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Optimal design of manure management for intensive swine feeding operation: A modeling method based on analytical target cascading

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ABSTRACT

One of the most significant challenges in existing livestock production is the negative impact of animal waste on the environment. Accumulative manure produced in intensive swine feeding operations (ISFO) cannot be efficiently utilized in a sustainable and economical way. A successful manure management system should maximize the overall economic benefits while satisfying the environmental requirements. To address the manure management problem in a region that lacks adequate land for manure spreading, this project presents a novel modeling approach (Analytic target cascading, ATC) to optimize the design and operation of a swine manure management system by formulating economic objectives, engineering objectives and environmental objectives into individual tasks. This modeling structure simplifies the formulation of a systematic problem, decomposes "all-in-one" model into small tasks, and integrates the professional assessment models into optimal design. We organized the local agricultural information (swine production, crop production) and treatment operational data into parameters and constraints, then optimized the design capacities of main components, operations of manure management and crop management sequentially through updating the targets and responses in each iteration. To explore the viability of the proposed models and solution methodology, a case study in Hangzhou, China (a swine farm with Anaerobic Digestion process + Ectopic Fermentation) is designed using ATC approach. Additionally, the scenario analyses are discussed to provide further insights of opportunities and risks. Our analysis will improve the ability to deal with agricultural systematic problems with social, environmental and economic agreements.

1. Introduction

Unite State Department of Agriculture predicts the global swine production will be 114.6 million metric tonnes while 3% higher in 2019. At the same time, this industry generates a large quantity of manure, which was widely recognized as organic fertilizer in agriculture but is treated as a kind of troublesome waste today. Swine manure contains excessive nutrients and high concentrations of heavy metals such as copper (Cu) and zinc (Zn). The manure management causes the problems such as hygiene, air, and water pollution (Heinonen-Tanski et al., 2006; Martens and Böhm, 2009; Moller et al., 2007). In the last ten years, intensive swine feeding operations (ISFO) make manure management more costly, difficult to process, and to transport (Hadrich et al., 2010). Moreover, the willingness of crop farm owners to fertilize crops by livestock manure is continuously decreasing (Makara and Kowalski, 2018).

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Nomenclature

Indices Description

t Productive season (t = 1,2,3,4)
r Crop rotation plan
m Crop field

Input data Description

Area Area of crop field m (ha)
Ta Ambient temperature (^oC)
D Distance list from swine farm to crop field m (km)
Yield Annual crop yield of crop field m with rotation plan r (metric tonnes/ha)
Hnu Harvested crop nutrient content (nu = N, P) for crop in crop rotation plan r (%)
Fnu Swine manure nutrient content from finishing barn or breeding barn (nu = N, P, %)
M Manure production rate (A:breeding barn, B: finishing barn) (metric tonnes/day)

Decision variables Description

Cap Capacity of anaerobic digestion (AD,m^3), ectopic fermentation (EF,m^3), liquid fertilizer storage (LS, metric tonnes)
W_t Influent of solid and liquid separation (metric tonnes/day)
$S_{1.t}$, $S_{2.t}$ Solid mass flows of raw solid manure in season t (metric tonnes/day)
$X_{1.t}$, $X_{2.t}$ Manure flows from breeding barn in season t (metric tonnes/day)
$X_{12.t}$ Amount of anaerobic digestion digestate used by ectopic fermentation system in season t (metric tonnes/day)
$X_{13.t}$ Amount of liquid fertilizer used by crop farms in season t (metric tonnes/day)
$Y_{1.t}$, $Y_{2.t}$ Manure flows from finishing barn in season t (metric tonnes/day)
DL_t Demand of liquid fertilizer from crop farm in season t (metric tonnes/season)
Z_{rm} Farming decision of crop rotation plan r at crop field m

Symbol Description

AccS Accumulated liquid fertilizer supply (metric tonnes)
AccD Accumulated liquid fertilizer demand (metric tonnes)
$Conc_{odor}$ Odor concentration at the residential area (%)
Co^{Sep} Operational cost of solid-liquid separation system (CNY)
Co_{AD} Energy cost for operating anaerobic digestion system (CNY)
co_{trans} Unit transportation cost of liquid fertilizer (CNY/metric tonnes)
Cf Annual operational cost of crop fertilization of liquid fertilizer (CNY)
CD Liquid fertilizer demand of crop in land m with rotation plan r (metric tonnes)
Dnu Nutrient (nu = N, P) demand of crop rotation plan r at crop field m in season t (metric tonnes)
DL Crop demands of liquid fertilizer in season t (metric tonnes)
$Freq_{odor}$ Odor annoyance-free frequency (%)
GF Gas production (CH_4) per unit waste (m^3/metric tonnes manure)
Ndays Number of days in season t
N, P Nitrogen and phosphorus content of manure in season t (metric tonnes/metric tonnes manure)
So Concentration of volatile solid in raw manure (kg/m^3)
PAN Plant available nitrogen content in manure in season t (metric tonnes/metric tonnes manure)
Po Annual operational profit of swine manure treatment (CNY)
Q_w, Q_g, Q_m Heat loss through digester envelope of the slurry portion, gas portion and inlet manure (J)
UC Unit capital cost of anaerobic digestion (AD), ectopic fermentation (EF), liquid fertilizer storage (LS) and manure separation (Sep) (CNY/metric tonnes)

