DEVELOPMENT OF DYNAMIC COMPUTATIONAL MODEL FOR AN INTEGRATED FARMING SYSTEM

BY

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THESIS

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ABSTRACT

The use of fossil fuels on farming systems is now widely recognized as unsustainable because of diminishing supplies and the contribution of these fuels to the increasing carbon dioxide concentration in the environment. Moreover, farming systems with higher nutrient usage efficiency are important to meet increasing human food demand. Integrated Farming Systems (IFS) that utilize wastes from one subsystem as sources for another subsystem represent a promising way for producing renewable energy and for recycling nutrients. The benefits of IFS are recognized; however, the dynamic properties of the system are not well understood. Previous models have taken static approaches which do not address the dynamic energy/nutrient relationships between subsystems. The current study, instead, focuses on a new approach that proposes the development of a dynamic model for IFS and applies that model to several computer simulations based on different scenarios.

This dynamic system model for IFS integrates swine production, swine barn energy requirements, anaerobic digestion (AD) processes, anaerobic digester heat requirements, combined heat and power (CHP) production, and nitrogen requirements for crop production. In this system, swine manure is collected during swine production and is taken as feedstock to the AD system to produce bio-methane. Bio-methane is then fed into the CHP unit for heat and power production. Nutrients from the AD system effluent can subsequently be fed to the cropping system to recycle nutrients for crop growth. Heat/power production by the CHP unit provides energy to maintain operations for swine facilities and digesters. A series of virtual simulations for different scenarios were applied to the proposed model to show different energy usage portfolios.

Pig growth performance is affected by operation strategies that include the use and non-use of cooling systems during the summer as well as weather conditions specific to various locations. Therefore, the current study employed simulations to compare gilt production in two locations - Springfield, IL and Oklahoma City, OK - under 2010 weather conditions. The results demonstrated that in summer in Springfield higher temperatures *without* cooling pads increased the feed-to-gain ratio significantly to 3.19 from 2.93 compared to the ratio *with* cooling pads. The current study also found that in summer in Oklahoma City due to higher heat stress conditions even *with* cooling pads, gilts had a higher feed-to-gain ratio (3.34) compared to conditions of lower heat stress in Springfield, IL (2.93). On the other hand, in winter in both Oklahoma City and Springfield due to the maintenance of comfortable indoor temperatures for pig growth, swine had similar feed-to-gain ratios.

The anaerobic digestion simulation under 2010 weather conditions showed that in winter in Springfield the digester had higher heat requirements compared to the digester in winter in Oklahoma City; however, in summer in both locations the heat requirements for the digester were similar. With all digesters being maintained in mesophilic condition at 35℃, the biogas production portfolios for the digesters in both cities were similar.

Simulations were also conducted of the total energy/nutrient production and consumption portfolios between operation strategies in summer and winter in both locations. As the swine facility in Springfield was found to need more heat in winter, this study proposes the use of only one CHP unit to provide sufficient power and to utilize extra biogas as fuel for heaters to support the swine facility heat requirements. On the other hand, because the heat requirements for the swine facility in Oklahoma City in winter were found to be lower, this study proposes two CHP units to produce more power and to generate sufficient heat to support swine production in that location.

The simulations, based on different scenarios as applied to the proposed dynamic IFS model, demonstrate how engineering design and operation strategies affect dynamic system properties. The simulations further show the feasibility for future research in the use of the proposed dynamic IFS model to examine new technologies and operation strategies.

To Father and Mother

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TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION 1

1.1 Justification for Research 1

1.2 Objectives 2

1.3 IFS Model Overview and Thesis Organization 3

CHAPTER 2 LITERATURE REVIEW 5

2.1 Integrated Farming System (IFS) 5

2.2 Swine Production System 7

2.3 Anaerobic Digestion and CHP System 9

CHAPTER 3: SWINE PRODUCTION SYSTEM 14

3.1 System Description 14

3.2 Simple Pig Growth Model 18

3.3 Swine Barn Energy Consumption Model 30

3.4 System Model Application and Discussion 43

CHPATER 4 ANAEROBIC DIGESTION AND CHP SYSTEM 51

4.1 System Description 51

4.2 Anaerobic Digestion Model 54

4.3 Anaerobic Digester Heat Requirement Model 63

4.4 CHP Unit 69

4.5 System Model Application and Discussion 70

CHAPTER 5 IFS MODEL AND APPLICATION 72

5.1 IFS System Description 72

5.2 Model Development 74

5.3 Model Inputs 77

5.4 System Model Application and Discussion 79

CHAPTER 6 CONCLUSION AND FUTURE RESEARCH 88
6.1 Conclusion 88
6.2 Future Research 89
REFERENCES 91

CHAPTER 1 INTRODUCTION

1.1 Justification for Research

Integrated Farming System (IFS) is a method of farming that utilizes nutrients more efficiently with the potential to produce more food than conventional farming systems (Franzluebbers, 2007; Morris & Winter, 1999). One feature of IFS is that waste from one IFS subsystem may become the input of another IFS subsystem (P. Edwards, Pullin, & Gartner, 1988). This integration leads to minimum external nutrient and energy input, thereby increasing nutrient usage efficiency. As human population growth and human food demand increase, a farming system that enhances the efficiency of nutrient, energy, and water usage becomes more important in meeting future human food demand (Tilman, Cassman, Matson, Naylor, & Polasky, 2002).

By comparison, conventional farming systems may negatively impact the environment and lead to degradation of natural resources. Non-treated manure in conventional livestock farming systems generate greenhouse gases, produce odor, and may have negative effects on the nearby ecological environment (Jackson, Keeney, & Gilbert, 2000). Excessive usage of industrial fertilizers and pesticides in conventional cropping systems also lead to environmental and food quality issues. By contrast, higher integration between livestock production and crop production through implementation of IFS is known to decrease industrial fertilizer usage, improve soil structure/productivity, and reduce pesticide usage through use of natural pest control processes. Studies that have compared food quality between conventional agriculture systems and integrated farming systems have found that IFS may provide food products that are of higher quality. (Franzluebbers, 2007; Morris & Winter, 1999).

Prior research of IFS has estimated mainly the annual nutrient/energy flows or analyzed the life cycle of energy or greenhouse gas emission (Cavalett, Queiroz, & Ortega, 2006; Dalsgaard, Lightfoot, & Christensen, 1995; Dalsgaard & Oficial, 1997; Kaparaju & Rintala, 2011; Nguyen, Hermansen, & Mogensen, 2010; Phong, De Boer, & Udo, 2011) while the dynamic behaviors of IFS have received scant attention. In order to investigate how operational strategies influence integrated farming systems, the current study examines the dynamic energy/nutrient relationships between individual subsystems.

To propose a dynamic IFS model, the current study combines models developed by previous research for swine production, anaerobic digestion, CHP production, and crop production. To test this model, computational simulations were applied to estimate dynamic energy/nutrient flows based on various scenarios of swine production in two locations.

1.2 Objectives

The overall goal of this research is to develop a dynamic computational model for an Integrated Farming System (IFS) and to analyze the dynamic properties of energy and nutrient flows that result from the combination of 1) swine production systems, 2) anaerobic digestion, 3) CHP production, and 4) crop production to meet feed requirements for swine production. In order to achieve this goal, the specific objectives are as follows:

1) To apply, modify, and verify a proposed pig growth model
2) To develop a swine barn energy consumption model based on a pig growth model
3) To apply and compare two different anaerobic digestion models
4) To develop an anaerobic digestion heat requirement model
5) To estimate annual crop production and develop a proposed IFS model by combining Items 1) through 4)

6) To demonstrate the application of the IFS model through simulations based on a comparison of various scenarios in two locations

1.3 IFS Model Overview and Thesis Organization

The computational dynamic IFS model proposed by this study combines several previously developed subsystem models into an overall systems approach. The subsystem models cover swine production, anaerobic digestion, CHP production, and crop production. The scope of the model proposed by this study is presented in a schematic diagram of energy and nutrient flow as shown in figure 1.1.

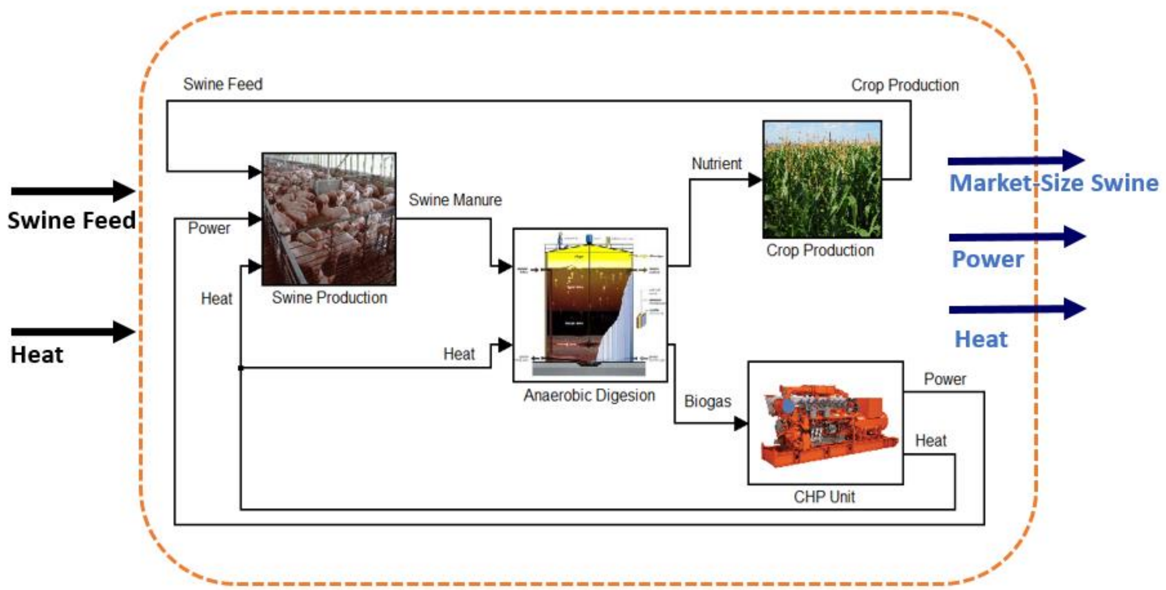

Figure 1.1 Overview of the proposed integrated farming system

Specifically, the proposed IFS model examines the usage of swine manure as AD feedstock for the production of biogas/bio-methane and uses of the resulting methane to generate power and heat. After the AD process is completed, power and heat are further utilized to satisfy swine barn and AD reactor energy requirements through the removal and transformation of a portion of carbon in animal waste to biogas. Nutrients, like nitrogen, that remain in the effluent after anaerobic treatment can be used as fertilizer. Based on the amount of nitrogen needed for swine feed and the amount of nitrogen in AD effluent, the proposed IFS model estimates the nitrogen recovery. Excess power and market-size swine are then exported to other subsystems. Additional heat and feed may be required under certain conditions to maintain the system.

This thesis is organized to address, first, a review of relevant literature in Chapter 2 followed by a description of the proposed integrated farming system under two major subsystems: the swine production system (Chapter 3) and anaerobic digestion and the CHP system (Chapter 4). To describe the two major subsystems, each chapter introduces and discusses several proposed sub-models. Empirical annual crop production estimations and the two major subsystem models are then combined for presentation of the proposed dynamic IFS model (Chapter 5). Several scenarios based on various conditions demonstrate the ability of the proposed model to simulate dynamic energy and nutrient flows. Finally, in Chapter 6, research conclusions are summarized and future research is recommended.

CHAPTER 2 LITERATURE REVIEW

This chapter covers an overview of research on Integrated Farming Systems (IFS) followed by review of research on swine production systems as well as anaerobic digestion and CHP systems. The research described here serves as the basis for the dynamic Integrated Farming System (IFS) model proposed by the current study.

2.1 Integrated Farming System (IFS)

In 1995, Dalsgaard et al. presented research that analyzed IFS by using indicators of ecological sustainability in agriculture. That study ranked farming systems based on four indicators of ecological sustainability: diversity, cycling, stability, and capacity and quantitatively showed the benefits of integrated farming systems in terms of ecological sustainability. The study demonstrated that low external input integrated resources management systems have the highest ecological sustainability and that high external input mono-cropping systems have the lowest ecological sustainability.

Two years later, Dalsgaard and Oficial (1997) proposed a programmatic framework to measure and model nutrient flow for small holder farming systems. The results of the annual mass-balanced nutrient flow model, which was based on weekly measurements, showed results of nutrient cycles in small holder farming systems. However, the dynamic properties of nutrient and energy cycles were not addressed.

Phong et al. (2011), who did research in the Mekong Delta, measured daily inputs and outputs for different agriculture–aquaculture IFS and implemented life cycle assessments of food production in integrated systems. Their findings showed that the greatest negative impacts to the environment occur as the result of two situations: external feed used in swine production and excessive fertilizers used in rice production, also CH_4 emission from the paddy fields.

Cavalett et al. (2006) utilized energy assessments to indicate better energy efficiency but less negative environmental impact on IFS compared to conventional farming systems. Research carried out by Cavalett et al. (2006) also indicated that integrated production systems are able to reduce external input by recycling materials within the system. Their research further demonstrated that energy assessments are helpful in making decisions about sustainable and environmentally sound development of agriculture. However, that approach did not address the dynamic properties of IFS.

A decade earlier, other researchers, who proposed schemes for integrated farming systems (1993) introduced crop models and livestock models that has proved useful for more recent studies. Several components of their livestock model include the interaction between organic resources and livestock, livestock and land, and livestock product utilization.

Over the past several years, other researchers have also recognized the benefit of IFS based on life cycle assessments. Their results show that IFS has lower negative impact on greenhouse gas (GHG) emissions and saves fossil energy for farming systems. Nguyen et al. (2010) examined an integrated swine farming system in Europe and showed that the system has the potential to reduce fossil energy by 61% and GHG emission by 49%. Kaparaju and Rintala (2011) demonstrated that greenhouse gas emission is mitigated by replacing fossil fuels with bio-methane that is achieved by connecting anaerobic digester and livestock production systems.

Although previous studies do not focus on specifically the development of a dynamic IFS model and often do not address exact elements that are included in the current study, those studies have proved helpful in presenting different approaches and concepts for IFS assessments that have been incorporated in the dynamic model proposed by the current study.

2.2 Swine Production System

2.2.1 Pig Growth Model

Swine production is highly correlated with nutrient intake and the surrounding environment. The growth of healthy pigs is also highly correlated with the efficiency of operation of barn facilities. Therefore, understanding the relationships between swine production, facilities operations, and pig growth inside the barn are very important. In order to develop a swine production system model, it is necessary to understand existing models on both swine barn operations and pig growth models.

In 1976, C. Whittemore and Fawcett developed a preliminary pig nutrient partitioning model by demonstrating substantial empirical relationships between different parameters. Whittemore (1986) suggested that pig growth models should remain flexible, allowing for effective forward prediction. His later article addressed the importance of testing ideas by the use of models and understanding, rather than merely measuring, the growth response.

Black et al. (1988) developed a model (AUSPIG) that simulates the entire productive cycle and includes predictions of the *ad libitum* effect. Black's model regards nutrition, genetics, and environment as input variables for development of a deterministic model of swine intake and growth.

Mougham et al. (1987) developed a simple pig growth model for the growing-finishing period of swine production to describe pig live weight changes on a daily basis. Unlike Black et al. (1987) who applied empirical relationships between parameters to determine nitrogen retention, Moughan constrained body protein retention by requiring a minimum level of body lipid. Their model showed accurate predictions with few parameters. However, Moughan's model did not take into account environmental factors, for example, indoor temperature, but rather assumed pig growth under thermoneutral condition.

Researchers in the U.S. developed a model (NCPIG) based on the interaction among environmental factors, diet intake, and genotypes. The model also predicted how *ad libitum* intake influences pig growth (Bridges, Turner, Stahly, Usry, & Loewer, 1992; Bridges, Turner, Usry, & Nienaber, 1992; Usry, Turner, Bridges, & Nienaber, 1992). However, that full model is difficult to use due to its complicated parameters. Three years later, in order to avoid those difficulties, Bridges et al. (1995) built a neural network model based on the NCPIG model that simplified parameters and computation processes.

2.2.2 Swine Barn Energy Consumption Model

Understanding heat and moisture production of livestock is important for maintaining a comfortable environment for pigs and workers. Researchers measured and developed livestock heat production models that include levels of animal activity (Albright, 1990; Brown-Brandt, Nienaber, Xin, & Gates, 2004; Pedersen & Sallvik, 2002). Recently, ASHARAE also published new empirical equations for swine heat and moisture production. The newest model shows that American pigs generate more heat and moisture compared to prior estimations (Brown-Brandl, 2014).

Strategies for heating and ventilation systems have been simulated by many researchers. Chao et al. (2000) built a computational model to compare the differences between a conventional ventilation system and a fuzzy logic control system. Their results show the improvement of energy consumption by implementing a fuzzy logic control system. Lambert et al. (2001) compared different kinds of control systems by simulation and concluded the benefit of temperature-humidity control systems over temperature control systems under cold weather conditions. Morsing et al. (2005) also simulated indoor psychrometric properties, air quality, and energy consumption based on levels animal heat and moisture production on swine barns in Portugal, Finland and Denmark.

Both swine barn HVAC system simulations and pig growth models are very mature, but few studies connect the two together. Bridges et al. (1998) connected NC-204 swine growth model (NCPIG) and natural-ventilated swine barn simulations to evaluate economic returns of misting-cooling systems. The same research group compared the NCPIG model with results from an on-farm experiment and found the predictions were accurate (Turner et al., 1998). However, with modern mechanical ventilation control systems, connecting a pig growth model with a mechanical-ventilated swine barn simulation is needed to show how mechanical-ventilated operation strategies affect swine production.

2.3 Anaerobic Digestion and CHP System

2.3.1 Anaerobic Digestion Process

The anaerobic digestion process is one of the oldest techniques used to produce bio-fuel and has been widely applied to different fields. The high volatile solid concentration of agriculture waste provides a good source as feedstock for the anaerobic digestion process. Because effluent has higher stability after anaerobic treatment, the effluent can also be used as fertilizer for crop fields.

Researchers have studied energy and nutrient recovery by aerobic digestion. Boersma et al. (1978) designed an experimental system to recover energy and nutrients. The experiment estimated total energy recovery from methane produced by anaerobic digestion and protein recovery (algae or bacteria) in various kinds of recovery systems. The report showed efficient rates of recycling energy and nutrient from swine production but did not address the dynamic properties in their recovery system.

