24

Table D.2. Greenhouse gas emission factors (IPCC, 2006; You and Wang, 2011; Rehl and Müller, 2011; Aguirre-Villegas and Larson, 2017; Wang et al., 2017a; Yang et al., 2018b).

Parameter	Unit
Ctfl.v	CNY 0.2 ton^{-1}
Ctfl.p	CNY 0.2 ton^{-1}
Ctvl.dv	CNY 0.45 ton^{-1} km^{-1}
Ctvl.ev	CNY 0.31 ton^{-1} km^{-1}
Ctvl.pip	CNY 0.18 ton^{-1} km^{-1}
EFt.dv	0.23 kg CO_2 e ton^{-1} km^{-1}
EFt.ev	0.20 kg CO_2 e ton^{-1} km^{-1}
EFt.pip	0.047 kg CO_2 e ton^{-1} km^{-1}
EFp	21.8 kg CO_2 e ton^{-1}
EFpw	12.5 kg CO_2 e ton^{-1}
EFcl	8 kg CO_2 e ton^{-1}
$MCF_{s.land}$	0.5 %
Os_{gas}	20 %
Os_{leach}	30 %
EF_{leach}	0.0075 kg CO_2 e
EF_{dep}	0.01 kg CO_2 e
$Credit_N$	1.526 kg CO_2 e kg-N^{-1}
$Credit_P$	1.631 kg CO_2 e kg-P^{-1}
$Credit_K$	0.6545 kg CO_2 e kg-K^{-1}

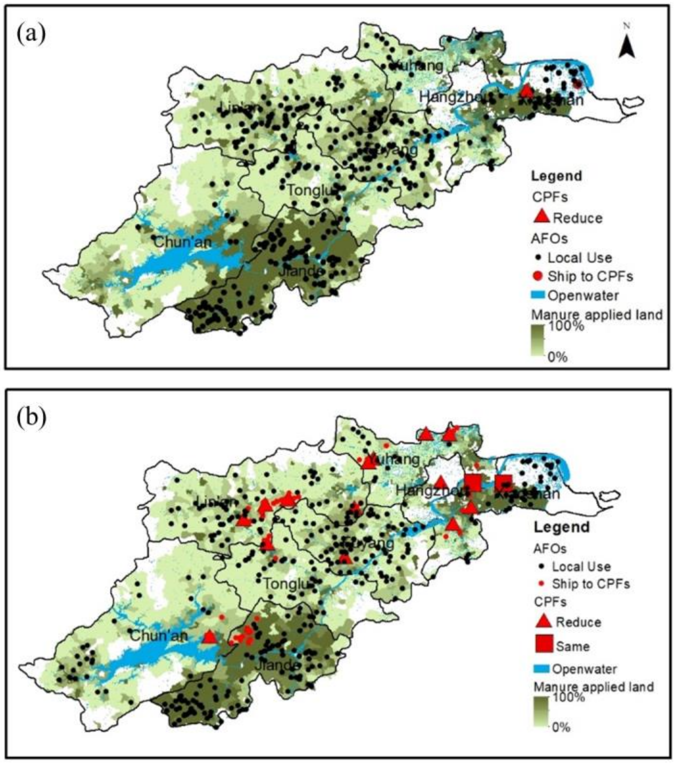


Figure D.1. The optimal slurry manure supply-chain configuration without solid and liquid separation at (a) $\varepsilon_{GHG.min}$ (b) $\varepsilon_{GHG.max}$.

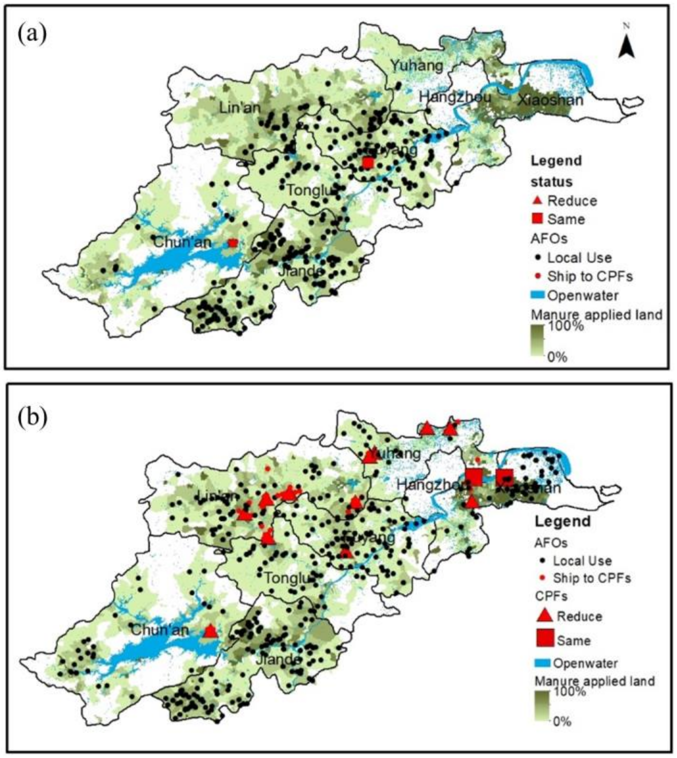


Figure D.2. The optimal slurry manure supply-chain configuration if the manure production level was reduced to the median level at (a) $\varepsilon_{GHG.min}$ (b) $\varepsilon_{GHG.max}$.

REFERENCE

Aarnink, A. J. A., and Elzing A. 1998. Dynamic model for ammonia volatilization in housing with partially slatted floors, for fattening pigs. *Livest. Prod. Sci.* 53(2):153-169.

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