Parameters Description

Bo The maximum rate of biogas production (0.481 m^3CH_4/kg volatile solids)
$co_{scraper}$ Unit operational cost of scrapping system (CNY/metric tonnes)
co_{Sep} Unit operational cost of solid-liquid separation (CNY/metric tonnes)
co_{EF} Unit operational cost of ectopic fermentation system (CNY/metric tonnes)
co_S Unit operational cost of raw solid manure storage (CNY/metric tonnes)
Cf Transportation fixed cost (CNY/metric tonnes)
Cv Transportation variable cost (CNY/metric tonnes km)
CF Volume of the fermentation bed per unit of manure (m^3/metric tonnes waste day)
Cp Heat capacity of liquid manure (4.186 kJ/kg)
f_a Capital recovery factors
f_{orgN} Organic nitrogen to total nitrogen
h_{gas} Heating value of biogas (23 M J/m^3)
HRT Hydraulic retention rate (days)
K Kinetic coefficient
$loss_{NH3}$ Ammonia loss in land application
Mf Organic nitrogen mineralization factor
r_{gas} Unit price of biogas (CNY/m^3)
r_{EF} Unit price of fermented fertilizer (CNY/metric tonnes)
r_S Unit price of raw solid manure (CNY/metric tonnes)
$Thred_{odor}$ Threshold is the odor intensity considering “faint” to human in a period (72 OU/m^3)
$T_{digester}$ Digester set-point temperature (^oC)
U_sA_s, U_gA_g Heat transfer coefficient for slurry and gas (W/K)
η_{sep} Liquid-solid separation efficiency
$\eta_{loss.nu}$ Nutreint loss (N = 0.3, P = 0.1) in manure treatment process
η_{heater} Efficiency of biogas heater

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), that 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 Fig. 1, a sustainable swine manure management must contain the manure treatment design and the crop-fertilizing plan for liquid fertilizer.

For most ISFOs, selecting and designing manure management is always a challenge with risks. Economic viability is the key for a successful design (Klavon et al., 2013). The innovation design is design with good performances and environmentally friendly but requires high capital cost. Many case studies, such as the nitrification and denitrification process, indicated the innovation design sometimes could not reach the theoretical performance and even worked improperly in real operations as it was in other farms (Vanotti et al., 2007, 2009). The conventional design, such as anaerobic or aerobic storage, the lagoon with agitator and composting, is safe to use and cost less compared to the innovation design (Frandsen et al., 2011). However, the conventional designs that are proved practicable today could be invalid in the future. In the Corn Belt states of the United States, the ISFOs are used to deep-pit design that benefits from the low manure processing cost due to the abundant arable lands for a long time. This economic advantage is currently facing challenges because of the negative impacts, such as water eutrophication and the increased logistics costs associated with the expansion of a single livestock farm (Motew et al., 2018).

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. The manure management planning software recommends feasible design options through integrating treatment descriptive analysis and life cycle assessment to calculate the manure nutrient flows and economic returns (Karmakar et al., 2010; NRCS et al., 2009). However, these approaches work for evaluating some classic designs, but are unable to help with optimal design and 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). A general approach is to formulate the optimization problem into an “all-in-one” problem, which only has one objective function and one constraint set (Baetz, 1990). For sustainability purposes, some studies utilize multi-objective models to add cleaner production targets to economic objective functions, such as “minimum greenhouse gas emission” or “maximum nutrient utilization” (Balaman, 2016; Liang et al., 2018). Some advanced optimization techniques, (such as multi-level formulation), are applied to simultaneously solve strategic-level decisions (configuration) and tactic-level decisions (logistics networks) (Balaman et al., 2018). Due to the complexity of mathematical formulation, those modeling approaches are not widely applied for manure management design.

The compatibility of the computational model is another challenge of applying optimization techniques in manure management design. Some environmental assessments, such as odor impact, are based on an entire design plan and conducted by professional models in a different coding language (Zhu et al., 2000). Furthermore, it is difficult to integrate a complete model into optimization algorithms. Collaborative optimizations have been well studied and recognized in various large-scale industrial systematic problems, such as aeroelastic optimization and smart grid design (Chell et al., 2019). This approach decomposes a multidisciplinary problem into several reasonable small problems that are solved independently and sequentially (Tappeta and Renaud, 1997). There is no particular document to consult the collaborative optimization method to solve agricultural production problems.

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 the 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 as a mean 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

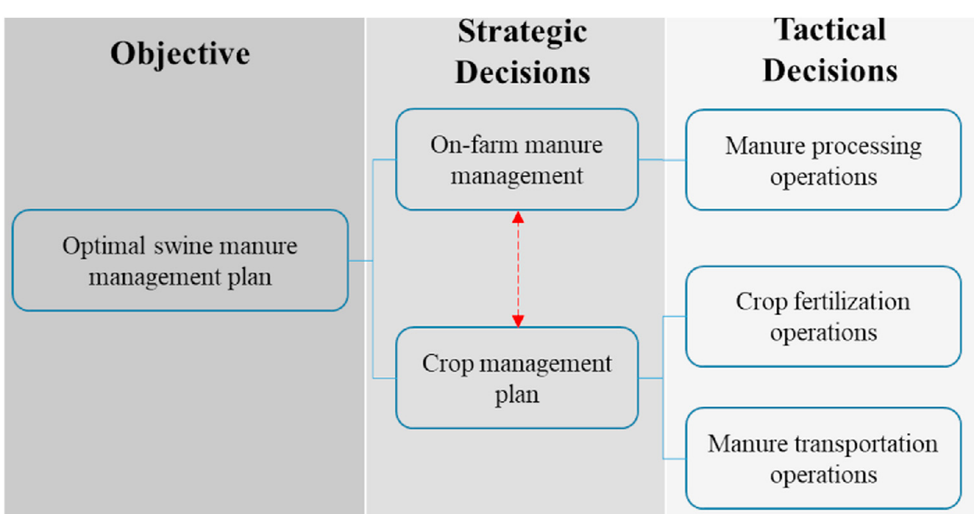

Fig. 1. Schematic diagram of swine manure management system design.

models for establishing an ideal approach to use the information and computational science.