Several researchers became interested in the methane production rate based on different AD feedstock which is correlated with this study. Møller et al. (2004) showed different methane production by applying different types of animal waste to anaerobic digestion. Balsam and Ryan (2006) introduced several anaerobic digestion considerations and listed biogas net returns by using as feedstock manure from different kinds of animals. Although these studies do not focus on anaerobic digestion modeling, the results show a baseline for drawing comparisons in the current study.

Empirical relationships among methane production, volatile solid content of feedstock, and retention time of process have been established (Chen & Hashimoto, 1978; Hashimoto, 1984). The model estimates methane production algebraically but lacks the ability to simulate carbon-dioxide/methane concentration and is not able to present real bio-physical-chemical processes.

Andrews and Graef (1970) quantified a dynamic model to describe anaerobic digestion that was built based on an understanding of the inhibition function to connect specific growth of methane bacteria and volatile acids concentration. The limitation on methane bacteria growth due to concentration of the non-ionized acid and other inhibition agent was considered. Biological and physical interactions between gas and liquid in anaerobic digestion were also considered. Their study proposed a pioneer dynamic modeling approach toward anaerobic digestion simulation.

A few years later, Hill and Barth (1977) also built a dynamic model for AD simulation on animal waste. To simulate the AD process on animal waste with a more realistic approach, Hill & Barth (1977) considered ammonia production in the anaerobic digestion process.

Bastone et al. (2002) developed a more generalized anaerobic digestion model (Anaerobic digestion model number 1, ADM1). The model structure includes multiple steps describing biochemical as well as physicochemical processes and contains 32 dynamic concentration state variables in the model. However, the complexity and stiffness of the model causes difficulties in computation. Rosen et al. (2006) discussed these computation difficulties and reformulated an ordinary differential equation system to a differential algebraic equation system to overcome these drawbacks.

Zaher and Chen (2006) reported practical analyses of solid wastes and manure to accurately estimate substrate composition for anaerobic digestion. Interfaces between ADM1 input and practical measurements were built by maintaining the nutrient balance. The study also lists animal manure waste characteristics, reporting carbohydrate and protein portions of different kinds of animal manure.

Because ADM1 was designed for municipal waste water treatment, some parameters in ADM1 needed to be modified to meet agriculture objectives. Gali et al. (2009) developed an anaerobic digestion model based on ADM1 and examined the bio-degradability of different types of agro-waste. Using different agro-wastes, the modified ADM1 model based on pig manure was validated in their research on a continuous lab scale reactor.

2.3.2 Anaerobic Digester Heat Requirement Model

In addition to fuel production from anaerobic digestion, researchers have also studied energy consumption from anaerobic digestion. Since temperature around 35℃ (mesophilic) in the anaerobic digestion process has higher efficiencies, it is necessary to maintain sludge temperature at a certain level. Ram et al. (1985) built a computational model for a digester combined with a shallow solar pond water heater to examine the feasibility of the engineering design. Axaopoulos et al. (2001) later developed a computational model to analyze and predict thermal behavior of a solar heated digester based on thermal properties of digesters and they predicted methane production based on Hashimoto's empirical model.

2.3.3 Combined Heat and Power (CHP) System

Within the anaerobic digestion process, combined heat and the power (CHP) unit is often connected to anaerobic digestion in order to utilize bio-methane. With greater attention worldwide directed toward issues of global warming, interest in CHP technologies has grown among energy consumers, regulators, legislators, and developers due to efforts by customers and researchers seeking to reduce energy costs while improving service and reliability (Dong, Liu, & Riffat, 2009). CHP systems, compared to conventional power production technologies, have the advantage of utilizing both heat and electric energy from feedstock; therefore, there exists potential for energy and environmental benefits over electric-only and thermal-only systems in power generation applications.

The development of small-scale and micro-scale biomass-fuelled CHP systems has been supported and funded by the governments of many industrialized nations. Bain (2000) reported that the U.S. National Renewable Energy Laboratory (NREL) funded a small modular bio-power project, aimed at development of biomass systems that have minimum negative impacts on the environment and that provide power between 5 kW and 5 MW. Pavlas et al. (2006) studied the retrofit of a fossil fuel-based micro-CHP system in a hospital and among the alternatives considered, they found that a biomass-fuelled micro-scale CHP could achieve the highest CO2 reduction.

Commercialization of CHP units is now well developed and widely utilized for waste water treatment plants and livestock production systems. This current study utilizes information of existing commercialized CHP units for the system design of the proposed IFS dynamic system, based on bio-methane production from anaerobic digestion model results.

CHAPTER 3: SWINE PRODUCTION SYSTEM

The goal of Chapter 3 is to describe the dynamic swine production system model, developed by this current study, which is proposed for use by farmers and engineers in commercial swine production systems. The model is developed for application in two different scenarios and includes two subsystem models. The first subsystem model addresses simple pig growth (Section 3.2) while the second subsystem model, built on the first subsystem model, addresses swine barn energy consumption (Section 3.3). Section 3.4 is an application of the swine production system model and demonstrates simulations of several different scenarios.

3.1 System Description

For the purpose of simulating both swine performance and commercial swine facility energy consumption, the swine production system model proposed by the current study is limited to the growing-finishing swine period (20 – 107 kg gilts and barrows) with animals being housed in a swine barn. Once the swine reach market size (107 kg), they will be removed from the barn and after the facility is cleaned, a new groups of piglets (20 kg) will be brought in.

The commercial swine barn proposed by the current study is 12.19 m (40 ft) wide by 146.30 m (480 ft) long and is designed to house a total of 2400 head of growing-finishing swine. The design of the insulated swine barn features a trussed roof with a flat fiberglass ceiling and eves that are 2.23 m (7.4 ft) in height. Wall construction materials are wood and concrete as shown in figure 3.1.

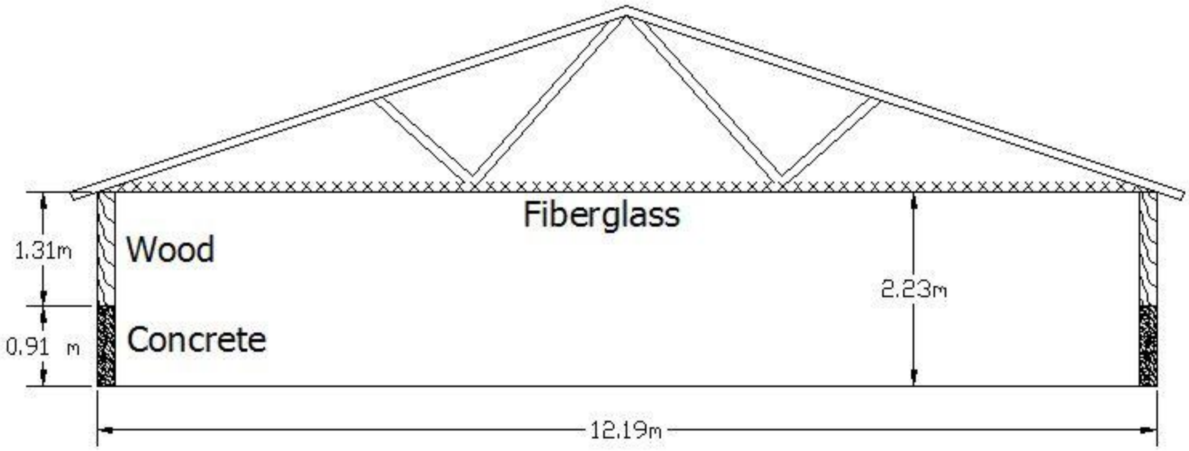

Figure 3.1 Elements of insulated swine barn

The current study proposes that pigs be split-sex fed in mechanical-ventilated buildings with a thermostatically controlled cooling system that includes a cooling pad or a sprinkler with eleven fans and three heaters. The fans and heaters are divided into six ventilation and three heat stages as shown in table 3.1. Three pit fans are included to provide minimum ventilation rate. If indoor temperature is lower than the set point temperature, then the heaters will be turned on. On the other hand, if indoor temperature is higher than the set point temperature, higher stages of ventilation will be turned on.

Feed used in the simulation is a corn-soy based ration with two phases fed to the barrows and only one phase fed for the growing-finishing period to the gilts. The lighting period for the swine barn is 8 hours from 6 a.m. to 2 p.m. with two rows of lighting fixtures over the pens. More details are described in sections 3.2.2 and 3.3.2.

Table 3.1 Stage control for ventilation fans and heaters

Heating/ Cooling	**Difference between set point and indoor temperature**	**Details of stages**		
Ventilation system		Ventilation rate (cfm)	Size and Number of Fans	Average Ventilating Efficiency Ratio (VER) (cfm/Watt)
	0	18540	24" x 3	15.1
	2	30300	24" x 3 +36" x 1	16.8
	4	42140	24" x 3 +36" x 2	17.5
	6	89140	24" x 3 +36"x 2 +48" x 2	19.7
	8	136140	24" x 3 +36"x 2 +48" x 4	20.4
	10	183140	24" x 3 +36"x 2 +48" x 6	20.7
Heater		Maximum capacity		
	-2	59kW		
	-4	118 kW		
	-6	177 kW		

A systematic diagram of the swine production system model is shown in figure 3.2. The Simple Pig Growth Model (SPGM) generates swine live weight which is used as an input variable for the swine barn energy consumption model. The swine barn energy consumption model provides output of, for example, indoor temperature and dynamic heat/power requirements based on swine live weight. The simulated indoor temperature generated from the swine barn energy consumption model is an input variable in SPGM. The scenarios of the swine production system model proposed by this study were developed by comparing heat/power requirements, feed-to-gain ratio, and days on feed.

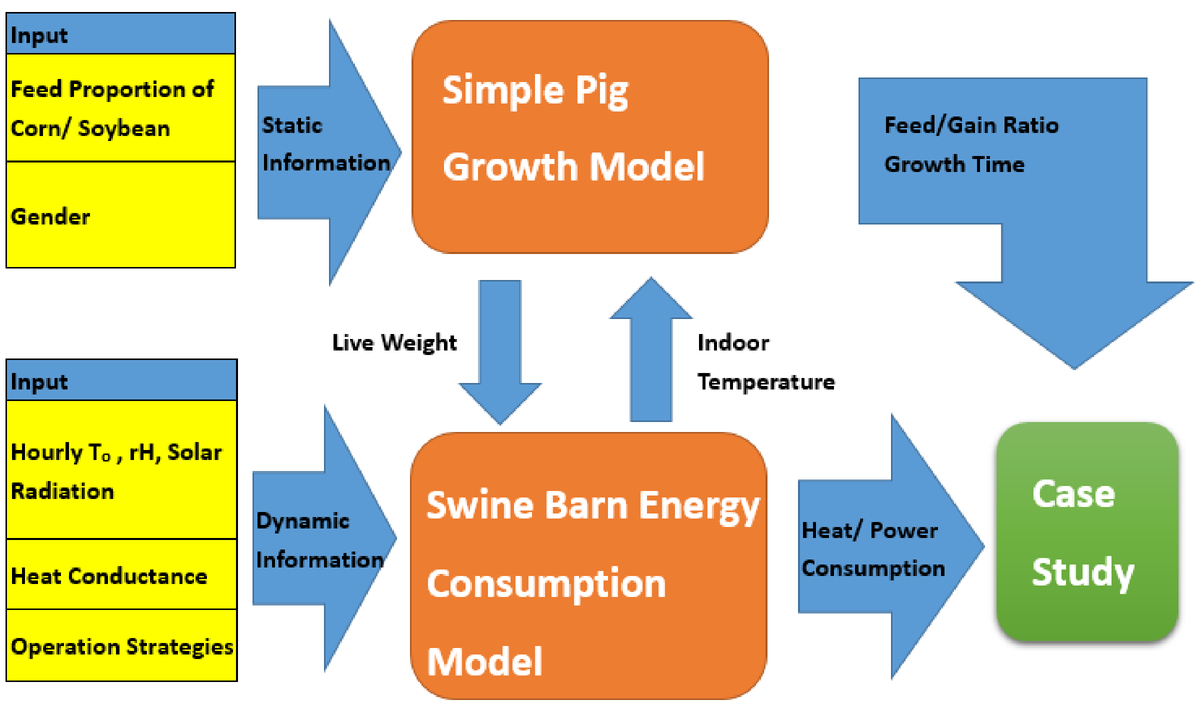

Figure 3.2 Systematic diagram of swine production system model

3.2 Simple Pig Growth Model

This section applies and modifies the pig growth model to simulate pig growth performance. The current study follows the simple pig growth model scheme developed by previous research (De Lange, 1995; Moughan et al., 1987) that was selected for its simplicity. Modifications based on several new empirical relationships and parameters for the purpose of the current study are made. While De Lange's model assumes that pig growth occurs under thermoneutral zones, this study considers indoor temperature as an environmental factor that affects pig growth.

3.2.1 Model Development

Basic principles of energy and amino acid partitioning for the period of swine growth are included in the modified SPGM. The concept of nutrient partitioning is shown in figure 3.3**.** The following simplifying assumptions are made:

1) Genetic differences between pigs are presented by parameters: e.g., maximum daily protein gain and minimum lipid to protein ratio.

2) Dietary nutrients other than amino acids and energy (such as vitamins, minerals, and essential fatty acids) are not limiting to growth.

3) SPGM presents only average performance with no individual variation included in the model. Disease effect is also not considered in the modified SPGM model.

Since consideration of all different genotypes are beyond the scope of this study, the model proposed here uses parameters set forth by previous studies for all genotype results as indicated in the first assumption. Nutrients other than amino acids and energy are important; however, amino acid and digestible energy in diet are two main contributors for pig growth as indicated in the second assumption. Because the pig growth model is deterministic, no other stochastic information (ex: individual variety, disease effect) is considered as indicated in the third assumption.

De Lange (1995) programmed the SPGM on a Quattro Pro spreadsheet. The current study then modified and reprogramed the SPGM in Simulink S-function to connect to the swine barn energy consumption model.

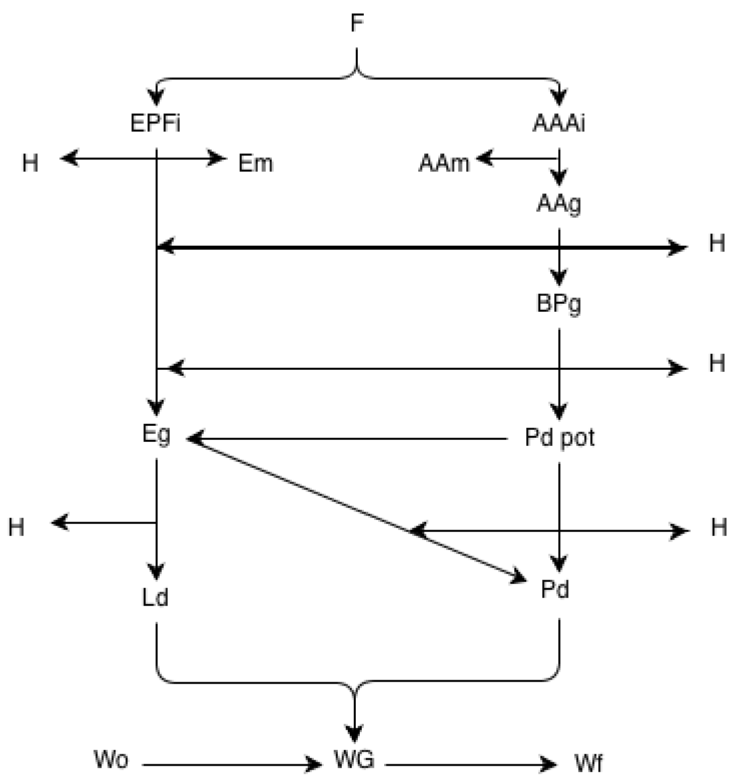

Figure 3.3 General representation of energy and protein partitioning in a simple pig growth model. Meaning of symbols: F- feed intake; EPFi – protein free digestible energy intake; H - heat loss; Em – energy requirement for maintenance; Eg – energy available for gain; Ld – body lipid deposition rate; AAAi – available amino acid intake; AAm – amino acid requirements for maintenance; AAg – amino acid available for gain; BPg – balanced protein deposition; Pd_{dot} – potential body protein deposition rate; Pd – actual body protein deposition rate; W_0 – initial body weight; WG – body weight gain; W_f – final body weight, see text for further details. Adopted from De Lange (1995)

Inputs to simulate swine growth processes are as follows: initial body weight, daily intake of available amino acids, maximum protein deposition rate, minimum lipid to protein ratio, gender, and protein-free digestible energy (DE). Additional details are listed in section 3.2.2.

Based on the general scheme of nutrient partitioning as shown in figure 3.3**,** the model proposed by the current study aims to estimate final body weight on a daily basis. With initial body weight (W_0, kg), initial protein weight (P_0) and minimum body lipid to body protein ratio (minLP), the minimum lipid weight (L_{min}) is:

$$L_{min} = minLP \times P_0 \tag{3. 1}$$

Initial empty body weight (WE_0, kg) is calculated as the sum of initial protein weight (P_0, kg), initial lipid weight (L_0, kg), initial body water weight (Wt_0, kg), and initial body ash weight (A_0, kg):

$$\mathrm{WE}_0 = P_0 + L_0 + Wt_0 + A_0 \tag{3. 2}$$

Where

$$\mathrm{Wt}_0 = (4.332 + 0.0044 \times Pd_{max}) \times P_0^{0.855} \tag{3. 3}$$

$$\mathrm{A}_0 = 0.189 \times P_0 \tag{3. 4}$$

Gut fill is predicted by equation

$$\text{Gut fill} = 0.3043 \times \mathrm{WE}_0^{0.5977} \tag{3. 5}$$

$$\mathrm{W}_0 = \mathrm{WE}_0 + \text{Gut fill} \tag{3. 6}$$

The reference voluntary daily digestible energy intake (DEvi, kJ/d) is given as a function of body weight (W, kg) as modified by National Research Council (2012) equations (modified to 1.05 times larger):

$$\mathrm{DEvi} = 1.05 \times 44225.1684(1 - e^{-e^{-0.0176} \times \mathrm{W}}) \tag{3. 7}$$

For gilts and barrows, the digestible energy intake are different:

For gilts:

$$\mathrm{DEvi} = 1.05 \times 45916.6356(1 - \mathrm{e}^{-e^{-3.803 \times W^{0.9072}}}) \tag{3. 8}$$

For barrows:

$$\mathrm{DEvi} = 1.05 \times 43739.4996(1 - \mathrm{e}^{-e^{-4.283 \times W^{1.0843}}}) \tag{3. 9}$$

To represent the impact of environmental temperature on digestible energy intake, the lower critical temperature (LCT) is estimated and DEVi is adjusted.

$$\mathrm{LCT} = 17.9 - 0.0375 \times \mathrm{W} \tag{3. 10}$$

$$\text{Fraction of DEvi intake} = 1 - 0.012914 \times [\mathrm{T_i} - (\mathrm{LCT} + 3)]$$
$$-0.001179 \times [\mathrm{T_i} - (\mathrm{LCT} + 3)]^2 \tag{3. 11}$$

Feed intake (F, g/d) is then calculated by digestible energy of diet content (DEd, kJ/g)

$$\mathrm{F} = \mathrm{DEvi}/\mathrm{DEd} \tag{3. 12}$$

Swine feed usage is correlated to feed by assuming voluntary daily feed intake rate (F%vi, %)

$$\mathrm{F_{usage}} = \mathrm{DEvi}/\mathrm{DEd} \div (\mathrm{F\%vi}/100) \tag{3. 13}$$

This model proposed by the current study assumes voluntary daily feed intake rate is 90%.