2. Problem description and formulation

2.1. Problem statement

According to the NRCS et al. (2009), the planning process of animal manure waste 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 condition, 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 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 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 paper 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 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 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 be also formulated into constraints (Cui et al., 2018; Mahmoodi-Eshkaftaki and Ebrahimi, 2019).

The proposed method uses the analytic target cascading

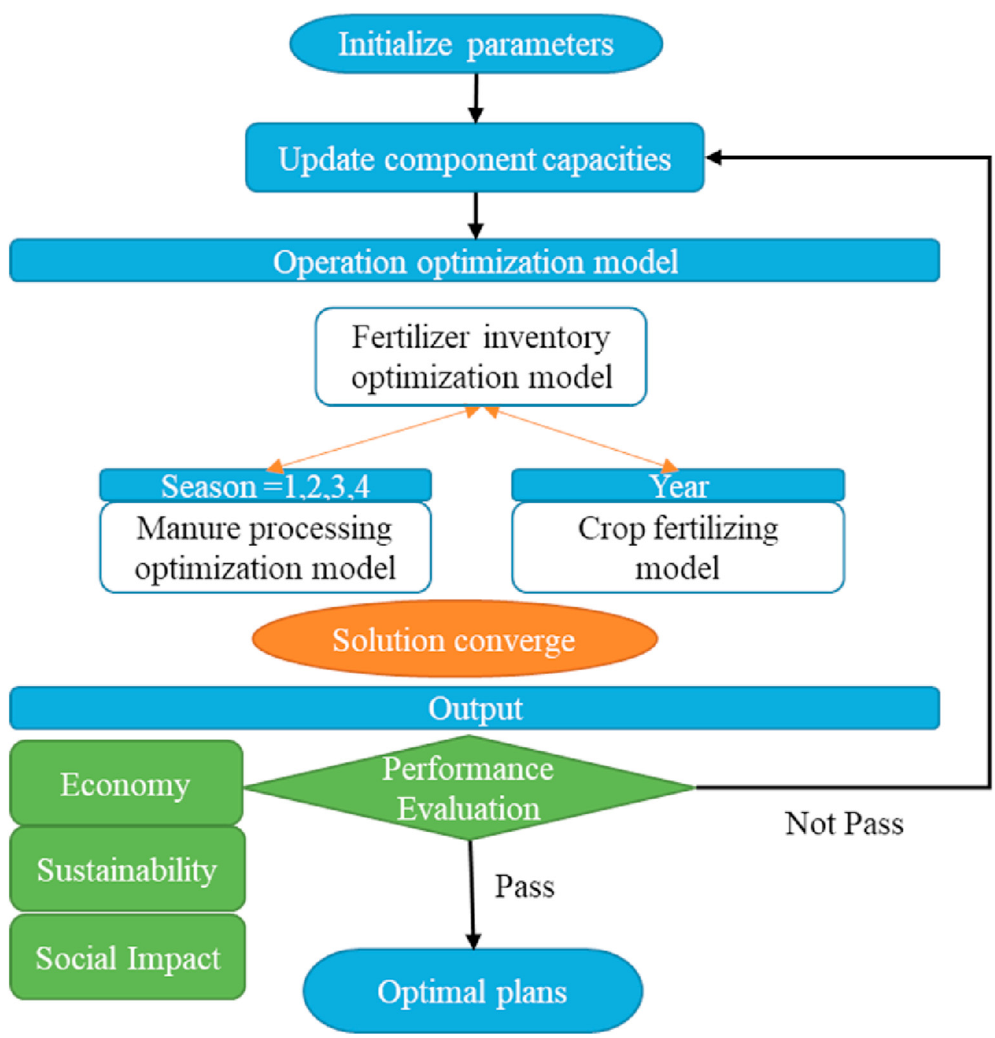

Fig. 2. Modeling structure of designing a swine manure management plan.

structure (ATC) to formulate the optimization problem. As shown in Fig. 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 the ATC structure. Given the design candidate in the DC matrix, the operational plans are optimized (section 2.2). Finally, the economic, sustainable, social performance of the proposed candidate and the operational plans will be evaluated (section 2.3); the results will form the post-design evaluation matrix (DE matrix).

2.2. Analytic target cascading structure

Analytic target cascading is the system design approach that enables the top-level design target to be cascaded down to lower levels of the modeling hierarchy (Kim, 2001). In swine manure management design, the fertilizer inventory capacity is the top-level decision and is optimized with respect to operational plans. Reducing the 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 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 decision of crop growth and crop rotation is a yearly basis. Unifying the study period will enlarge the number of optimal decisions, and cause the difficulty of 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.

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 Equation (1). The annualized profit includes annualized income and annualized cost. The annualized cost consists of operational cost and annualized capital cost of the process.

$$Annualized\ profit = Revenue - Annualized\ capital\ cost - Operational\ cost$$

The liquid fertilizer holding-amount is used for indicating the environmental risks of an annual operational plan as shown in Equation (2), which is equivalent to the holding cost of liquid fertilizer. The holding-amount (metric tonnes.day) is to measure the difference between liquid fertilizer supplies (AccS) and demands (AccD) over time. As shown in Fig. 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.

$$liquid\ fertilizer\ holding\ amount(MT.day) = \sum_t (AccS_t - AccD_t) \times Ndays_t$$

The odor annoyance-free frequency ($Freq_{odor}$) is used for indicating the social impact of the proposed plans as shown in Equation (3). In this study, we use the AERMOD model to predict the odor concentration ($Conc_{odor}$) at the residential area that is dispersed from swine farms (Li, 2009). The odor annoyance-free percentages describe the number of days that the odor concentration exceeds the threshold over a period. The threshold is the odor intensity considering "faint" to human in a period (Guo et al., 2005).

$$Freq_{odor}(\%) = \frac{\sum_t (Days|Conc_{odor} \geq Thred_{odor})}{\sum_t Days} \times 100\% \quad (3)$$

3. Case study: Manure management system for a swine farm in Hangzhou, China

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 of proposals and studies as well as an agreement from the government, communities, expertise, 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 manure management should also be upgraded to satisfy the business changes. In Hangzhou, the conventional manure management for swine farms is the storage-based system, such as

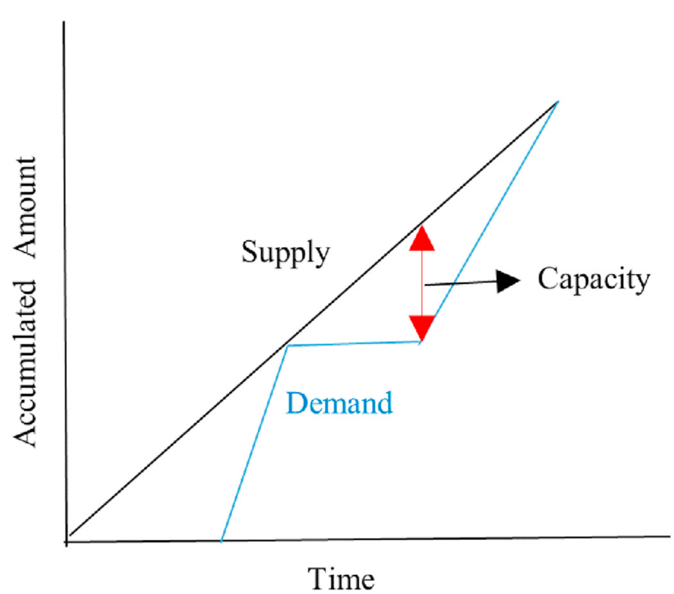

Fig. 3. Typical graphic example representing relationship between supply, demand and capacity.

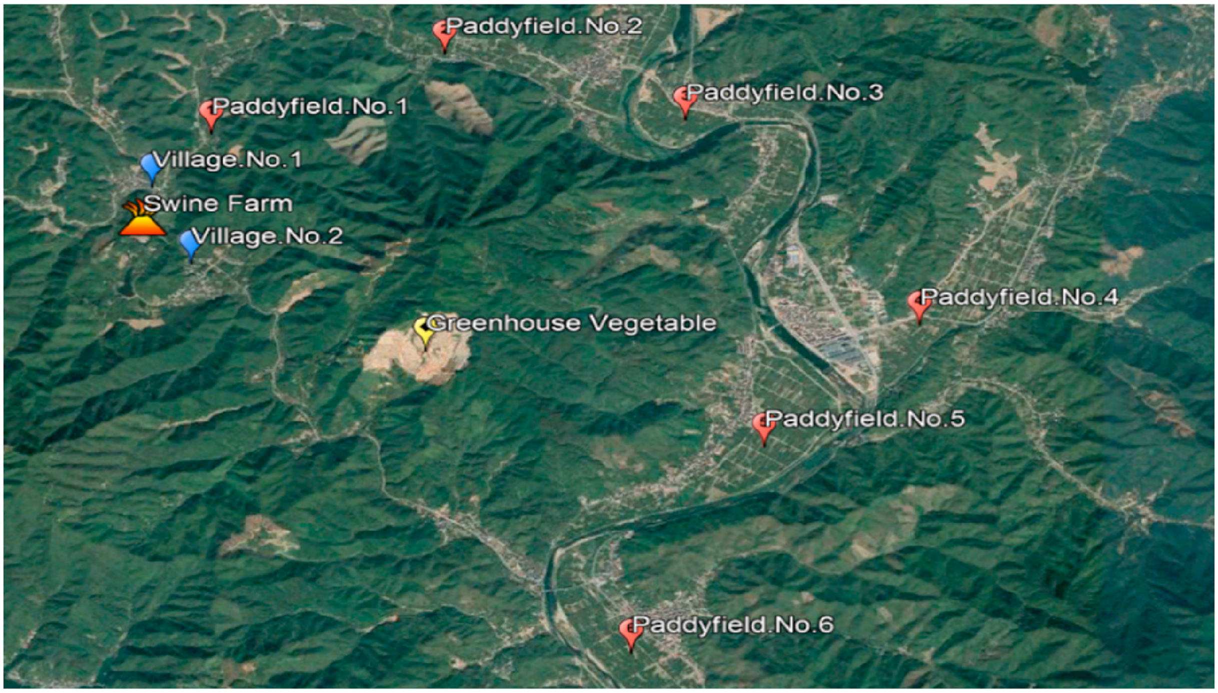

Fig. 4. Relative geospatial locations of swine farms, residential villages and cultivation fields.

anaerobic or aerobic storage. However, the mountainous area lacks arable lands to use all manure fertilizer generated from swine farms. For the treatment like compost and fermented-bed, the liquid portion of slurry manure can be reduced through evaporation. But the performance of these treatments is highly affected by weather since Hangzhou is in a humid subtropical climate region and has consecutive precipitation over few months every year. 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 (Zhejiang Environmental Protection Bureau, 2017). In this paper, we report a pilot study to demonstrate the optimal design in the treatment planning and operation stages under local conditions, which can guide the farmers in the real application.