With the dietary amino acid (AAd, g/kg) and apparent amino acid availabilities (AAa, g/kg) for different kinds of amino acids (lysine, methionine, methionine plus cysteine, threonine, tryptophan, and isoleucine), the available amino acid intake (AAAi, g/d) is calculated:

$$\mathrm{AAAi} = \mathrm{F} \times \frac{\mathrm{AAd}}{1000} \times \mathrm{AAa} \tag{3. 14}$$

The intake of available total protein (APi, g/d) is calculated in a similar way from the total dietary protein content. Protein-free digestible energy intake (EPFi, kJ/d) is calculated by gross energy content of protein (EP), which is assumed to be 23.6kJ/g

$$\mathrm{EPFi} = \mathrm{F} \times \mathrm{DEd} - \mathrm{APi} \times \mathrm{Ep} \tag{3. 15}$$

The maintenance requirement for total protein (Pm) or an amino acid (AAm, g/d) is given priority over the total protein or amino acid requirements for growth. The relationship between Pm, AAm, and body weight is given from metabolic rate:

$$\mathrm{Pm} = 0.9375\mathrm{W}^{0.75} \tag{3. 16}$$

$$\mathrm{AAm} = \mathrm{Pm} \times (\mathrm{AA\%bp}/100) \tag{3. 17}$$

Where AA%bp is the amino acid content of balanced (‘ideal’) protein (%) for different kinds of amino acids, the amount of total protein that can be used for gain (Pg, g/d), and amino acid that are available for gain (AAg, g/d) with absorptive efficiency of utilizing protein and amino acid at 85% are:

$$\mathrm{Pg} = (\mathrm{APi} - \mathrm{Pm}) \times 0.85 \tag{3. 18}$$

$$\mathrm{AAg} = (\mathrm{AAAi} - \mathrm{AAm}) \times 0.85 \tag{3. 19}$$

The amount of balanced protein that can be derived from each amino acid and that can potentially be utilized for growth (BP(AA)g (g/d)) are calculated:

$$\mathrm{BP(AA)g} = \mathrm{AAg}/(\mathrm{AA\%bp}/100) \tag{3. 20}$$

The actual amount of balanced protein that can be utilized for body protein deposition (BPg, g/d) is equal to the smallest quantity of balanced protein that can potentially be utilized for growth and that is supplied by each individual amino acid or total protein.

The potential body protein deposition rate (Pd_{pot}, g/d) is determined by BPg or the animal’s upper limit to body protein retention (Pd_{max}, g/d), which is affected by pig gender, strain, and breed.

$$\mathrm{Pd_{pot}} = \min[\mathrm{BPg}, \mathrm{Pd_{max}}] \tag{3. 21}$$

With the supply of energy and minimum body lipid to body protein ratio, the model proposed by the current study can determine whether the potential body protein deposition rate equals the actual body protein deposit rate.

Energy derived from amino acids and unbalanced amino acids that are inevitably catabolized (E1) is calculated as:

$$\mathrm{E1} = (\mathrm{APi} - \mathrm{Pm} - \mathrm{BPg}) \times 11.5 \tag{3. 22}$$

Energy derived from balanced protein that can be utilized for growth but that is supplied in excess of that required to support the potential body protein deposition rate

$$\mathrm{E2} = \left(\mathrm{BPg} - \mathrm{Pd}_{pot}\right) \times 11.5 \tag{3. 23}$$

The amount of energy that is available for growth (Eg, kJ/d) is then calculated

$$\mathrm{Eg} = \mathrm{EPFi} + \mathrm{E1} + \mathrm{E2} + \left(\mathrm{Pd_{pot}} \times \mathrm{Ep}\right) - \mathrm{Em} \tag{3. 24}$$

Em represents the maintenance energy requirements. In cold weather conditions, Em will be higher due to the needs of thermogenesis. If the temperature is higher than LCT, there is no thermogenesis. If the temperature is lower than LCT, the relationship in equation 3.25 takes place:

$$\mathrm{Em} = \text{standard Em} + \text{Em for thermogenesis}$$

$$\text{Standard Em} = 824.248 \times \mathrm{W}^{0.60}$$

$$\text{Em for thermogenesis} = 0.07425 \times (\mathrm{LCT} - \mathrm{T}) \times \text{Standard Em} \tag{3. 25}$$

The potential body lipid deposition rate (Ld_{pot}, g/d) is then calculated:

$$\mathrm{Ld_{pot}} = (\mathrm{Eg} - \mathrm{Epd} \times \mathrm{Pd_{pot}})/\mathrm{Eld} \tag{3. 26}$$

Where Epd is the energy cost of body protein deposition (kJ/g) and body lipid deposition (kJ/g). The final protein and lipid weight are then calculated:

$$\mathrm{Pf} = \mathrm{Po} + \mathrm{Pd_{pot}}/1000$$

$$\mathrm{Lf} = \mathrm{Lo} + \mathrm{Ld_{pot}}/1000 \tag{3. 27}$$

With the relationship between water, ash weight, and protein weight, the final body weight is calculated:

$$W_f = \frac{P_f + L_f + W_{tf} + A_f}{0.95} \tag{3.28}$$

Weight gain (WG) equals $W_f - W_0$

The current study programs the above process in S function (S_piggrowth) in Simulink. The model in Simulink is shown in figure 3.4. Since the modified SPGM is a discrete model but indoor temperature is simulated continuously, this study assumes the critical temperature for swine growth is the daily maximum temperature. The Relational operator and Max resettable block are utilized to find the daily indoor maximum temperature. Although pig weight, feed, and heat production are generated discretely, Simulink takes these discrete signals as continuous by interpolation for the calculation of other continuous subsystems.

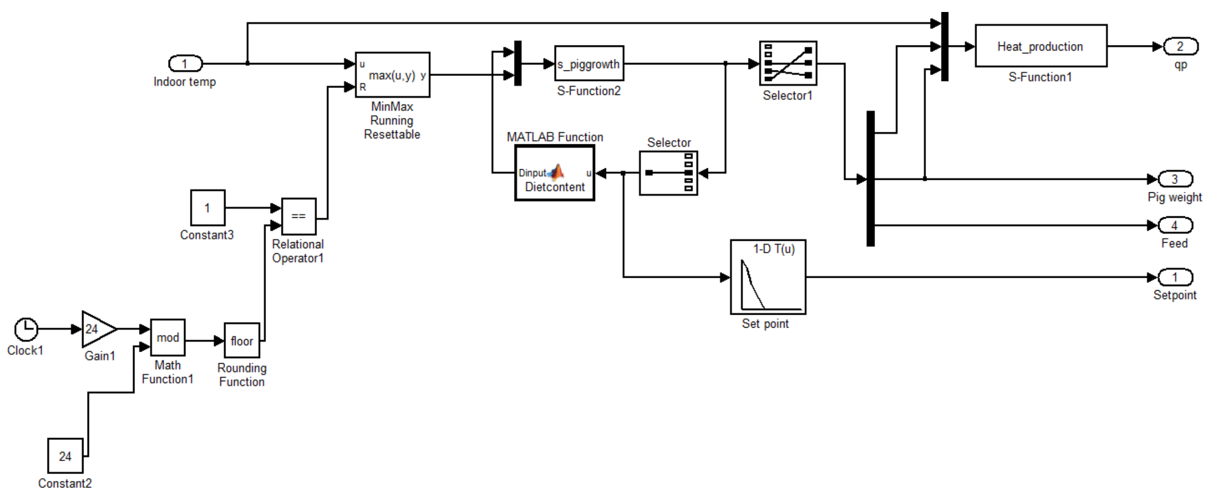

Figure 3.4 Static model of the SPGM

The model shown in figure 3.4 requires amino acid content for estimating balanced amino acid intake (equation 3.20 and 3.21). In order to simplify estimation of amino acid content in swine feed, the results of the research to calculate amino acid based on feed proportion of corn and soybean meal (SBM) as shown in table 3.2.

Table 3.2 Amino acid content in Corn and SBM

Critical Amino Acid	Corn	Reference	Critical Amino Acid	SM	Reference
Protein % (per dry weight)	7.70%	Huang et al. (2012)	Protein % (per SBM weight)	47.50%	Thakur and Hurburgh (2007)
Moisture % (per dry weight)	21.20%	Huang et al.(2012)	Moisture % (per SBM weight)	12%	Thakur and Hurburgh (2007)
LYS (g per kg N)	167	Sosulski and Imafidon (1990)	LYS (g per kg N)	406	Sosulski and Sarwar (1973)
MET (g per kg N)	126	Sosulski and Imafidon(1990)	MET (% per SBM weight)	0.65	Thakur and Hurburgh (2007)
MandC (g per kg N)	255	Sosulski and Imafidon(1990)	MandC (g per kg N)	188	Sosulski and Sarwar(1973)
THR (g per kg N)	256	Sosulski and Imafidon(1990)	THR (g per kg N)	231	Sosulski and Sarwar(1973)
TRP (g per kg N)	59	Sosulski and Imafidon(1990)	TRP (g per kg N)	81	Sosulski and Sarwar(1973)
ILEU (g per kg N)	200	Sosulski and Imafidon(1990)	ILEU (g per kg N)	306	Sosulski and Sarwar(1973)

3.2.2 Model Inputs and Verification

The modified SPGM, which is modified from previous research (De Lange, 1995; Moughan et al., 1987), requires all the typical parameters associated with nutrient partitioning. Table 3.3 provides a summary of the model parameters. This section illustrates the model input and provides model verification by comparing the modified SPGM proposed by the current study, experiments, and the NCPIG model.

Table 3.3 Parameters for SPGM

Parameter	Description	Value	Unit
Pdmax	Maximum protein retention rate	160	g/day
Min LP	Minimum lipid to protein ratio	1	NA
Epd	Energetic cost of body protein deposition	37	kJ/g
Eld	Energetic cost of body lipid deposition	48	kJ/g
Ep	Gross energy content of protein	23	kJ/g

The modified SPGM can consider various diet content. However, in order to be consistent with the on-farm experiments, the current study used traditional corn-soybean meal (SBM) to verify results of the experiments (Turner et al., 1998). Turner et al. (1998) worked with an independent commercial swine producer to test the NCPIG model against measured on-farm data. Several assumptions are inherent from Turner et al. (1998) and Bridges et al. (1992) to maintain the same environmental conditions for pigs. The diet table used for the experiments is listed in table 3.4.

Table 3.4 Diet content for swine

Feedstuff Ingredients	Diet NO. 1 20-60 kg Barrows 20 kg- mkt. Gilts % Each Feedstuff by weight	Diet NO. 2 60 kg –mkt. Barrows %Each Feedstuff by weight
Corn	76.45	80.525
Soy Bean Meal (SBM)	20	16.25
Suppl. or pre-mix		
Vitamin	0.2	0.175
Lysine	0.1	0.1
CuSO4	0.1	
Di-Cal	2	1.75
Calcium Carbonate	0.75	0.75
Salt, iodized	0.35	0.35
Antibiotic	0.05	0.1
Total	100	100
ME	13.877 kJ/kg	13.981 kJ/kg

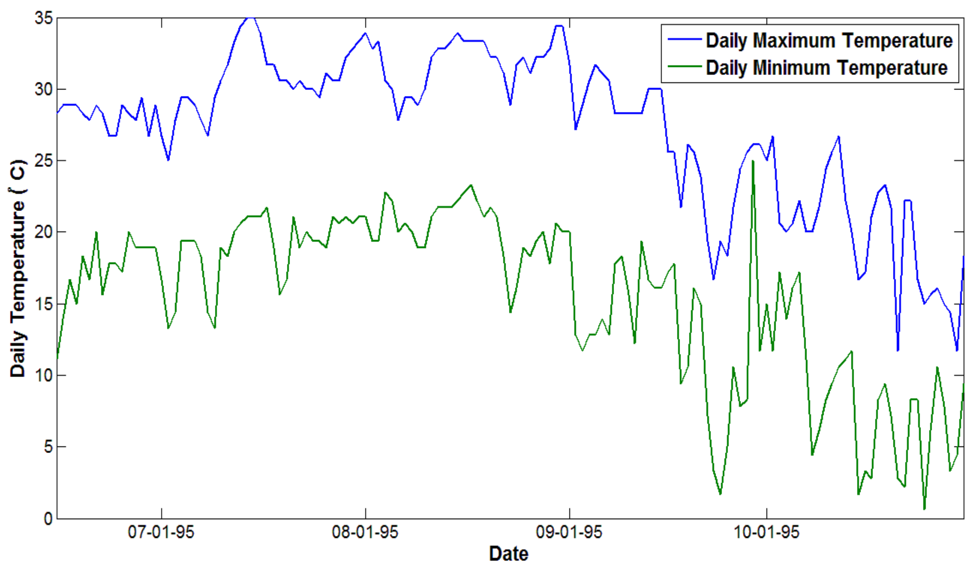

Figure 3.5 Daily maximum and minimum temperature in Bardstown, Kentucky

In order to validate the modified SPGM model, the current study compared between the modified SPGM results to previous research in 1998, which includes experimental results and simulations of the NCPIG model, by Turner et al.

Temperature information from the year 1995 in Bardstown, KY is collected from National Oceanic and Atmospheric Administration (NOAA) as previous research (Turner et al., 1998) and shown in figure 3.5. Unlike the NCPIG model, SPGM proposed by the current research simulated pig growth performances by a daily basis instead of 0.1hour time steps. Therefore, estimation of diurnal temperature and humidity profile is not necessary as in NCPIG model implemented in Turner et al. (1998).

As shown in table 3.5, the verification results of the modified SPGM compare experimental and modeling results from Turner et al. (1998). Because the modified SPGM was not designed for modeling *ad libitum* effect, like the NCPIG model and the experiments, the amount of swine feed use to grow barrows as estimated by the modified SPGM is lower than the on-farm measurement.

In order to modify the effect to a more accurate estimation on swine feed usage, the current study introduced a modification factor of 1.1 to estimate real swine feed usage based on the modified SPGM results. The modified feed-to-gain ratio (F/G) and average daily feed are presented in table 3.5 in brackets.

The results simulated by the modified SPGM model shows that the time needed to raise barrows from 20kg to 107 kg is closer to experiments compared to the NCPIG model. The NCPIG model and the modified SPGM have very similar estimations for the average daily gain for gilts**.** The results show the benefits of the modified SPGM due to simple input parameters compared to NCPIG with sufficient accuracy.

Table 3.5 Production performance, white group, 6/15/95 start date, grow-finish period

	Producer Barrow	NCPIG Barrow	**Modified SPGM Barrow**	Producer Gilt	NCPIG Gilt	**Modified SPGM Gilt**
Days on feed	102.1	108	102	109.9	110	109
Slaughter wt., kg	107	107.6	107.3	107.2	107.5	107.3
ADF, kg/day	2.51	2.39	2.11 (2.32)	2.19	2.08	1.99 (2.18)
ADG, kg/day	0.82	0.78	0.86	0.77	0.77	0.80
F/G, kg/kg	3.06	3.06	2.47 (2.70)	2.9	2.71	2.49 (2.73)

3.3 Swine Barn Energy Consumption Model

This section aims to develop a swine barn energy consumption model for a commercial swine barn as described in section 3.1. Principles of thermal environmental modeling are used for the IFS model proposed by the current study to develop a building thermal model. The algorithm proposed by the current study considers the content of swine diet, the ventilation rate, space heater capacities, and heat generated by occupants (pigs). The information gathered (i.e., building characteristics, swine type and equipment inventory) are used to develop the model. The objective of this section is to simulate swine barn energy consumption (both heat and power) as part of the swine production process by applying the modified SPGM to simulate swine heat production.

3.3.1 Model Development

Heat transfer in a building can be analyzed by understanding internal features and examining the heat transfer process. The control volume approach is used in this proposed model and only the building envelope is examined (Albright, 1990). The control volume for energy and mass balance is bounded by the walls, floor, and ceiling as shown in figure 3.6. Simplifying assumptions are made as follows:

1) Attic temperature is the same as the ambient temperature.

2) There are no radiation heat fluxes between the interior surfaces and occupants.

3) Indoor air is complete mixing, which implies temperature transfer in all surfaces is spontaneous.

Thermal dynamic properties of swine barn and other meteorology information are considered during the virtual simulation processes. The first assumption is made because during summer the amount of the heat gain through the ceiling is relatively small compared to the heat gain from animals, and during winter the percentage of heat loss through the ceiling is relatively small compared to the heat loss through ventilation (Li, 2000). Because the current research aims to estimate a maximum energy consumption scenario, Li's results support the assumption that considers attic temperature to be the same as the outside ambient temperature.

It is further assumed that there are no radiation heat fluxes between the surfaces and between the animals and the surfaces. This implies that all heat generated and lost in the room are instantaneous. Although the assumption introduced errors to the model, the model proposed by the current study is proposed to include only few model parameters to simplify the computational processes.