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 metric tonnes of manure waste. The original manure management of this farm includes two types of manure collection systems (breeding barns: deep pit, finishing barn: scrapping system) and lagoon storage. The scrapping system splits the manure into a liquid portion and a solid portion. As illustrated in Fig. 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.

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 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.

3.2. Mathematical formulations

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 A". 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 Fig. 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).

3.2.1. Economic optimization

The objective of the economic optimization model (Equation (4)) is to maximize annual swine manure management profit that includes three parts: annual operational profit of swine manure treatment (Po), 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 the main components including anaerobic digestion, ectopic fermentation, liquid fertilizer storage, and scrapping system for finishing barn.

$$profit = Po - Cf - f_a \times (UC_{AD}Cap_{AD} + UC_{EF}Cap_{EF} + UC_{LS}Cap_{LS} + UC_{Sep}) \quad (4)$$

For manure treatment management, the annual profit (Po, Equation (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 scrapping system cost.

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, $Ndays_t$ 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. Chen (1983) 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 (Equations (A1, A2 and A3)). The energy cost (Co_{AD}) related to maintaining the operation of the AD system is estimated from the energy balance (Equation (A4)). The hydraulic

$$
\begin{aligned}
&Po = \sum_t Po_t(Cap_{AD}, Cap_{EF}) = \sum_t \max_{X,Y,S} Po_t^{AD} + Po_t^{EF} + Po_t^{S} + Ndays_t \times co_{scraper}\\
&\text{where}\\
&Po_t^{AD} = Ndays_t \times GF_t \times r_{gas} \times (X_{1.t} + Y_{1.t}) - Co_{AD} - Ndays_t \times co_{trans} \times X_{13.t}\\
&Po_t^{EF} = (r_{EF} - co_{EF}) \times CF_t \times (X_{12.t} + X_{2.t} + Y_{2.t} + S_{1.t})\\
&Po_t^{S} = Ndays \times (r_s - co_s) \times S_{2.t}\\
&s.t.\\
&h_1: \ X_{1.t} + X_{2.t} - M_A = 0\\
&h_2: \ Y_{1.t} + Y_{2.t} - (1 - \eta_{sep})M_B = 0\\
&h_3: \ S_{1.t} + S_{2.t} - \eta_{sep}M_B = 0\\
&h_4: \ X_{1.t} + Y_{1.t} + X_{13.t} - X_{12.t} = 0\\
&g_1: \ X_{1.t} + Y_{1.t} - \frac{Cap_{AD}}{10} \le 0\\
&g_2: \ \frac{Cap_{AD}}{40} - X_{1.t} - Y_{1.t} \le 0\\
&g_3: \ 1.48Y_{1.t} - 3.27X_{1.t} \le 0\\
&g_4: \ CF_t(X_{12.t} + X_{2.t} + Y_{2.t} + S_{1.t}) - Cap_{EF} \le 0\\
&g_5: \ CF_{min}Cap_{EF} \le CF_t(X_{12.t} + X_{2.t} + Y_{2.t} + S_{1.t})\\
&g_6: \ DL_t - X_{13.t} \le 0
\end{aligned}
\quad (5)
$$

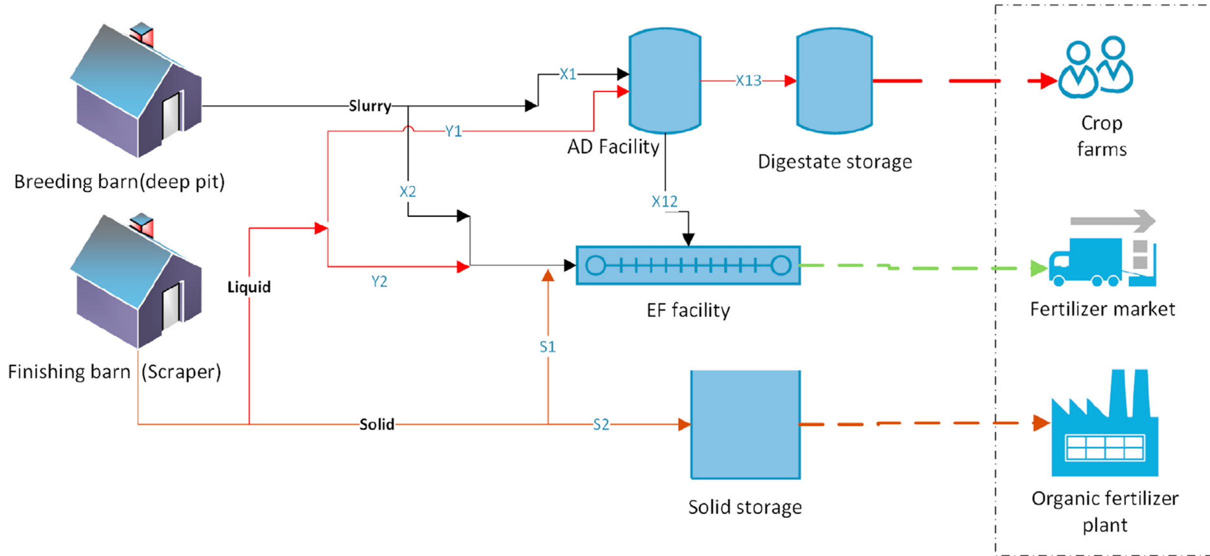

Fig. 5. Conceptual design of manure treatment system for a swine farm in Hangzhou. China.

retention time constraints (g_1, g_2) ensures the amount of the influents is within a feasible range for the 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 fertilizer. Bo et al. (2017) indicated the capability of manure treatment in the 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 the fermentation bed.