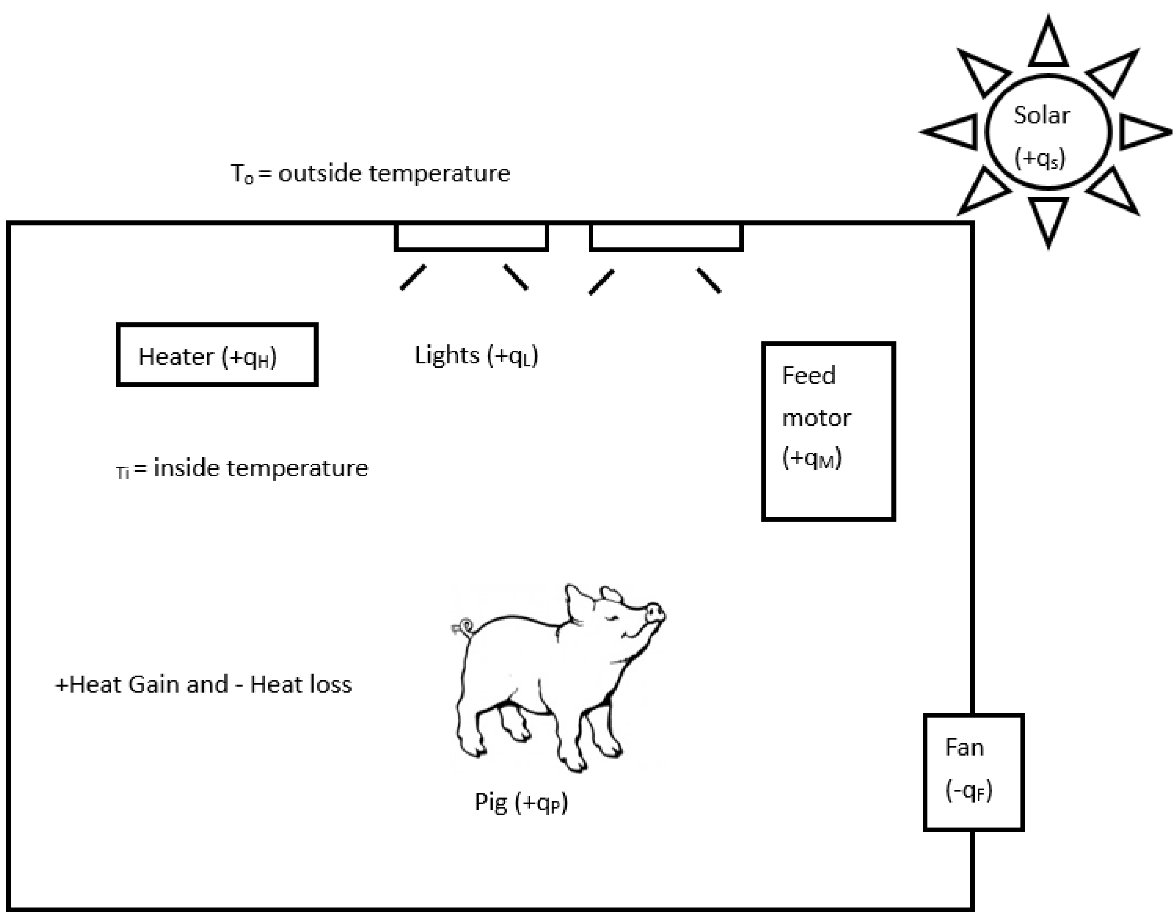

Figure 3.6 Heat gains and heat losses in a swine production room

Ogilvie et al. (1988) assumed that the air in the control volume is completely mixed so that the temperature of the exhaust air is equal to the average room temperature. Previous studies found use of that assumption simplified the computational process yet offered sufficient accuracy (Bantle & Barber, 1989; Li, 2000; Ogilvie, Zhang, & Barber, 1988). Therefore, the third assumption was supported.

Based on information of building characteristics, occupants (growing-finishing swine), heat production, and swine barn operation strategies, the model proposed by the current study designed an environmental simulation to estimate heat and electricity consumption for a swine barn. Typical sources of heat/mass gains and losses in a swine production barn are shown in figure 3.5.

The general mathematical model for building energy conservation used in this study is:

$$\rho_a C_p V \frac{dT_i}{dt} = (\mathrm{q_p} + q_L + q_M + q_H - q_B - q_F) \times 86400 \qquad (3.29)$$

Where:

$\mathrm{q_P}$ is the total heat generated by pigs, W

$\mathrm{q_L}$ is the heat generated by lights, W

$\mathrm{q_M}$ is the heat generated by feeding machine, W

$\mathrm{q_H}$ is the supplemental heat generated by heaters, W

$\mathrm{q_B}$ is the heat loss through building envelope, W

$\mathrm{q_F}$ is the heat loss through ventilation fans, W

C_P^a is the heat capacity for air

T_i is the indoor air temperature

V is the total swine barn volume

ρ_a is the air density

t is the time, day

As q_L and q_M is negligible compared to q_p and q_H, this thesis does not take them in to heat balance account.

Based on Brown-Brandt et al. (2004) and Pedersen & Sallvik (2002), the following equations are used in the current study to determine heat (total, sensible and latent) production and moisture generated by pigs. Previous studies noted that pig weight, ambient temperature, feed intake, and animal activity had significant impact on the heat production.

$$\Phi_{\mathrm{tot}} = 5.09m^{0.75} + (1 - (0.47 + 0.003\ \mathrm{W}))(DEvi \times 0.011574 - 5.09\mathrm{m}^{0.75}) \tag{3. 30}$$

Where:

Φ_{tot} is total heat production at 20℃

W is the pig live mass (kg), the same as in simplified pig growth model

DEvi is the feed energy intake (kJ/d), the same as in simplified pig growth model

For temperatures different from 20℃, the total heat production can be calculated by

$$\Phi_{\mathrm{tot}}^{*} = \Phi_{\mathrm{tot}} + 0.012\Phi_{\mathrm{tot}}(20 - T_i) \tag{3. 31}$$

Where T_i is room air temperature (℃)

The sensible and latent heat production is determined by the ratio (r) between sensible heat production and total heat production based on Sällvik and Pedersen (1999).

$$\mathrm{r} = \frac{0.62\Phi_{tot_1} - 1.15 \times 10^{-7} T^6}{\Phi_{tot_1}} \tag{3. 32}$$

Where:

$$\Phi_{tot_1} = 1000 + 12\Phi_{\mathrm{tot}}(20 - T_i) \tag{3. 33}$$

$$\Phi_{\mathrm{sen}}^{*} = \mathrm{r}\Phi_{tot}^{*} \tag{3. 34}$$

$$\Phi_{\mathrm{lat}}^{*} = \Phi_{tot}^{*} - \Phi_{sen}^{*} \tag{3. 35}$$

With different levels of animal activity, the heat and mass production by individual pigs differ. Both experimental measurements and approximations in modeling can be used to estimate animal activity and modify heat production equations. Because there is no measured animal activity data available, a single sinusoidal model, simulating diurnal variation of animal activity, was used in this study.

$$\mathrm{A} = 1 - \mathrm{a} \times \sin\left(\frac{2\pi}{24}(h + 6 - h_{min})\right)$$

$$\mathrm{q_P} = A \times \Phi^{*}_{\mathrm{sen}} \qquad (3.\ 36)$$

Measurements conducted by previous research showed that the minimum activity occurs at 2 am (h_{min}) and the diurnal variation for pigs was approximately 20% (a=0.2) (Pedersen & Sallvik, 2002). By applying Pederson's results, the hourly correction factor for animal heat production can be calculated and modified by diurnal variations of the heat production generated by pigs.

The total heat transmission through the building envelope include heat loss through the ceiling, floor, and external walls as described by:

$$\mathrm{q_B} = q_w + q_f + q_c \qquad (3.\ 37)$$

Where:

$\mathrm{q_B}$ is the total heat loss through building envelope, W

$\mathrm{q_w}$ is the heat loss through external walls, W

$\mathrm{q_c}$ is the heat loss through the ceiling, W

$\mathrm{q_f}$ is the heat loss through the floor, W

As normal commercialized swine barns do not have windows, direct solar gain is negligible. However, the effect of increased outer building surface temperature due to solar radiation is considered.

Sol-air temperature (T_e), an equivalent outdoor temperature that presents radiation effects and gives the same rate of heat entry into external wall surface, is determined to further estimate heat loss through external walls.

$$T_e = T_o + \frac{\alpha E_t}{h_o} - \frac{\varepsilon \Delta R}{h_o} \qquad (3.38)$$

Where:

T_e is sol-air temperature (°C)

T_o is the outdoor temperature (°C)

α is the absorptance of surface for solar radiation

E_t is the total radiation incident on surface, W/m^2

h_o is the coefficient of heat transfer by long-wave radiation and convection at outer surface, W/(m^2 K)

ε is the hemispherical emittance of surface , dimensionless

ΔR is the difference between long-wave radiation incident on the surface of the barn structure from the sky and surrounding buildings and radiation emitted by blackbody at outdoor air temperature, W/m^2

For horizontal surfaces that receive long wave radiation from the sky only, an appropriate value of ΔR is about 63 W/m^2, so that ε = 1 and ho = 17 W/(m^2 K), the long-wave correction term is about 4 K (Bliss, 1961).

Because vertical surfaces receive long-wave radiation from the ground and surrounding buildings as well as from the sky, an accurate ΔR is difficult to determine. It is common to assume $\varepsilon\ \Delta R$ = 0 for vertical surfaces.

ASHRAE (2005) recommended α/h_o=0.026 for light-colored surfaces and 0.052 for the maximum value for this parameter (dark-colored surfaces)

With sol-air computation, heat loss through external walls is determined by

$$q_w = UA_w(T_e - T_i) \tag{3. 39}$$

Where:

q_w is the heat loss through external walls, W

T_e is the sol-air temperature, C

T_i is the indoor temperature, C

U is the overall external wall's thermal transmittance, $W/m^2 C$

A_w is the surface area of external walls, m^2

Heat loss through the ceiling:

Heat transmission through the ceiling can be computed using the following equation.

$$q_c = UA_c(T_o - T) \tag{3. 40}$$

Where:

q_c is the heat loss through ceiling, W

T_o is the outdoor temperature, C

T_i is the indoor temperature, C

U is the overall external ceiling's thermal transmittance, $W/m^2 C$

A_c is the surface area of ceiling walls, m^2

Heat loss through the floor:

Heat transmission through the floor is relatively small and can be computed using the following equation:

$$q_f = F_h \times P(T_o - T_i) \tag{3. 41}$$

Where:

q_f is the heat loss through floor, W

T_o is the outdoor temperature, C

T_i is the indoor temperature, C

F_h is the perimeter heat loss coefficient based on insulation (ASHRAE, 2005), W/m

P is the perimeter length of exposed edge, m

Heat loss through ventilation fans:

The heat loss through ventilation fans is calculated as follows

$$q_F = \rho \dot{V} C_P^a (T_o - T_i) \tag{3. 42}$$

Where:

q_F is heat loss through ventilation fans, W

ρ is the density of air, kg/m^3

$\dot{V}$ is the ventilation rate, m^3/s

C_P^a is the specific heat of air, J/kg-K

T_o is the outdoor temperature, C

T_i is the indoor temperature, C

However, the cooling system can be opened above 25℃. With an evaporative cooling pad, the cooled air temperature (T_C) is calculated as:

$$T_c = T_w + \eta(T_o - T_w) \tag{3. 43}$$

Where $\eta = 80\%$ and t_w is wet bulb temperature and can be calculated by (Stull, 2011)

$$T_w = T_o \operatorname{atan}[0.151977(RH\% + 8.313659)^{1/2}] + \operatorname{atan}(T_o + RH\%) - atan(RH\% - 1.676331) + 0.00391838(RH\%)^{3/2} \operatorname{atan}(0.023101\, RH\%) - 4.686035 \tag{3. 44}$$

If cooling pads are operated, the outdoor temperature T_o in equation 3.42 will be changed to T_c.

By combining equation 3.29 through 3.44, indoor temperature T_i can be calculated as:

$$\frac{dT_i}{dt} = \left(\frac{1}{\rho C_P^a V}(q_H + q_p) - \frac{\dot{V}}{V}(T_i - T_o) - \frac{UA_C}{\rho C_P^a V}(T_i - T_o) - \frac{UA_W}{\rho C_P^a V}(T_i - T_e) - \frac{F_h P}{\rho C_P^a V}(T_i - T_o)\right) \times 86400 \tag{3. 45}$$

The equation 3.45 can be designed in Simulink as shown in figure 3.7. The Matlab function in Simulink is created to calculate sol-air temperature of four walls and inlet ventilation air temperature.

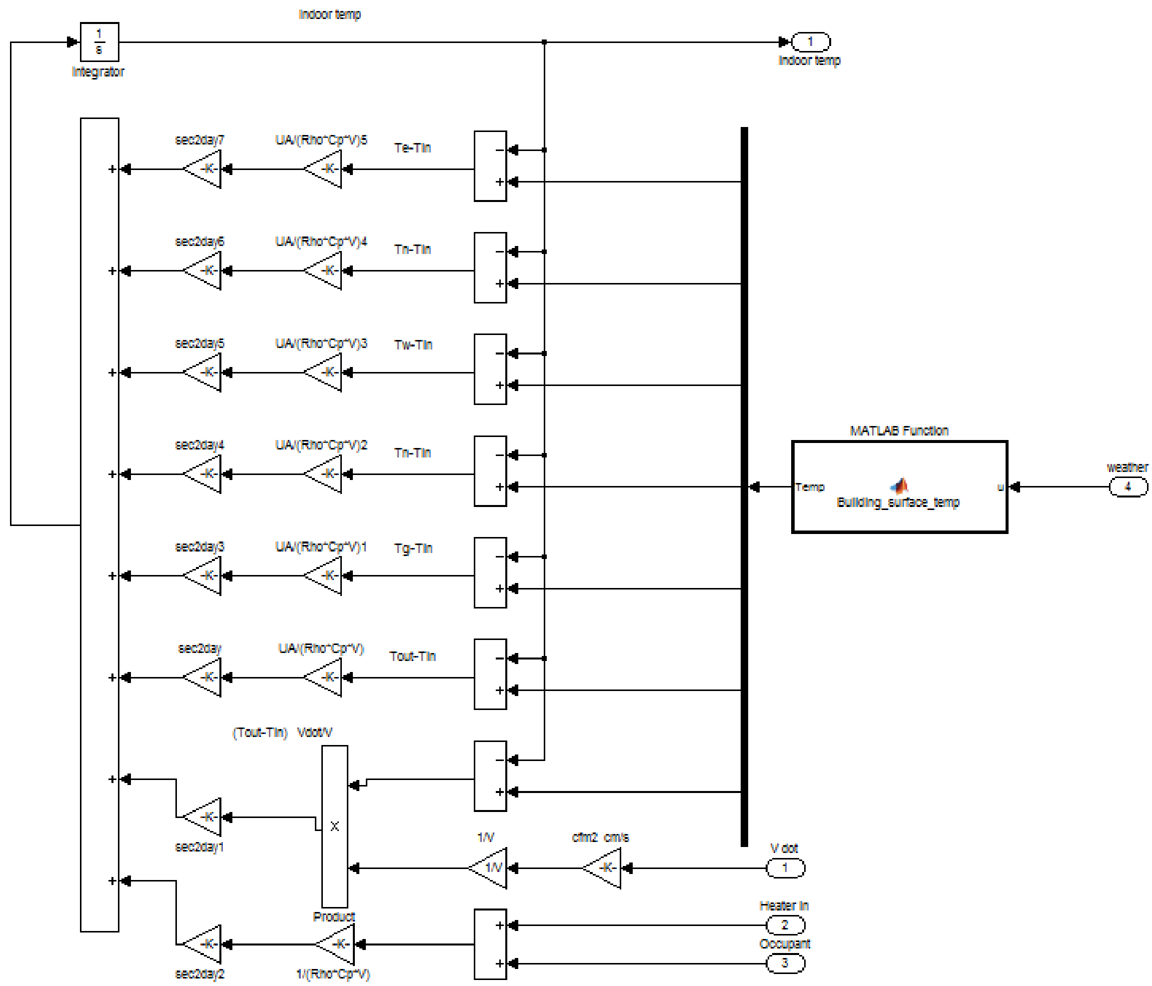

Figure 3.7 Dynamic model of swine house as shown in equation 3.45

MWPS-28 Wiring Handbook suggests 55 lux for grow-finish lighting (daytime) and estimates 0.57 watts/square foot for 100-watt incandescent bulbs. The lighting schedule from 6 am to 2 pm is shown in section 3.1. Because closure of the swine barn due to the virus prevented on-site investigation of lighting during the period, the current study relies on the Handbook information to estimate electricity usage for light. Almost 90% of the total electric consumption is used for ventilation fans and lights; therefore, the current study used only lighting and ventilation power requirement and assumed other power consumption is negligible.

By understanding carbon dioxide, moisture, and heat production by swine, the theoretically minimum ventilation curve is calculated by indoor air quality requirements. For a commercial swine barn facility setup, it is difficult to control the ventilation fans by all three parameters. Most fans and heaters in swine barns are controlled by the differences between indoor temperature and indoor set point temperature as shown in table 3.1. Set point temperature is determined by the recommended temperature under different swine weight as shown in table 3.6

Table 3.6 Set point temperature at different body weight

Set point temperature	22℃	22℃	21℃	19℃	18℃	17℃	16℃	16℃	16℃	16℃
Body Mass	<25kg	25kg	30kg	35kg	40kg	45kg	50kg	55kg	60kg	>70kg

Based on the ventilation rate, stage operation on exhausted fan control was applied to calculate energy consumption. This was computed by fan efficiency and fan capacity.

$$E_F = \left(\frac{\dot{V}/VER}{1000}\right) \tag{3.46}$$

Where:

E_f is the Energy consumption of ventilation fan (kW)

$\dot{V}$ is the ventilation rate, cfm

VER is the Ventilating Efficiency ratio, cfm/W

The current study implemented switch block and lookup table block to create control strategies in the Simulink Dynamic model as shown in figure 3.8. By utilizing switch block, the heater will turn on only when the indoor temperature is lower than the set point temperature, and the higher stage (table 3.1) of ventilation fans will turn on only when the indoor temperature is higher than the set point temperature. The thermal model block is a subsystem that estimates indoor temperature as shown in figure 3.8.

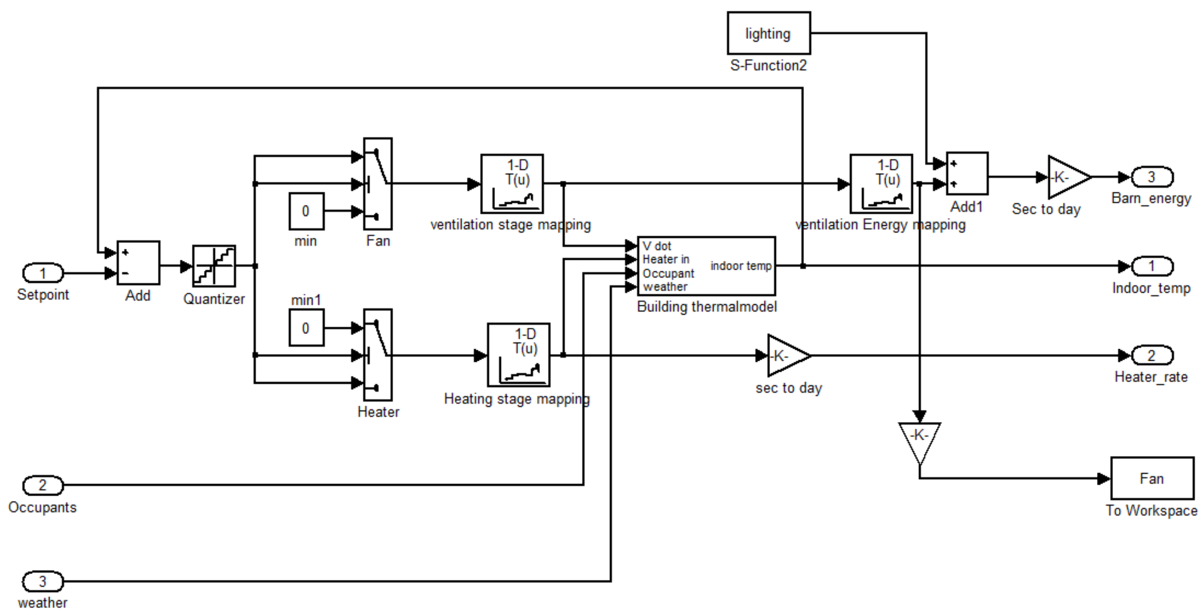

Figure 3.8 Control simulation blocks and dynamic building thermal model

Because swine growth models are highly correlated to the surrounding environment and because swine facility operation is determined also by swine growth conditions, it is necessary to connect the modified SPGM and the swine barn thermal environment model. As described in section 3.1, the modified SPGM generates information (pig weight) needed for swine barn simulations. Conversely, Swine Barn simulations generate indoor temperature back to the modified SPGM. The relationships between the modified SPGM and the swine barn energy consumption model are described in section 3.1. A combined computational model is shown in figure 3.9. The pig growth block is the same as shown in figure 3.4 of section 3.2.1. The swine barn block is the dynamic building thermal model shown in figure 3.8.

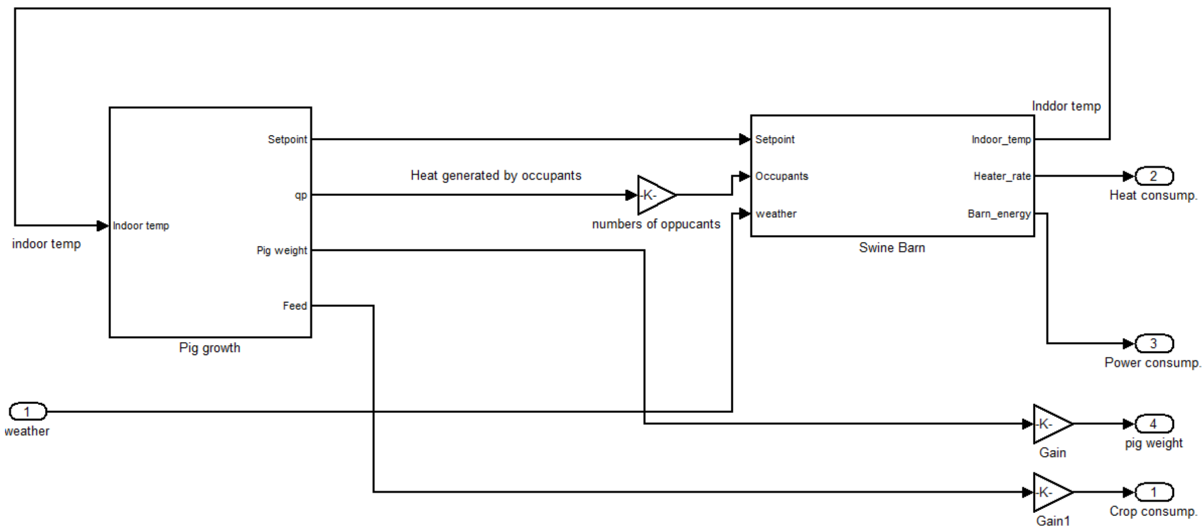

Figure 3.9 Swine production model that connects the simple pig growth model and swine facility energy consumption model

3.3.2 Model Inputs

General commercialized designs are chosen by the current study to present the application of the model shown in section 3.1. All model parameters are determined based on a review of previous studies. Details for thermal properties and heat conductance are listed in table 3.7**.** Based on construction material as shown in table 3.7, the overall heat conductance for the building envelope is shown in table 3.8.

Three sets of weather information were collected from stations as input variables for the system model proposed by the current study. Hourly weather dataset from the National Solar Radiation Data Base (NSRDB) during 2010 in Springfield, IL and Oklahoma City, OK were collected and organized. Temperature dataset from 1995 in Bardstown, KY was also collected from the National Oceanic and Atmospheric Administration (NOAA). Each set of weather information was used as input variables for different scenarios.

The location of Bardstown, KY was selected for verification of growing-finishing pigs' performance. The locations of Springfield, IL and Oklahoma City, OK were chosen to represent different weather conditions. Because Illinois is one of the states that has ranked highest for pork production for many years and Springfield has available the most complete weather information, Springfield was chosen to represent cold weather conditions. The majority of swine production facilities in the U.S. are located in the upper Midwest or Corn Belt states, however, since the 1990s significant pork production has also developed in the Oklahoma-Texas Panhandle region. Weather information for Oklahoma City is complete, therefore, that location was chosen to represent the warm weather conditions in the Oklahoma-Texas Panhandle region.

Table 3.7 Construction material of building components

	Materials	**Thermal transmittance through conduction (W/ m^2-K)**	**Thermal resistance (m^2-K/W)**	**Total Thermal transmission: U-Value (W/ m^2-K)**
Wall	ho	22.7	0.04	
	Wood Walls		3.28	0.51
	Concrete Walls		1.53	
	hi	0.57	1.75	
Ceiling	ho	0.57	1.75	
	Fiberglass insulation		5.28	0.1139
	hi	0.57	1.75	

Table 3.8 Calculated UA-Value for growing to finishing swine building

Building construction	U-Value (W/ m^2-K)	Length (m)	Width (m)	Height (m)	Surface Area (m^2)	UA Value (W/ K)
Floor		146.30	12.19			538.9
North/south Wall	0.51	146.30		2.24	327.7	167.13
East/West Wall	0.51		12.19	2.24	27.3	13.87
Ceiling	0.114	146.30	12.19		1783.4	203.3

3.4 System Model Application and Discussion

This section discusses different simulation scenarios that present the application of the swine production process proposed by the current study. Three scenarios are discussed: 1) Effects of the cooling system for a swine barn in Kentucky under 1995 summer conditions. 2) Pig growth under Illinois summer/winter conditions in 2010; and 3) Swine barns located in 2010 weather conditions in Illinois and Oklahoma.

3.4.1 Cooling System for Swine Barn in Kentucky

This study considered the same model scenarios as described in section 3.2.2 but without a misting system. A comparison is drawn between swine performance with/without a cooling system. The time needed to grow pigs *without* a misting system is longer than *with* a misting system for growing-finishing pigs as shown in table 3.9. The feed-to-gain ratio (F/G) is also higher than with a cooling misting system.

The results show the importance of implementing a cooling system to reduce the cost of maintaining a swine barn due to the shorter growing period and lower F/G ratio.

Table 3.9 Production performance, white group, 6/15/95 start date, grow-finish period in Kentucky

	Producer Barrow With misting	NCPIG Barrow With misting	Modified SPGM Barrow With misting	Modified SPGM Barrow Without misting
Days on feed	102.1	108	102	137
Slaughter wt., kg	107	107.6	107.3	107.9
ADF, kg/day	2.51	2.39	2.32	1.84
ADG, kg/day	0.82	0.78	0.86	0.64
F/G	3.13	3.06	2.70	2.88

3.4.2 Pig Growth under Illinois Summer/Winter Conditions

Changes in pig raising seasons have different effects on pig growth rate and the feed-to-gain ratio. Thus, evaluations of different growing seasons and comparisons of outcomes for different seasons is necessary. Table 3.10 shows simulation results on two different season scenarios (winter/summer) in 2010 under Springfield climate conditions. Energy consumption and pig growing performance are estimated to analyze the differences.

This study applied a previously proposed swine production system model and analyzed growing information as shown in table 3.10**.** Higher feed-to-gain ratio under summer conditions compared to winter conditions is similar to on-farm experience. The F/G ratio and total electricity usage *with* a cooling system is lower than *without* a cooling system. The main reason for lower electricity requirements occurs is attributable to lower ventilation rate with cooled inflow air. The results also show that the time needed for growing pigs is shorter in winter. However, a swine barn has higher heat requirements to maintain small pigs under winter conditions. The results demonstrate the importance of pig growth scheduling for higher pig growth performance.

Table 3.10 Production performance, 2400 heads of white gilts, 20 kg to 107 kg during grow-finishing period in Illinois

	With cooling under summer	Without cooling under summer	Winter
Start date	April 12 (day 105)	April 14 (day 107)	January 01 (day 1)
Days on feed	151	169	106
Slaughter wt., kg	107.67	107.44	107.42
ADF, kg/day	1.70	1.63	2.25
ADG, kg/day	0.58	0.51	0.82
F/G	2.93	3.19	2.74
Total electricity consumption (kWh)	35709	39722	15199
Total Heat consumption (kWh)	3455	3014	59295

In order to examine a full-year energy consumption portfolio, the current study makes several assumptions. First, this study assumes there is no time lag between two all-in all-out groups. Second, this study takes Jan-01 2010 as the first day of simulation for importing 20kg piglets. Figure 3.10 shows that higher electricity usage is needed during summer because ventilation fans are the main contributors of electricity usage and higher temperatures in summer require higher ventilation rates. Simulation results are consistent with on-farm experience.

Heat requirements for the whole year is shown in figure 3.11. For small (around 20 kg) growing-finishing pigs under winter conditions, the higher heat loss and higher set point temperature for piglets create large heat requirements. Modeling results (fig. 3.11) show that most heat consumption occurs during first month of the year.

Although most commercial operations do not heat swine barns during summer, this model requires heat when market size swine are removed and 20kg piglets are imported. In the IFS model proposed by the current study, the indoor set point temperature changes dramatically from 16C to 22C as the occupants (pigs) change in size. Because of the high heat capacity of the swine barn, much energy is needed to increase the indoor temperature. Simulation results indicate the importance of set point temperature. Based on different set point temperature designs, energy consumption portfolios differ.

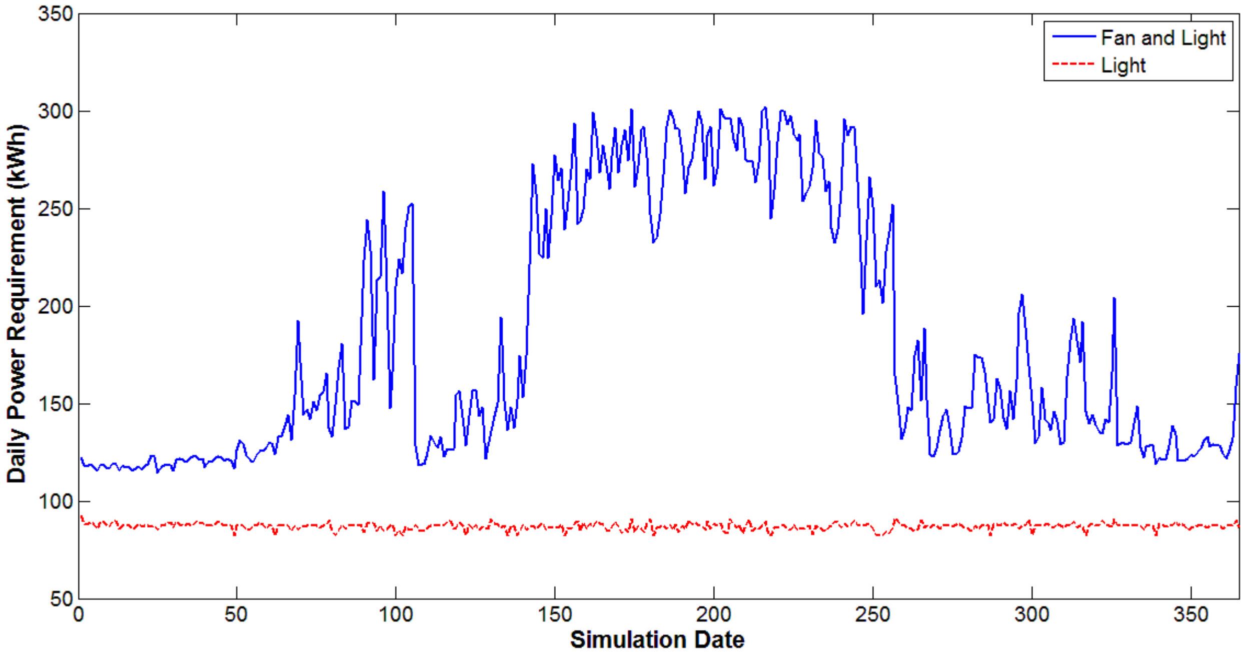

Figure 3.10 Daily electricity usage with cooling pad, including fan and lighting

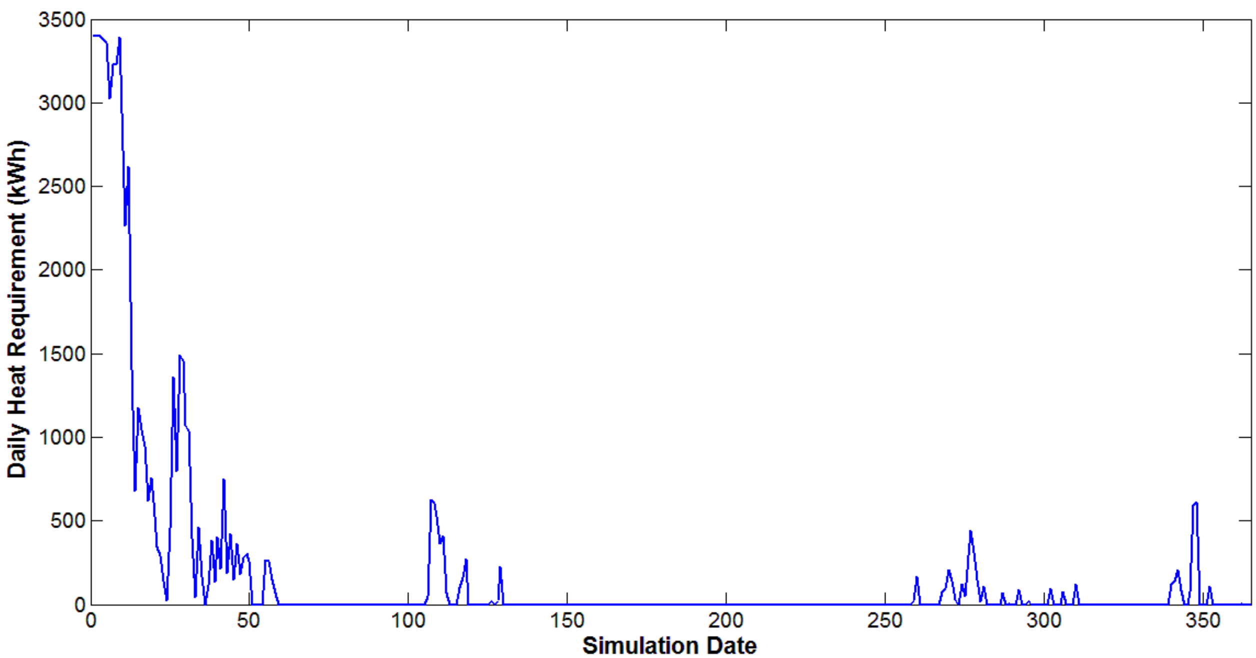

Figure 3.11 Heating requirement for maintaining indoor temperature with cooling pad

The pig growth curve is affected by heat stress in summer as shown in figure 3.12. When pigs reach market size (107 kg), large pigs will be removed and small pigs will be imported. Comparisons between pig growth performance under winter conditions and under summer conditions are considered in table 3.10.

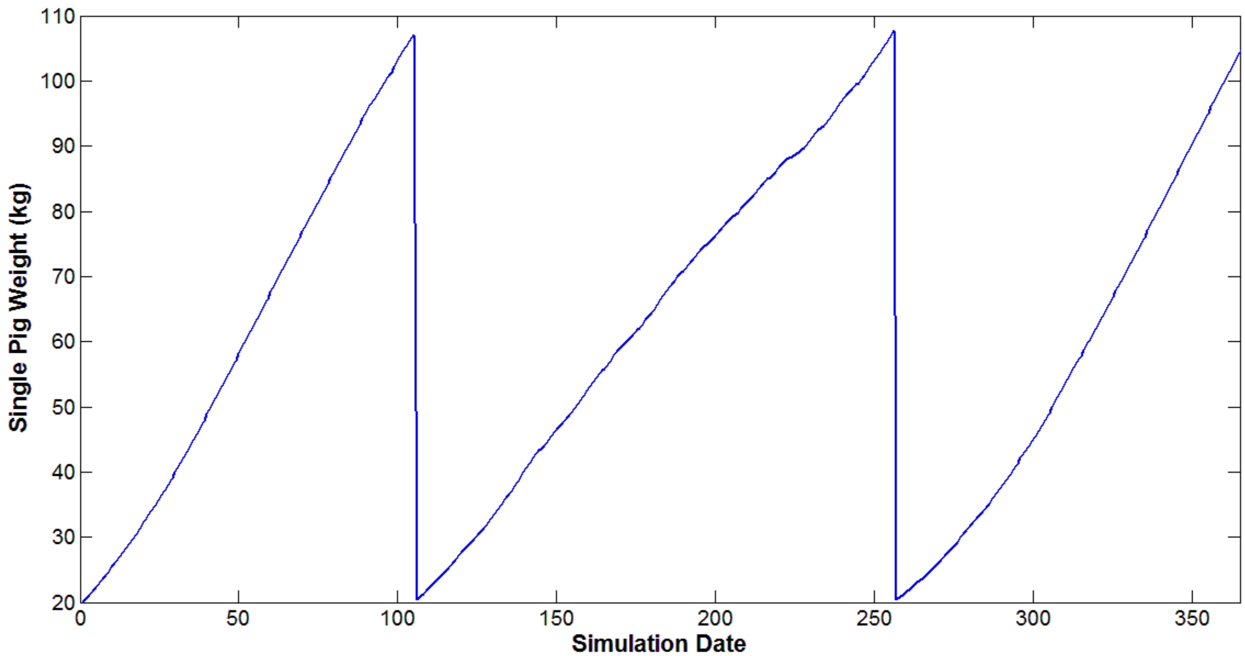

Figure 3.12 Single pig growth curve with cooling pad in Springfield, IL

3.4.3 Swine Barns in Different Climate Locations: Illinois and Oklahoma

Table 3.11 shows maximum and minimum temperatures in 2010 in Springfield, IL and in Oklahoma City, OK. The location of Oklahoma City at a lower latitude experiences higher temperatures so that it is logical to expect that barns in Oklahoma City have different features than barns in Springfield. However, in order to estimate energy usage and pig performance under the same swine barn design, this section assumes that input variables, with the exception of weather conditions, remain the same.