For the operational cost of crop fertilization, the total cost (Cf, Equation (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 (c_f) and variable cost (c_v). The crop rotation decisions are binary variables and constrained by which each land only has one rotation plan per year.

$$Cf = \sum_t Cf_t(X_{13.t}) = \sum_t \sum_r \sum_m \left(c_f + c_v D_m\right) Z_{rm} CD_{rm.t}$$
$$s.t. \quad \sum_r Z_{rm} = 1, \quad Z_{rm} \in \{0,1\} \tag{6}$$

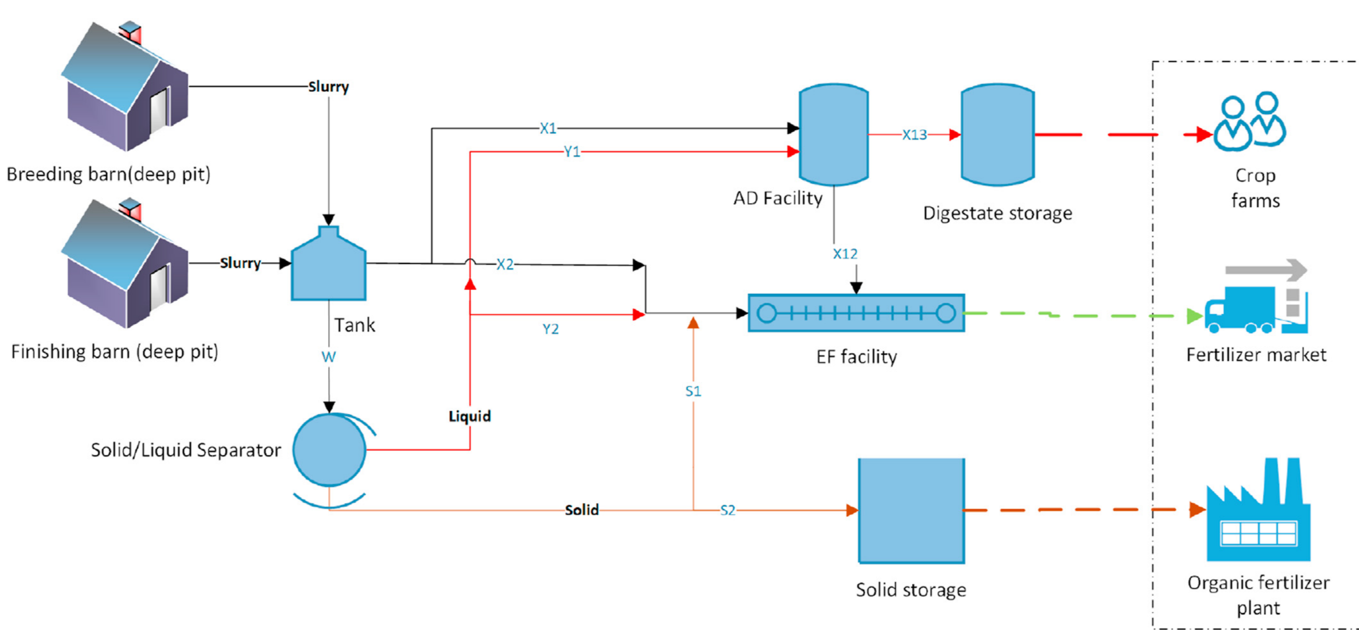

Fig. 6. Alternative designs of manure processing plan for the proposed farm.

3.2.2. 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, Equation (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 A1). The nutrient demand matrixes (Equation (8)) for nitrogen and phosphorus (DN, DP) are estimated based on the crop yield and crop nutrient concentration (HN, HP). At the end, the total amount of fertilizer demand at season t (DL_t) is the sum of liquid fertilizer demand of each individual field (Equation (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 (Equation (10)).

$$PAN_t = f_{orgN} \times N_t \times mf + \left(1 - f_{orgN}\right) \times N_t \times (1 - loss_{NH3}) \quad (7)$$

$$Dnu_{rm} = Area_m \times Yield_r \times Hnu_r \times 100\% | nu = N, P \quad (8)$$

$$DL_t = \sum_r \sum_m Z_{rm} CD_{rm.t} \quad (9)$$

$$CD_{rm.t} = min\left(\frac{DN_{rm}}{PAN_t}, \frac{DP_{rm}}{P_t}\right) \quad (10)$$

3.2.3. Fertilizer inventory optimization

The nutrient content of liquid fertilizer in each season (Equation (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 (Equation (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 (Equation (2), Fig. 3). The liquid fertilizer demand of crop farms is adjusted for each season by deducing the leftover from the previous season (Equation (13)). The liquid fertilizer transportation cost is also adjusted along with the fertilizing plan changes (Equation (14)).

$$Fnu_t = \frac{X_{1.t} \times Fnu_{breeding} + Y_{1.t} \times Fnu_{finishing}}{X_{13.t}} \times (1 - \eta_{nu.loss}) \times 100\% | nu = N, P \quad (11)$$

$$\min_{Z_{rm}} \sum_t \left(\sum_r \sum_m Z_{rm} CD_{rm.t} - X_{13.t} \right)^2 \quad s.t. \quad h_1 : \sum_r Z_{rm} = 1, \quad Z_{rm} \in \{0, 1\} \quad (12)$$

$$NewDL_t = DL_t - max(X_{12.t-1} - DL_{t-1}, 0) \quad (13)$$

$$co_{trans} = \frac{\sum_r \sum_m \left(c_f + c_v D_m\right) Z_{rm} CD_{rm.t}}{\sum_t Ndays_t X_{13.t}} \quad (14)$$

3.2.4. 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 the 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 (Equation (4)), liquid fertilizer holding-amount (Equation (2)) and odor annoyance-free frequency (Equation (3)) for the proposed plan.