Table 3.11Maximum/ Minimum temperature of two scenarios

	Maximum temperature (°C)	Minimum temperature(°C)
Springfield, Illinois 2010	36.1	-22.8
Oklahoma City, Oklahoma 2010	39.4	-13.9

Swine barns located in Oklahoma City under winter conditions have smaller heat requirements but with power requirements that are higher compared to barns in Springfield as shown in table 3.12. The main reason is that in Springfield the temperature is lower compared to that of Oklahoma City. Higher heat requirements for barns located in Springfield is, therefore, required to maintain the same set point in winter. As Oklahoma City has higher temperatures in the summer, barns there require more ventilation to maintain set point temperatures.

Because in winter barns in both Oklahoma City and Springfield share the same set point temperature, pig growth performance is similar in the two locations due to controllable indoor temperature. On the other hand, under summer conditions the indoor temperature is higher than the set point temperature even with full load ventilation rate in Oklahoma City. Therefore, under summer conditions due to heat stress, barns in Oklahoma City have lower pig performance than barns in Springfield. Simulation results carried out by the current study demonstrate that the same control strategies and set point temperatures under different weather conditions may cause severe non-efficiencies in energy and nutrient usage. Therefore, different indoor temperature design systems may be needed under different weather condition for efficient swine farming.

Table 3.12 Production performance, 2400 heads of white gilts, 20 kg to 107 kg, grow-finish period in Illinois/Oklahoma under summer/winter conditions with cooling pads

	Summer in Illinois	Summer in Oklahoma	Winter in Illinois	Winter in Oklahoma
Start date	April 12 (day 105)	April 15 (day 108)	January 01 (day 1)	January 01 (day 1)
Days on feed	151	185	106	107
Slaughter wt., kg	107.67	107.61	107.42	107.59
ADF, kg/day	1.70	1.57	2.25	2.21
ADG, kg/day	0.58	0.47	0.82	0.82
F/G	2.93	3.34	2.74	2.70
Total electricity consumption (kWh)	35709	45741	15199	15876
Total Heat consumption (kWh)	3455	1334	59295	34106

CHPATER 4 ANAEROBIC DIGESTION AND CHP SYSTEM

The goal of Chapter 4 is to describe the dynamic anaerobic digestion and CHP system model, developed by this current study, which is proposed for use by farmers and engineers in a commercial swine manure treatment facility. The model is developed for application in two different scenarios and includes three subsystem models. The first subsystem model addresses anaerobic digestion process (Section 4.2) while the second subsystem model builds on the first subsystem model and addresses anaerobic digestion heat requirements (Section 4.3). The third subsystem model surveys industrial CHP systems (Section 4.4) and estimates heat/power production. Section 4.5 is an application of the anaerobic digestion and CHP system model. It also demonstrates simulations based on several different scenarios.

4.1 System Description

The system model proposed by the current study is developed to simulate the methane production rate of a cylindrical above-ground Continuous Stirred Tank Reactor (CSTR) with a constant inflow rate (25m^3/day). Swine manure from growing-finishing swine is considered as the feedstock for the anaerobic digestion process. Specific manure characteristics for the current study can be referred to in section 4.2.2.

The cylindrical above-ground CSTR is constructed as a 12-inch thick concrete tank with 6-inch thick insulation as shown as figure 4.1. The size of the anaerobic digester, with 575 m^3 for sludge space and 57.5 m^3 for head space, is correlated with feedstock characteristics. The inner diameter of the CSTR is 14.8m and the inner height is 3.7m. More detailed calculations are described in section 4.2.2 and 4.3.1.

A hot water coil heat exchanger is proposed by the current study to maintain the reactor temperature. When the temperature is lower than 35℃, the heater will be turned on to maintain the temperature of the sludge.

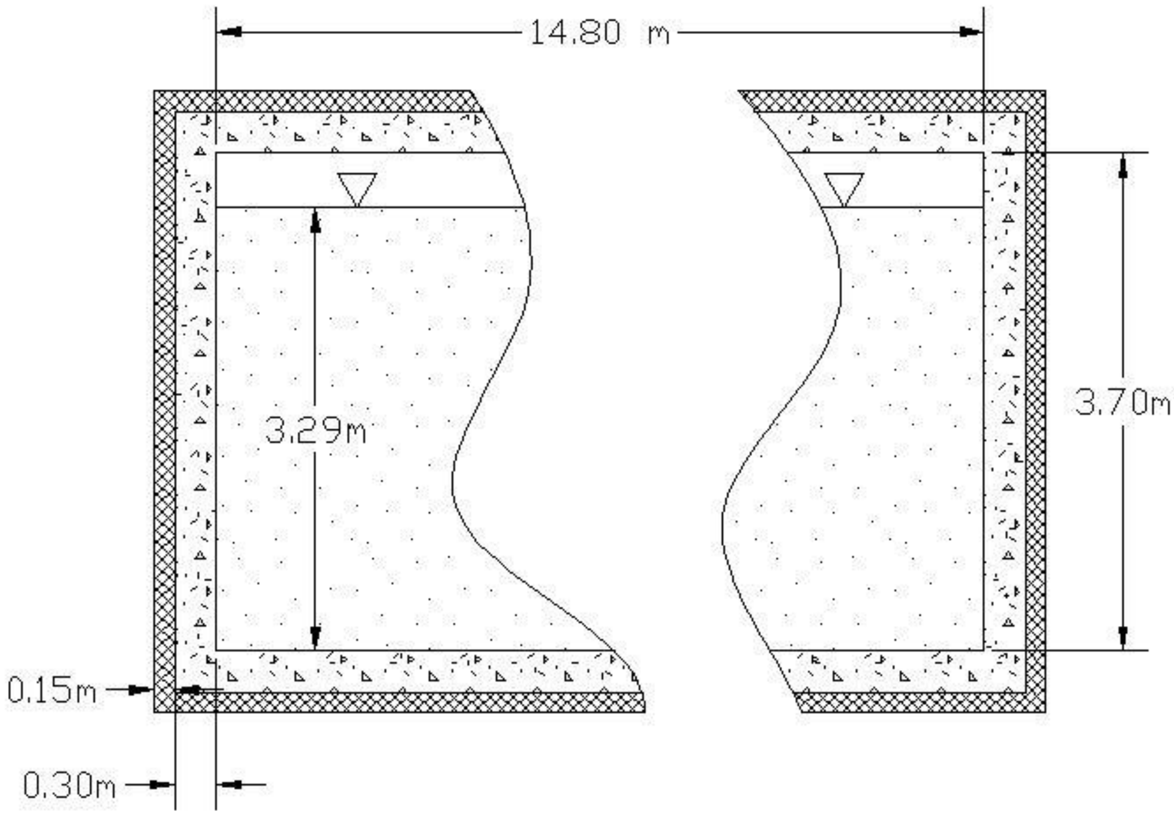

Figure 4.1 Elements of above-ground concrete CSTR

A Combined Heat and Power (CHP) system is proposed to utilize bio-methane is generated by the anaerobic digestion process to generate heat and power to support digester operations. More detailed information about the industrial CHP unit is included in section 4.4.

This chapter describes an anaerobic digestion model that is combined with an anaerobic digester heat requirement model and commercialized CHP system to estimate power/heat production as well as consumption portfolios. Anaerobic Digestion Model Number 1 (ADM1) is applied to examine the rate of methane production under different hydraulic retention time periods. After determining the hydraulic retention time, the digester size is determined followed by construction of a digester heat requirement model. The energy production/consumption portfolio is then estimated. The modeling process is shown in figure 4.2.

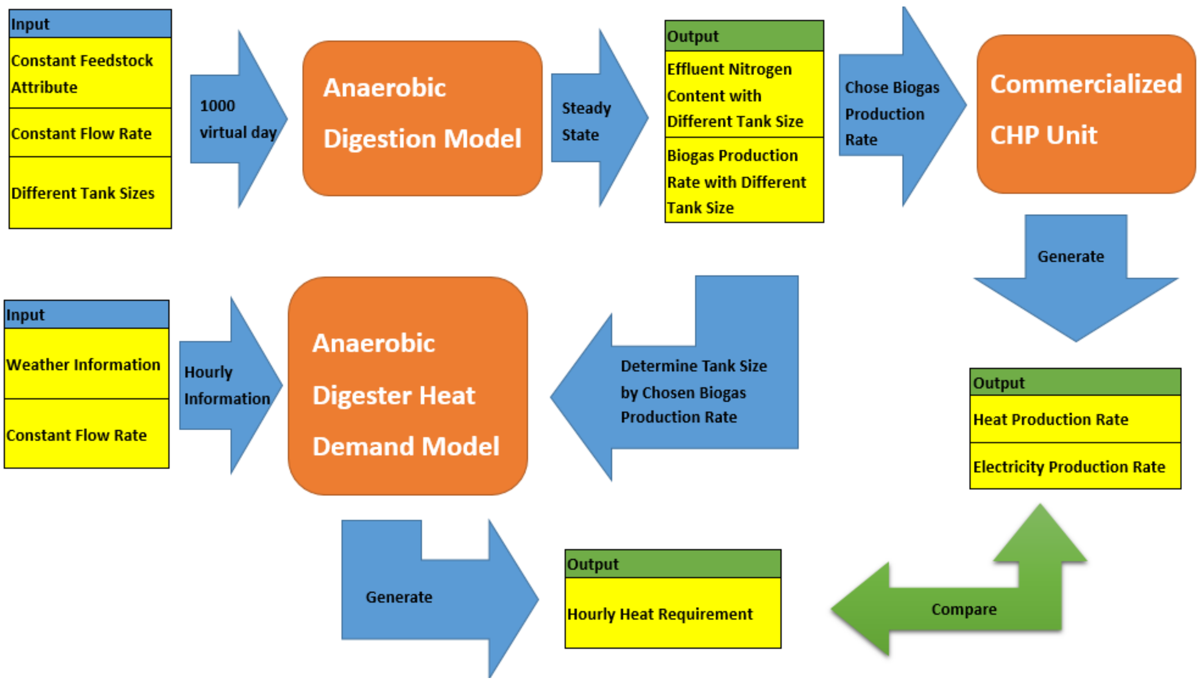

Figure 4.2 Systematic diagram of anaerobic digestion and CHP unit system model

4.2 Anaerobic Digestion Model

This section introduces an anaerobic digestion model with modified parameters. In section 4.2.1, ADM1 is introduced and combined with a transformer model to reduce the number of input variables. As ADM1 was originally designed for simulating municipal waste, the parameters and input variables of previous studies have been modified for swine manure. For purposes of comparison, an empirical bio-methane estimation is introduced as a baseline for ADM1. All input variables and verifications are described in section 4.2.2.

4.2.1 Model Development

The proposed system model applies the Anaerobic Digestion Model Number 1 (ADM1) and connects the Transformer model to reduce the number of model inputs. All model parameters and input variables are listed in section 4.2.2. This section on model development describes the model structure and methodology.

The anaerobic digestion process can be divided into two major categories: biochemical processes and physicochemical processes. Biochemical processes include disintegration of homogeneous particulates, extracellular hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Physicochemical processes describe both the liquid-liquid exchanges and gas-liquid exchanges of elements. All processes are shown in figure 4.3.

An understanding of these processes is important for simulating anaerobic digestion. The current study introduces and applies ADM1 with more details about coefficients in the Peterson matrix described in previous research (Batstone et al., 2002). The following simplifying assumptions are made:

1) The digester is well-mixed, namely the substrate is evenly distributed in the digester tank.

2) The model does not include nutrients of solid-liquid phase exchanges.

3) All model parameters are assumed to be under 35℃ conditions.

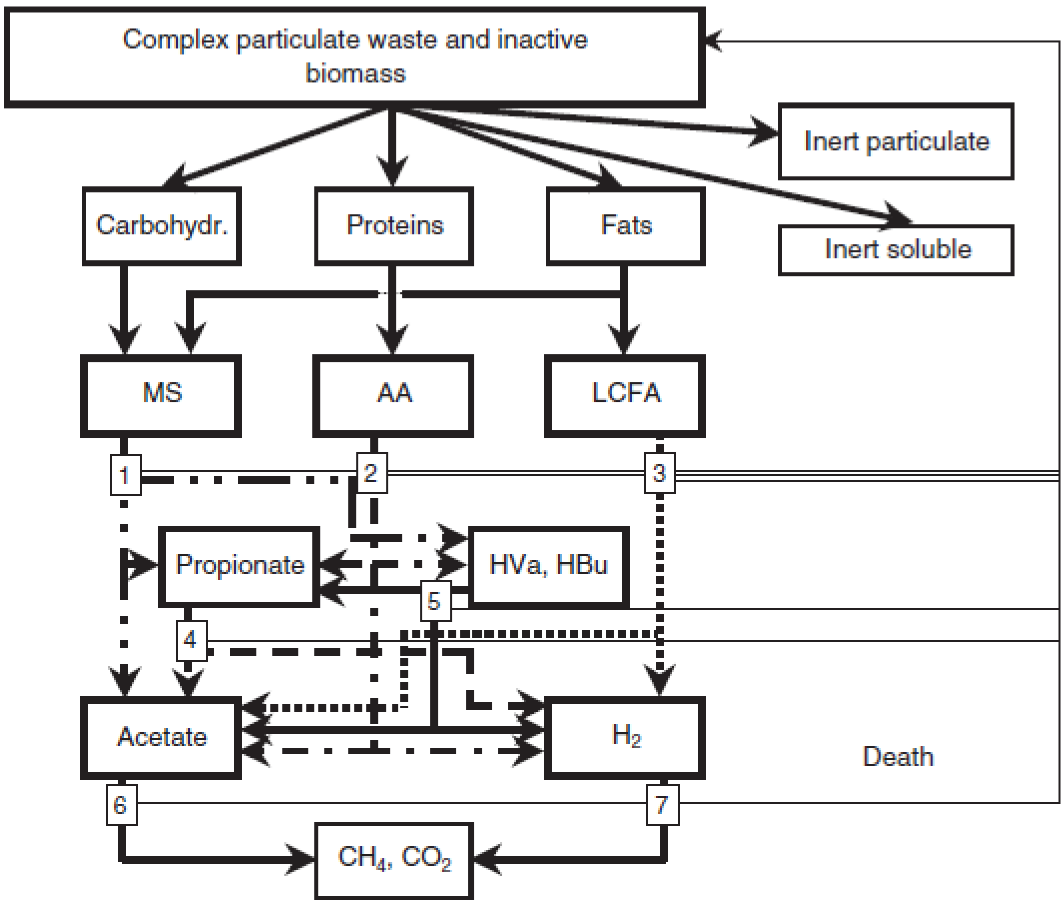

Figure 4.3 The ADM1 including biochemical processes: (1) acidogenesis from sugars, (2) acidogenesis from amino acids, (3) acetogenesis from long chain fatty acid (LCFA), (4) acetogenesis from propionate, (5) acetogenesis from butyrate and valerate, (6) aceticlastic methanogenesis, and (7) hydrogenotrophic methanogenesis. Adopted from Batstone et al. (2002)

The first assumption is set forth because the model contains several ODE equations and is a stiff system. A non-homogeneous system would be too complex to simulate. Further, because modeling precipitation in solid-liquid reaction is complicated and may introduce instability of the system, the second assumption is made.

Simulation of the temperature inside the digester and the changing dynamic parameters based on different temperatures is difficult and may over-complicate the chemical and biological processes; therefore, a representative temperature of 35℃ is assumed (Rosen, Vrecko, Gernaey, & Jeppsson, 2005).

The equation on anaerobic digestion process is described by equation 4.1:

$$\frac{d\,S_{liq,i}}{dt} = \frac{\dot{V}_{in}S_{in,i}}{V_{liq}} - \frac{\dot{V}_{out}S_{liq,i}}{V_{liq}} + \sum_{j=1-19}\rho_j v_{i,j} \qquad (4.\ 1)$$

Where $\sum_{j=1-19}\rho_j v_{i,j}$ is the sum of the kinetic rates for process j multiple by $v_{i,j}$ More detailed parameter equations in Peterson matrix form can be found in previous research (Batstone et al., 2002).

Except for the liquid-liquid reaction, a rate term for transfer of gas components to the gas headspace is also considered in ADM1. Take carbon-dioxide for example, the transfer rate is described as:

$$\rho_{10,T} = k_L a_{CO_2}(S_{CO_{2,liq}} - K_{H,CO_2}\,P_{CO_{2,gas}}) \qquad (4.\ 2)$$

Where $\rho_{10,T}$ is the additional rate term for gas-liquid reaction, $k_L a_{CO_2}$ is the dynamic gas-liquid transfer coefficient, K_{H,CO_2} is the Henry's law equilibrium constant, $P_{CO_{2,gas}}$ is the partial pressure in headspace and $S_{CO_{2,liq}}$ is the liquid carbon-dioxide concentration.

Several inhibition processes are also considered in ADM1, including non-competitive inhibition, substrate limitation, and empirical equations that describe the inhibition process under different pH values. A detailed model setup and description can be found in previous research (Batstone et al., 2002).

Since ADM1 requires 27 input variables and some of these variables, e.g., fatty acid concentration in influent, are difficult to measure. Zaher and Chen (2006) have used the Continuity-Based Interference Method (CBIM) to reduce the number of input variables. The interface maintains the continuity of major elements for the model and achieves COD and charge balance throughout the anaerobic digestion processes.

Based on results of the Transformer model, Zaher and Chen (2006) successfully reduced the 27 ADM1 input variables to 13 variables that are easier to measure. The input variables for the Transformer model are particulate chemical oxygen demand (COD), volatile fatty acid (VFA) of soluble substrate, VFA, total organic carbon, organic nitrogen, total ammonia-nitrogen, organic phosphorus, orthophosphate, total inorganic carbon, total alkalinity, fixed solids, and flow rate.

Figure 4.4 shows the combination of the Transformer model and ADM1 in Simulink. The model scheme is similar to previous co-digest research but without separating the hydrolysis tank and the digestion tank (Zaher, Li, Jeppsson, Steyer, & Chen, 2009). The source code applied by the current study is developed by a Lund University research group and Dr. Zaher's group.

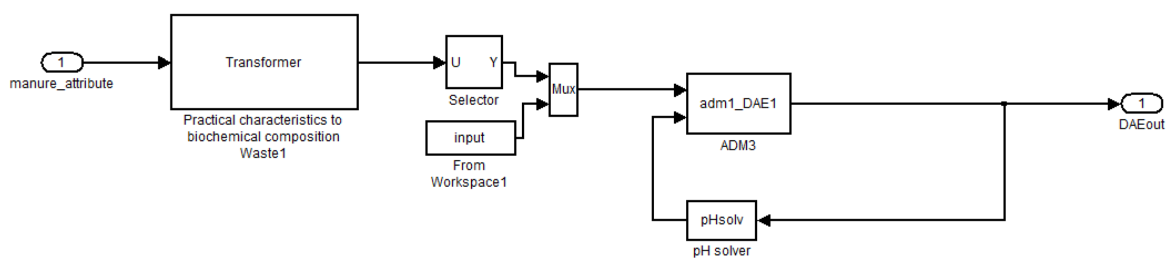

Figure 4.4 Dynamic model of ADM1 and transformer process

4.2.2 Model Inputs and Model Results Comparison with Empirical Equations

This chapter takes growing-finishing swine manure as feedstock and a set constant flow rate at 25 m^3 per day to demonstrate the application of the model proposed by the current study. Research by Zaher and Chen (2006) presents several features of swine manure, but it lacks several input variables and needs user-defined parameters to simulate ADM1. The parameters include VFA (COD equilibrium), COD_s, TIC (mol HCO^-_3), and total Alkalinity (cations equilibrium).

In order to assume reasonable numbers for user-defined parameters, results of the following studies were reviewed. Van Velsen (1981) found that VFA concentrations for pig manure lie between 8.7 and 15.9 g COD/l at VS concentrations between 38 and 65 g/l. More recently, based on experiments, Massé et al. (2000) presented several swine manure properties, e.g., COD_t, COD_s, Alkalinity, total solid, and volatile solid. The current study assumes manure properties as simulation of input parameters that combine data from previous experimental research. All input parameters are listed in table 4.1.

After determining input variables, parameters in ADM1 are further modified in the current study for agriculture purposes. Several pig manure related parameters in this model are taken from Gali et al. (2009). Other kinetic and stoichiometric parameters are taken from the AMD1 model. All parameters for modified ADM1 in the current study are listed in table 4.2.

Prior research has established empirical relationships among rates of methane production, influent volatile solids concentration, ultimate CH_4 yield per volatile solid, and maximum specific growth rate. The modified ADM1 can be compared with empirical results (Chen & Hashimoto, 1978; Hashimoto, 1984). All empirical relationships are listed as equation 4.3.

$$\gamma_v = \frac{B_0 S_o}{HRT}\left(1 - \frac{K}{HRT \times \mu_m - 1 + K}\right) \tag{4. 3}$$

Where γ_v is the methane production rate from anaerobic fermentation, and K is a kinetic parameter that can be calculated as:

$$\mathrm{K} = 0.6 + 0.0206 e^{0.051 \times S_0} \tag{4. 4}$$

B_0 is ultimate CH_4 production rate (l CH_4/ g VS), S_0 is influent volatile solid concentration, μ_m is the maximum specific growth rate (day^{-1}) and can be calculated as equation 4.5:

$$\mu_m = 0.013T - 0.129 \tag{4. 5}$$

Where T is in Celsius

As described in this section on model comparisons, the current study assumes B_0 equals to 0.48 based on previous experiments (Hashimoto, 1984). The current study also assumes T=35℃ to be consistent with ADM1 simulation results. All input variables for Hashimoto's model are listed in table 4.3. With input variables for both the ADM1 and the empirical models, the modified ADM1 is compared with the empirical model.

Table 4.1 Input parameters for the Transformer model and ADM1 (per m^3)

CODp[a] (gCOD)	CODs-VFA[d] (gCOD)	VFA[c] (g COD)	TOC[a] (gC)	Norg[a] (gN)	AN (gN)	TP-orthoP[a] (gP)	orthoP[a] (gP)	TIC[b] (mol HCO_3^-)	Scat[b] (equ)	FS[b] (g)
97072	22340	15900	47094	2976	3752	854	1709	336.8	336.8	19640

a: Data collect from Zaher and Chen (2006); b: Data collect form Masse et al. (2000); c: Data collect from V. Velsen (1981); d: Data calculate by a and c

Table 4.2 Stoichiometric parameters and kinetic parameters at mesophilic conditions

Constant	Value	Constant	Value	Constant	Value	Constant	Value
f_sI_xc	0.143	C_ac	0.0313	k_m_aa	50	k_dec_Xac	0.02
f_xI_xc	0.033	C_bac	0.0313	K_S_aa	0.3	k_dec_Xh2	0.02
f_ch_xc	0.461	Y_su	0.1	k_m_fa	6	R	0.083145
f_pr_xc	0.202	f_h2_aa	0.06	K_S_fa	0.4	T_base	298.15
f_li_xc	0.161	f_va_aa	0.23	K_Ih2_fa	5.00E-06	T_op	308.15
N_xc	0.002	f_bu_aa	0.26	k_m_c4	20	pK_w_base	14
N_I	0.002	f_pro_aa	0.05	K_S_c4	0.2	pK_a_va_base	4.86
N_aa	0.007	f_ac_aa	0.4	K_Ih2_c4	1.00E-05	pK_a_bu_base	4.82
C_xc	0.03	C_va	0.024	k_m_pro	13	pK_a_pro_base	4.88
C_sI	0.03	Y_aa	0.08	K_S_pro	0.1	pK_a_ac_base	4.76
C_ch	0.0313	Y_fa	0.06	K_Ih2_pro	3.50E06	pK_a_co2_base	6.35
C_pr	0.03	Y_c4	0.06	k_m_ac	8	pK_a_IN_base	9.25
C_li	0.022	Y_pro	0.04	K_S_ac	0.15	k_A_Bva	1.00E+10
C_xI	0.03	C_ch4	0.0156	K_I_nh3	0.0018	k_A_Bbu	1.00E+10
C_su	0.0313	Y_ac	0.05	pH_UL_ac	7	k_A_Bpro	1.00E+10
C_aa	0.03	Y_h2	0.06	pH_LL_ac	6	k_A_Bac	1.00E+10
f_fa_li	0.95	k_dis	0.17	k_m_h2	35	k_A_Bco2	1.00E+10
C_fa	0.0217	k_hyd_ch	10	K_S_h2	7.00E-06	k_A_BIN	1.00E+10
f_h2_su	0.19	k_hyd_pr	10	pH_UL_h2	6	P_atm	1.013
f_bu_su	0.13	k_hyd_li	10	pH_LL_h2	5	kLa	200
f_pro_su	0.27	K_S_IN	0.0001	k_dec_Xsu	0.02	K_H_h2o_base	0.0557
f_ac_su	0.41	k_m_su	30	k_dec_Xaa	0.02	K_H_co2_base	0.0271
N_bac	0.00625	K_S_su	0.5	k_dec_Xfa	0.02	K_H_ch4_base	0.00116
C_bu	0.025	pH_UL_aa	5.5	k_dec_Xc4	0.02	K_H_h2_base	7.80E-04
C_pro	0.0268	pH_LL_aa	4	k_dec_Xpro	0.02	k_P	5.00E+04

Table 4.3 Parameters for Hashimoto's model

Parameter	Value
B_0	0.48 l CH_4/g VS
T	35℃
S_0	74.12 kg/m^3

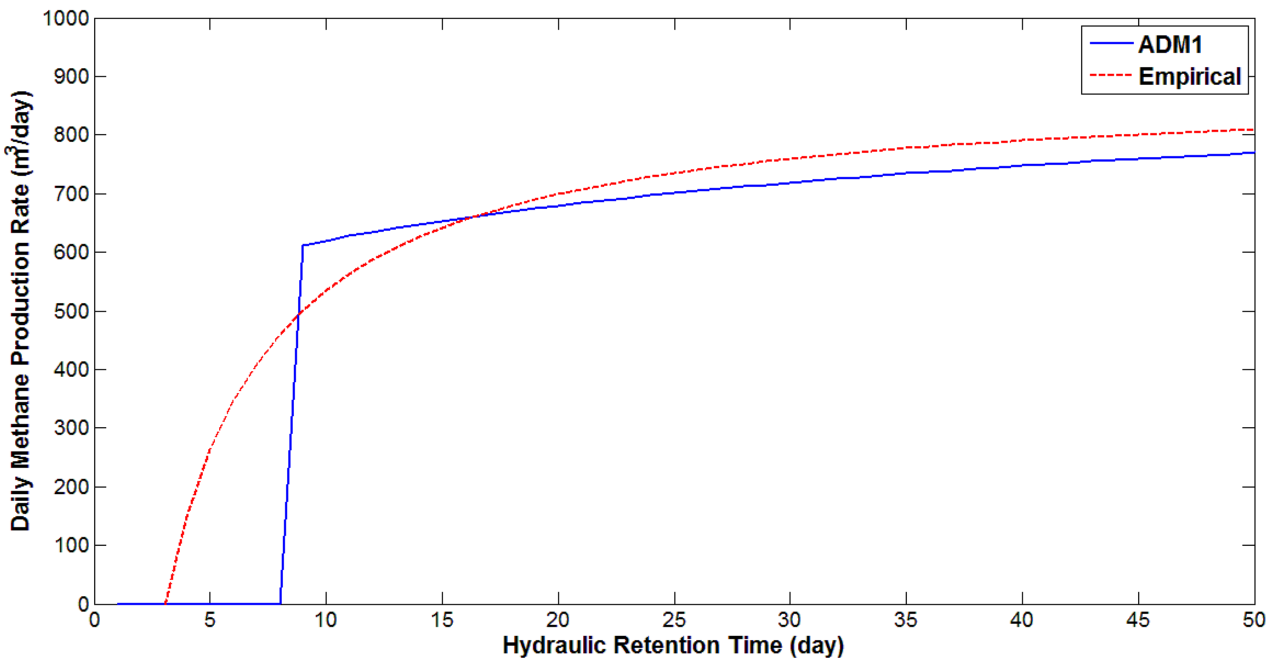

Figure 4.5 Methane production comparison between ADM1 and Chen and Hashimoto (1978)

Figure 4.5 shows estimations of different methane production rates based on ADM1 and empirical equations under different periods of Hydraulic Retention Time (HRT). When HRT is smaller than 8, ADM1 shows a rate of zero methane production due to washed-out effects. Equation 4.1 shows that the first two terms on the right hand side are dominant with small HRT when the chemical dynamic process $\sum_{j=1-19} \rho_j v_{i,j}$ is a small number. The first two terms imply an exponential decrease when neglecting the third term. The numerical effect shows a physical washed-out effect in a continuous tank experiment. Note that when all ADM1 results are calculated under steady state (1000 virtual days), there is a jump start around 8 HRT days since the wash-out effect does not occur. Figure 4.6 shows methane/ hydrogen/carbon dioxide concentration of biogas under different HRT. The production of methane starts when HRT is greater than 9 days, and hydrogen concentration is high when HRT is small. The reasons for this occurrence are similar to those shown in figure 4.5. Since methane bacteria is a slow growing microbe, H_2 is not yet converted to CH_4 and shows higher concentration.

The results of ADM1 and Hashimotos' model show similar results while ADM1 provides more information on the biogas composition. Also, Hashimoto's model shows only empirical relationships among several parameters rather than real mechanisms.

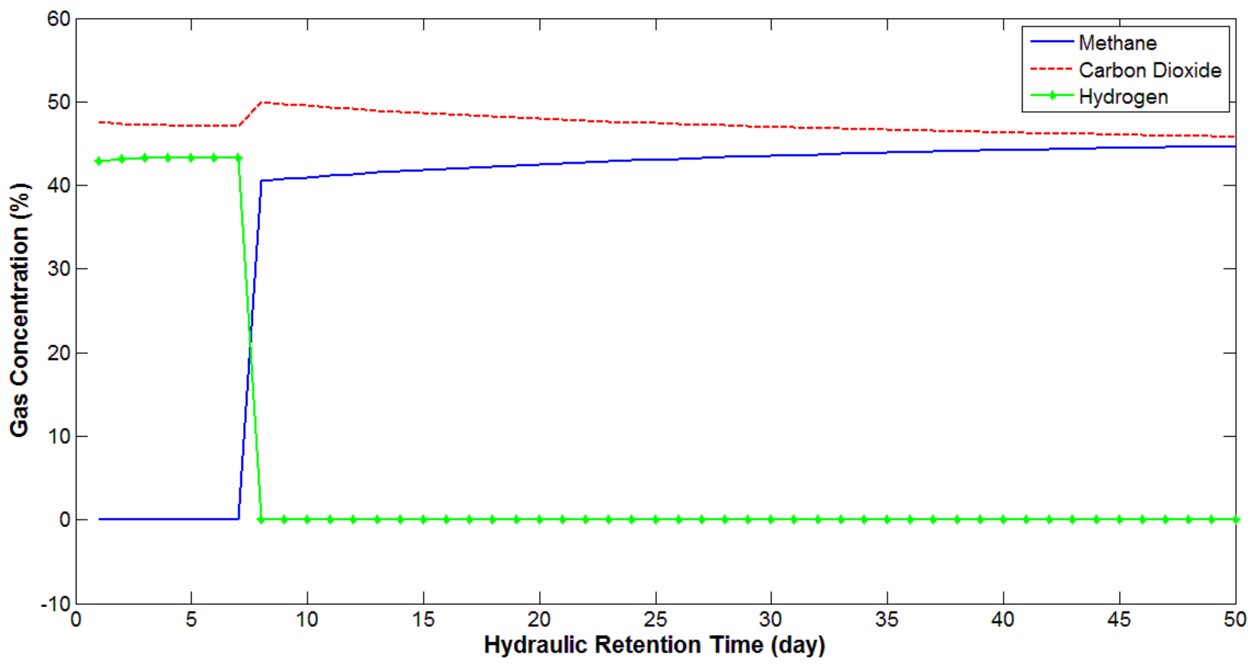

Figure 4.6 Gas percentage of biogas under different HRT by ADM1

4.3 Anaerobic Digester Heat Requirement Model

4.3.1 Model Development

This section proposes an anaerobic digester heat requirement model. With usage of a larger volume reactor, the methane production rate will be higher; however, the energy required to maintain reactor temperature will also be higher.

Heat transfer in an anaerobic digestion reactor can be analyzed by understanding internal features and examining the heat transfer process. Similar to the swine barn energy consumption model, the current study uses a control volume approach to estimate energy consumption for the anaerobic digestion process. Several assumptions are set forth to simplify the energy consumption model:

1) Influent feedstock never freezes. The fluent manure temperature is 5℃ when the ambient temperature is lower than 5℃. The manure temperature is equal to the ambient temperature when the temperature is higher than 5℃.
2) No heat is produced during anaerobic digestion process.
3) The digester is well mixed: that is, the temperature is homogenous throughout the digester.

In industry, the major portion of heat consumption used to operate the digester is consumed by the preheating process for the influent feedstock. Swine manure has higher temperature after excretion compared to the ambient temperature and the manure loses heat during other processes, for example, during storage and transportation. Since the current study assumes that swine manure is transferred to the digester within a short period of time, only a small amount of heat will be lost during the process. Therefore, the first assumption is made.

Anaerobic digester (AD) is a heat generation process that provides parts of heat to maintain digestion temperature. However, heat production is difficult to estimate because it differs due to environmental conditions and feedstock properties. Overall, the heat produced during the anaerobic process is relatively small compared to the supplemental heat needed to maintain constant temperature at a certain level. The current study estimates the maximum potential energy consumption during the process; therefore, the second assumption is made as an approach to estimate maximum potential energy production.

In order to simplify the heat transfer process, a control volume approach is used in the current study and homogeneous temperature distribution is assumed. For purposes of simplifying the model, the third assumption is made to be consistent with assumptions in section 4.2.1., even though the third assumption is known to introduce errors.