3.2.5. Scenario analyses

3.2.5.1. 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 Fig. 4, the closest residential communities are approximately 400 m north and 500 m southeast from the swine farm. Six paddy fields with total area of 18.3 ha are available for using liquid fertilizer.

Inputs to the model are drawn from several sources. Swine manure properties and treatment operational parameters that describe the mechanical and processing performance of the equipment are obtained through technical standards and recommendation values in the manure utilization handbook (Zhejiang Environmental Protection Bureau, 2017; Moller et al., 2002; Yang, 2015). 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 local database. The crop agronomic information and fertilizing information were acquired indirectly from local surveys of agronomic practices and Zhejiang Agriculture Bureau (2017). A detailed summary to assumption and data sources is listed in supplementary information. Optimization results for this base scenario were obtained with respect to the parameters made in Table A1. 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.

3.2.5.2. 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 modeling structure in model adaption. As shown in Fig. 6, alternative design applies deep-pit system for both breeding barn and finishing barn while the original design uses 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 baseline case were applied for the evaluating alternative design.

4. Results and discussion

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 capable 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 metric tonnes to 5773 metric tonnes. 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 metric tonnes in this design plan. The liquid fertilizer holding-amount is 3960 metric tonnes.days, while the inventory is zero in winter and spring. The odor assessment of the manure treatment was conducted to the optimal plan as well as in the optimization model (Developed in Python2.7) integrated the AERMOD model (Based on C language) in a connective way. 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/metric tonnes. All the solid raw manure is directly sold to the organic fertilizer makers for profits. As shown in Fig. 7 and Fig. 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.

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 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.

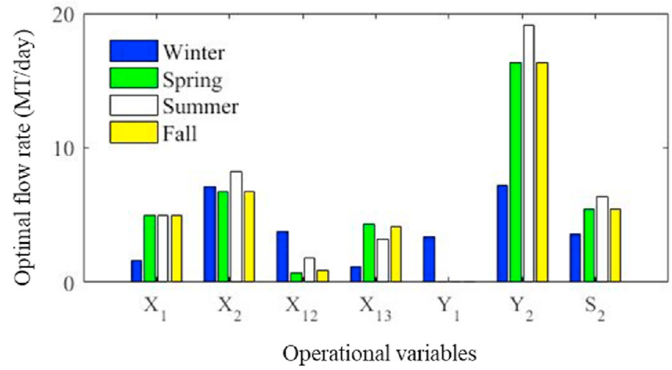

Fig. 7. Optimal manure processing plans based on the parameters made in Table A1 (MT: metric tonnes).

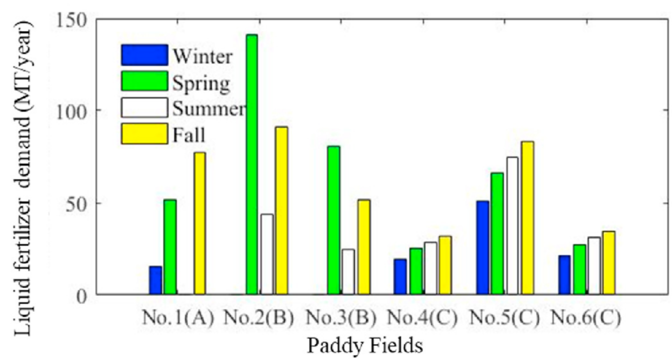

Fig. 8. Optimal crop cultivation plans (MT: metric tonnes) and fertilizing plans based on the parameters made in Table A1. (A): Spring grain/Vegetable; (B): Late rice/Vegetable; (C): Oil crop/Late rice.

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

Table 1
Scenarios setting and the optimal results (MT: metric tonnes).

	F1	F2	F3	F4[b]	F5
Description	Manure production +10%	Bedding material cost +20%	Organic fertilizer market closure	More crop farms	Reducing water usage by 10%
Parameter changes	$M_A + M_B$ (MT/day) = Winter: 25 Spring/Fall:37 Summer: 42	co_{EF} = CNY 260/(m^3 for 6 months)	$r_{EF} = 0$ $r_S = 0$ (CNY/MT)	Add vegetable farm (17 ha)	$M_A + M_B$ (MT/day) = Winter: 22.5 Spring/Fall:35 Summer: 30
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 LS storage (MT)	340	745	5297	63	0
Liquid fertilizer holding-amount (MT.day)	37,997	161,363	927,505	2848	0
Months with odor problem[c]	June	June	June	—	—
Crop cultivation plans[a]	B, C	B, C	B	C, D	A, B, C

[a] Crop rotation plan: (A): Spring grain/Vegetable; (B): Late rice/Vegetable; (C): Oil crop/Late rice; (D): Early rice/late rice.
[b] Liquid fertilizer is applied as basal fertilizer before sowing.
[c] The month of odor annoyance-free frequency ≤ 97%.

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 waste 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.

The cross evaluation is shown in Fig. 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 Fig. 9(d), the maximum nutrient demand of 7 crop farms for liquid fertilizer is 6750 metric tonnes/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.

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 the alternative 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 submodules 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 metric tonnes/day) comparing to scrapping 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 A1.

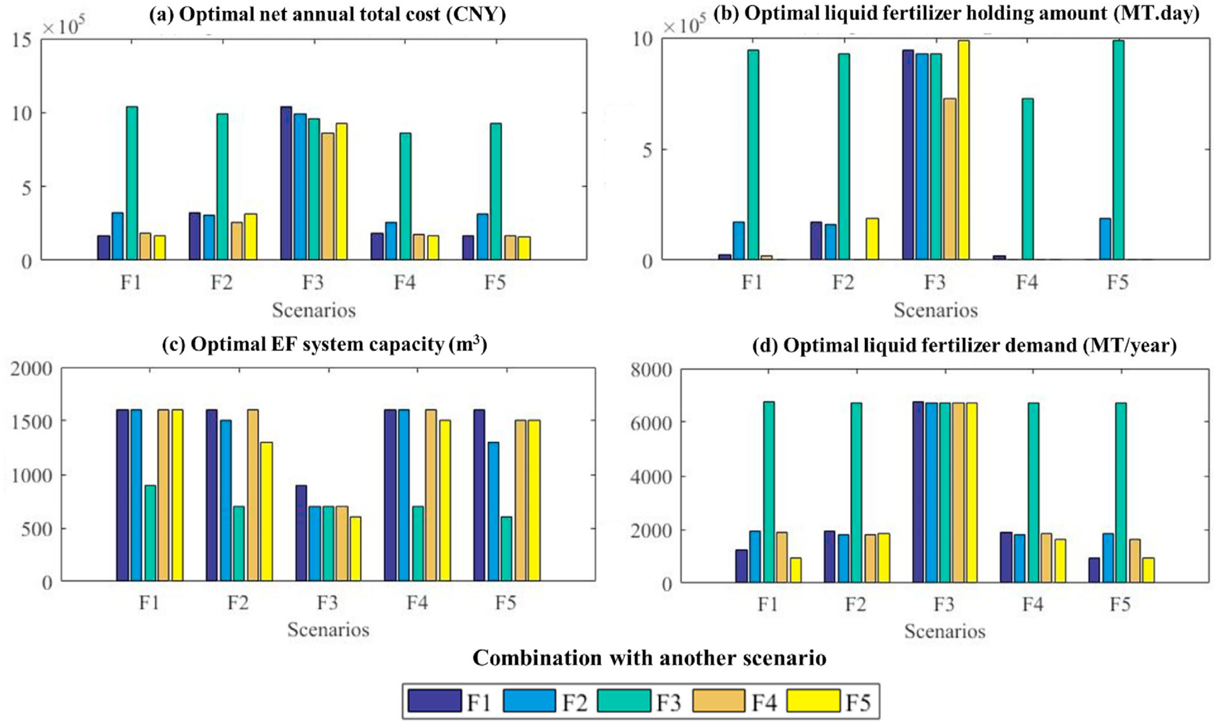

Fig. 9. Cross evaluation of the optimal results if two scenarios happen at the same time (MT: metric tonnes). *The cases of combining same scenario (like F1+F1) is the control group that represents no combination for this scenario.

$$Co_t^{Sep} = N\,days_t \times co_{Sep} \times (Y_{1.t} + Y_{2.t} + S_{1.t} + S_{2.t})$$
$$s.t.$$
$$h_{1q} : X_{1.t} + X_{2.t} + W_t = M_A + M_B \qquad (15)$$
$$h_{2q} : Y_{1.t} + Y_{2.t} - (1 - \eta_{Sep}) \times W_t = 0$$
$$h_{3q} : S_{1.t} + S_{2.t} - \eta_{Sep} \times W_t = 0$$

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 metric tonnes) and the liquid fertilizer holding-amount is 26 times higher than the amount in the base scenario. Comparing the operational plan in Fig. 10 and Fig. 7, the inflows of AD treatment was reduced ($Y_1 = 0$ metric tonnes/day 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.

5. Conclusions

Numerous research groups focus on identifying the best manure management method for animal farms. The design criteria not only concerns functionality and economy but focuses more on cleaner

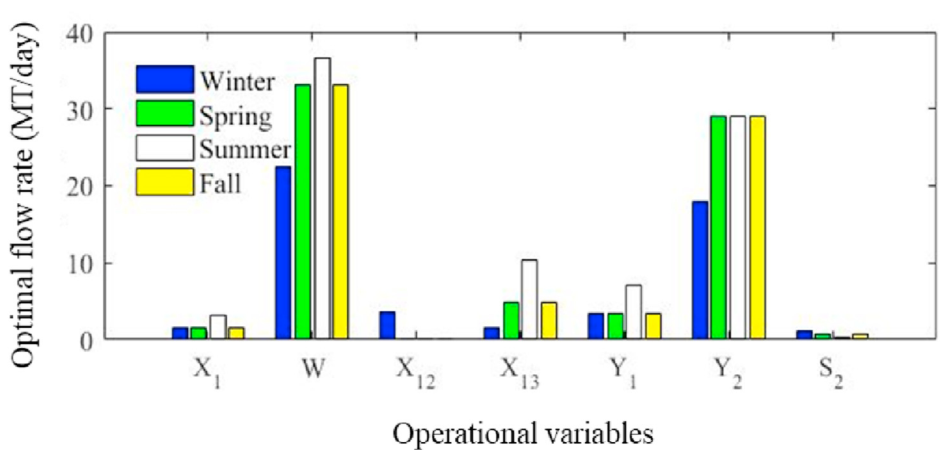

Fig. 10. Optimal manure processing operational plans of the alternative design (MT: metric tonnes).

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 scrapping 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.

CRediT authorship contribution statement

Jiangong Li: Writing - original draft, Methodology, Software, Investigation, Visualization. **Xinlei Wang:** Conceptualization, Writing - review & editing, Supervision, Data curation, Project administration, Funding acquisition. **Harrison Hyung Min Kim:** Writing - review & editing, Methodology. **Richard S. Gates:** Writing - review & editing, Validation. **Kaiying Wang:** Writing - review & editing, Conceptualization, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124550.

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