Assume temperature is maintained at constant temperature for both slurry and biogas,

$$q_{in} + q_S + q_{\mathrm{e}} - q_w - q_m - q_g = 0 \qquad (4.\ 6)$$

Where:

q_{in} = heat loss through inlet manure

q_S = solar heat gain

q_e = heat gain from heat exchanger, also is taken as calculated heat requirement

q_w = heat loss through digester envelope of sludge portion.

q_g = heat loss through digester envelope of gas portion

The heat balanced is shown in figure 4.7

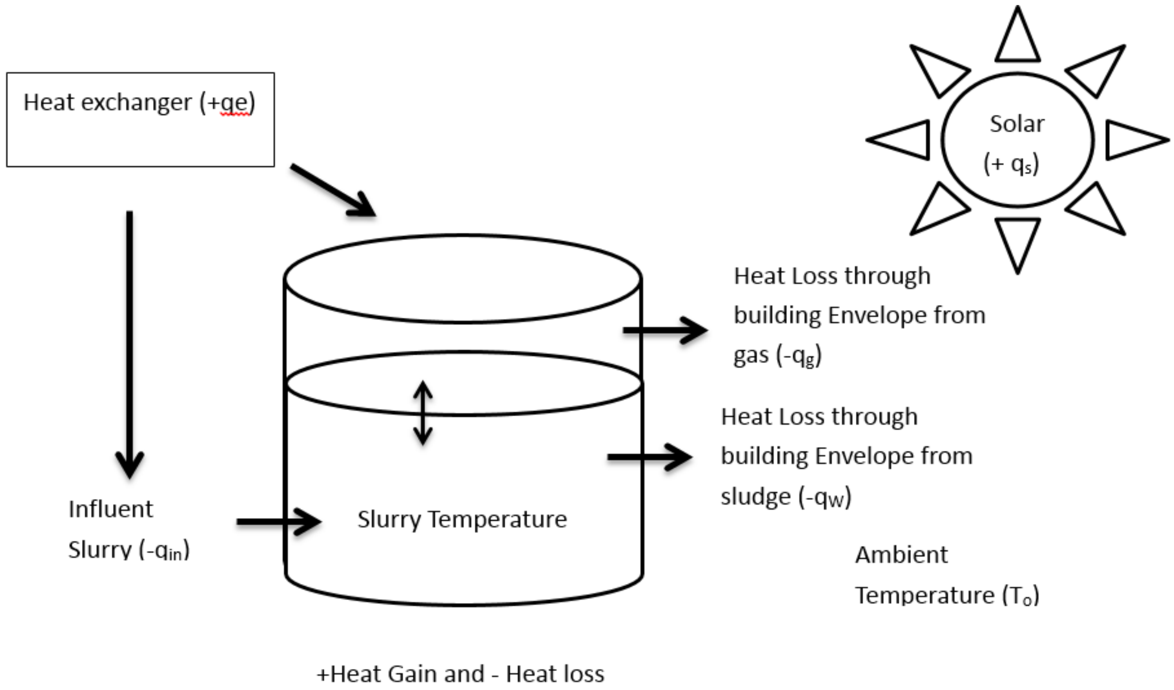

Figure 4.7 Heat gains and heat losses in anaerobic digestion process

Based on the assumptions that homogeneous temperature is distributed and that solar heat gain is conducted in sol-air temperature as t_e in the same way as described in Chapter 3, heat loss through the digester from sludge is calculated by the equation:

$$q_W = U_S A_s \times (T_e - T_S) \tag{4. 7}$$

Where:

U_s = total heat conductivity on sludge to outside digester

A_S = surface areas that contact sludge

T_e = sol-air temperature

T_S = slurry temperature, assumed to be 35℃

Because gas has different properties compared to sludge, the heat loss through the digester walls and floor from biogas is noted separately:

$$q_g = U_g A_g \times (T_e - T_a) \qquad (4.\ 8)$$

Where:

q_g = heat loss through the digester envelope from the biogas portion

U_g = total heat conductance from biogas to ambient

A_g = the surface area of the digester that contacts the biogas

T_a = biogas temperature, assumed to be 35℃

Heat loss through inlet manure due to temperature difference of inlet manure and digesting sludge is estimated by the equation

$$\mathrm{q_{in}} = m_{in} C_p^s (T_i - T_m) \qquad (4.\ 9)$$

Where:

m_{in} = influent mass flow rate of swine manure

C_p^s = specific heat of swine manure, J/kg-K

T_m = influent swine manure temperature, ℃

Since the current study assumes that inlet manure is not always equal to ambient temperature, T_m should be modified as:

$$\mathrm{T_m} = \mathrm{T_o}\ when\ \mathrm{T_o} > 5℃$$

$$\mathrm{T_m} = 5 \text{ when } \mathrm{T_o} \leq 5°\mathrm{C} \qquad (4.\ 10)$$

All algorithms above were written in a Matlab function in Simulink (dataprocess_AD_tank) and connect to the Transformer model and ADM1 as shown figure 4.8**.** The AD process Subsystem is described in figure 4.4**.**

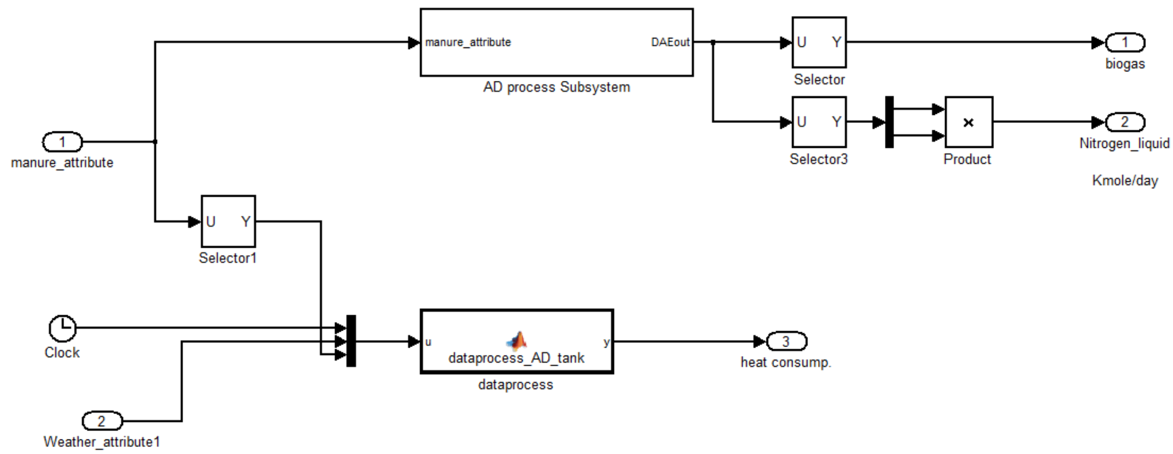

Figure 4.8 Systematic model of heating requirement for anaerobic digestion and ADM1

4.3.2 Model Inputs

This model aims to simulate a commercialized scale digester and several specifications are defined and listed in table 4.4. Based on modeling results in section 4.2.2, the current study chooses a tank size of 575 m^3 liquid space and 57.5 m^3 head space. The size was chosen based on a methane production rate at HRT that equals 90% for 50 days HRT. The diameter and height of the cylindrical shaped digester are listed in table 4.4.

Hourly weather data for 2010 in Springfield, IL and Oklahoma City, OK were collected from the National Solar Radiation Data Base (NSRDB) and taken as input variables for the simulations of different scenarios as proposed in the current study.

Table 4.4 Simulation parameters for reactor thermal model

Materials	**Thermal transmittance through conduction (W/ m^2-K)**	**Thermal resistance (m^2-K/W)**
Ho	17	0.0589
6" Fiberglass insulation		4.24
12" Concrete		0.3386
hi (slurry to tank)	58	0.0172
hi (biogas to tank)	8.2	0.1220
Sizes	**Value**	**Unit**
Digester height	3.7	m
Digester diameter	14.8	m

Table 4.5 Maximum/ Minimum temperature for two scenarios

	Maximum temperature	Minimum temperature
Springfield, Illinois	36.1	-22.8
Oklahoma City, Oklahoma	39.4	-13.9

4.4 CHP Unit

Based on estimated methane production, commercialized CHP units were selected according to CHP unit capacity of heat and electricity generation. A list of engine generator capacities is shown in table 4.6. The current study assumes the CHP unit utilizes bio-methane as fuel, which is given $35 \times 10^6\ J/m^3$ heating value for CHP estimation.

Table 4.6 CHP gas engine modules in biogas operation

CHP unit	No. of cylinders	Output electrical (kW)	Output thermal (kW)	Gas usage (kW)
Vitobloc: BM-36/66	R4	36	66	122
Vitobloc: BM-55/88	R6	55	88	165
Vitobloc: BM-190/238	V12	190	238	493
Vitobloc: BM-366/437	V12	366	437	950
GE Jenbacher type 2: J208 (50Hz)		299	400	785
GE Jenbacher type 2: J208 (60Hz)		335	407	900
GE Jenbacher type 3: J312		527	626	1322
GE Jenbacher type 3: J316		637	725	1564
GE Jenbacher type 3: J320		1,063	1,193	2605

Based on estimated methane production and assumed heating value, a commercialized CHP unit was chosen. Assumptions for further heat/power production are made as follows:

1) If gas heating value is smaller than module requirement, the CHP unit will still maintain its heat/power generation efficiency if the difference is small.
2) Extra biogas that exceeds the module requirements will be fed directly to a heater that has 70% efficiency.

The first assumption introduces errors to the estimation. However, the efficiency may show only a small difference. The second assumption recognizes that because methane is a crucial greenhouse gas that has a negative impact of more than 20 times that of carbon-dioxide, the transformation of methane to carbon-dioxide is necessary. The transformation of methane to carbon-dioxide generates extra heat from the process and that heat is also utilized. Most commercialized methane heaters have more than 90% efficiency. However, due to the lower heating value of biogas, this research assumes 70% efficiency to make a conservative estimation.

4.5 System Model Application and Discussion

Based on section 4.2.2, methane production is around 667 m^3/day with 575 m^3 size CSTR. The energy production is about 270 kW by assuming $35 \times 10^6\ \mathrm{J/m^3}$ fuel heating value.

Both the two Vitobloc BM-36/66 modules and the one Vitobloc BM – 55/88 can be implemented to utilize biogas. The current study proposes that extra biogas be burned to reduce greenhouse effects. Based on implementation of two Vitobloc BM-36/66 modules, heat production from CHP would be 132 kW (3168 kWh/day). Based on implementation of one Vitobloc BM – 55/88, heat production from CHP would be 88 kW (2112 kWh/day). Both choices can provide enough heat to support the anaerobic digestion process. However, by utilizing the extra biogas, implementation of one Vitobloc BM – 55/88 module will produce higher heat production yet lower power production compared to implementation of the two Vitobloc BM-36/66 modules.

Simulations of anaerobic digesters were located in Springfield, IL and Oklahoma City, OK under 2010 conditions of local weather and solar radiation collected from the National Renewable Energy Lab (NREL).

As shown in figure 4.8, maximum heat requirements for swine production in winter are around 1800kWh/day. Two CHP modules generate 3168 kWh/day, which is sufficient to meet the digester heat requirement in winter. Figure 4.9 shows that reactor heating requirements are different in the two locations. Since the ambient temperature in Oklahoma City is higher than that in Springfield, the heat requirement for Springfield is higher than for Oklahoma City.

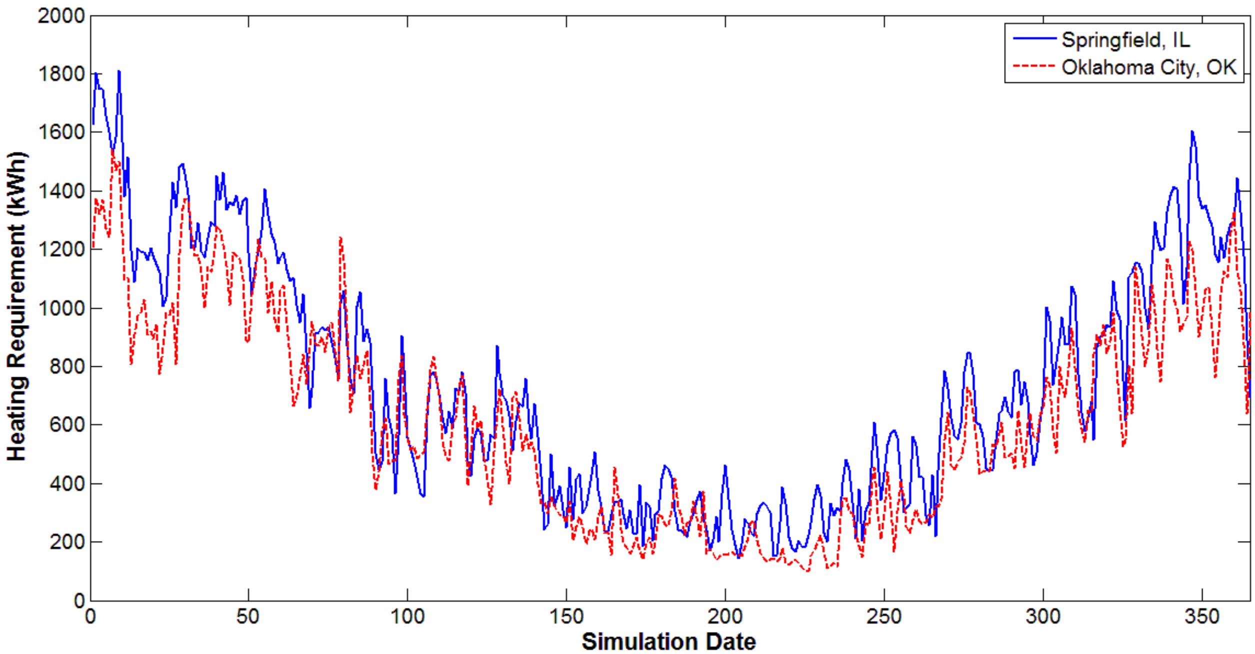

Figure 4.9 Heating requirement for maintaining temperature at 35°C

CHAPTER 5 IFS MODEL AND APPLICATION

Chapter 5 combines the dynamic swine production system model described in Chapter 3 combined with the dynamic anaerobic digestion and CHP system model presented in Chapter 4. These two chapters together estimate the power and heat production requirement portfolios. Together, the two models also present the overall dynamic Integrated Farming System (IFS) model proposed by the current study for use by farmers and engineers in a commercial scale swine barn (2400 pigs per barn) with a commercial scale digester (575 m^3). Section 5.2 addresses how the dynamic IFS model proposed by current study was developed. Section 5.3 addresses the input variables for the dynamic IFS model. Section 5.4 is an application of the dynamic IFS model and demonstrates simulations based on several different scenarios.

5.1 IFS System Description

Three separate commercial swine barns are proposed as presented in Chapter 3. In order to maintain stable production of the market-size swine and manure for biofuel, the current study proposes a staggered production over three swine raising periods. Growing- finishing pigs (20 - 107 kg barrows and gilts) in different barns are simulated separately with different initial pig weight to create the staggered production scenarios. The flexibility of the model allows engineers and researchers to calculate different types of staggered production schedules. The specific pig growth phase selected for the current study is described in section 5.3.

An above-ground concrete Continuous Stirred Tank Reactor (CSTR) of size 575 m^3 is proposed to treat swine manure, as described in Chapter 4. Figure 5.1 demonstrates the virtual design of the overall IFS model proposed by the current study. Three commercial swine barns are operated separately and each operation is described in Chapter 3. This model proposes that swine manure be pumped daily to CSTR for biogas generation. The industry Combined Heat and Power (CHP) system is implemented to utilize the biogas for the purpose of providing heat and power to support the three swine barns and the CSTR.

Figure 5. 1 Virtual design of an Integrated Farming System (IFS)

Figure 5.2 shows how the overall IFS model was developed. The swine production system model (Chapter 3) was first applied to estimate swine production and the swine barn energy consumption portfolios. The manure excretion rate was then estimated empirically based on applying the relationship between swine live weight and manure production rate. Next, the anaerobic digestion and CHP system model (Chapter 4) were applied to generate both the energy consumption and production portfolios. Simulation of the overall heat/power consumption and production portfolios is discussed in section 5.4.

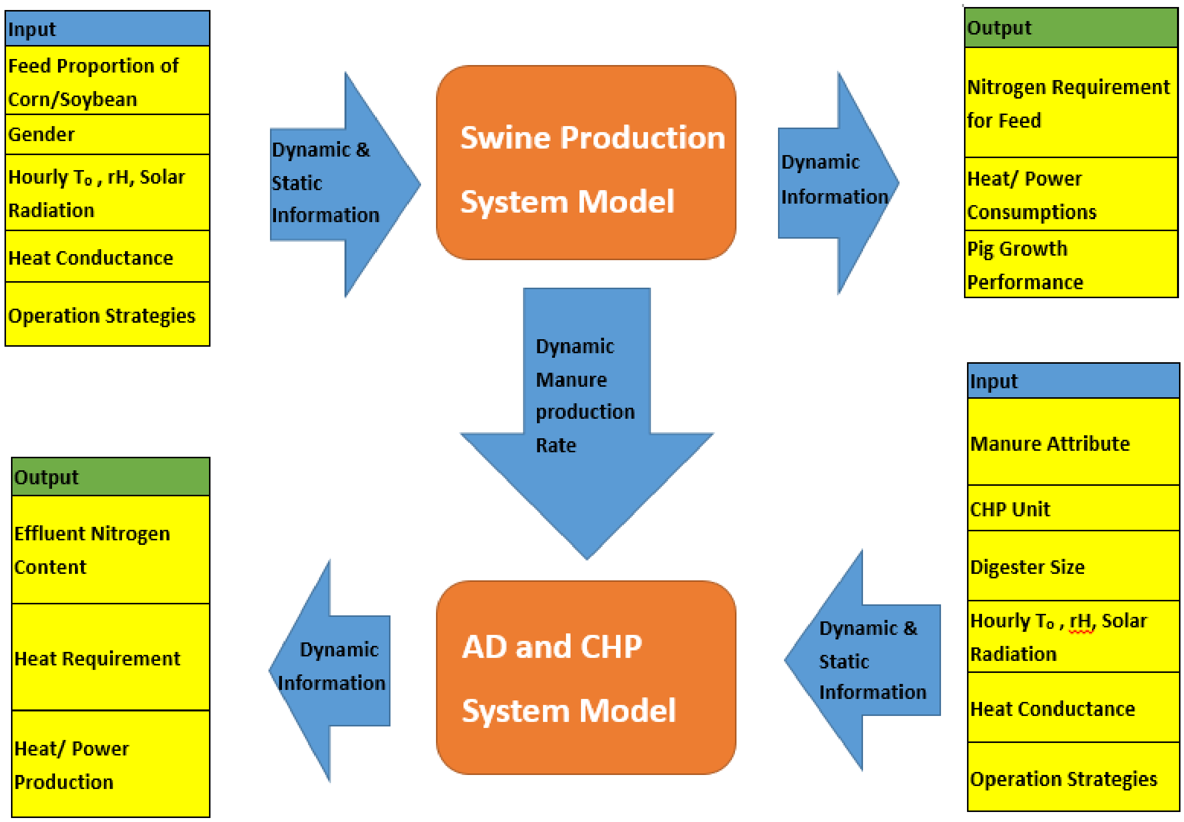

Figure 5.2 Modeling systematic diagram of Integrated Farming System

5.2 Model Development

5.2.1 IFS System Design and Modeling

Most models of anaerobic digester systems are based on the stable manure production rate of dairy cows. By contrast, the rate of swine manure production fluctuates dramatically over the production cycle due to the fluctuation of the live weight of growing-finishing pigs. In order to maintain stable swine manure as feedstock for processing by the anaerobic digester, the current study proposes a staggered production system that operates in three commercial swine barns (2400 pigs per barn) with different phases of the growing-finishing period. Some staggered production systems introduce problems with diseases, therefore, the proposed system isolates the barns to reduce the potential for diseases. Chapter 5 simulates the dynamic IFS model based on several intrinsic assumptions inherited from the subsystem models. Additional assumptions are follows:

1) No interaction between barns

2) The swine manure production in the simulation is rate correlated based only on body weight and a steady state of manure properties.

Because each barn is assumed to be operated separately to avoid disease problems, the first assumption is set forth to simulate the swine production system.

Without on-farm manure excretion experiments, the simulation of manure excretion is needed. However, current manure excretion models are not able to provide chemical attributes of feedstock that are necessary for the ADM1 model and the Transformer model. In order to connect the swine production system model as well as the anaerobic digestion and CHP system model, the current study reviewed chemical properties from previous research and set those properties as static variables for the proposed dynamic IFS model. The second assumption simplifies the integrated model and provides reasonable estimations. Therefore, the second assumption is made.

Spline fit is used to interpolate the swine manure production rate based on different pig body weight. The relationships can be referred to in UI extension work. Figure 5.3 shows the manure production rate based on different pig body weight.

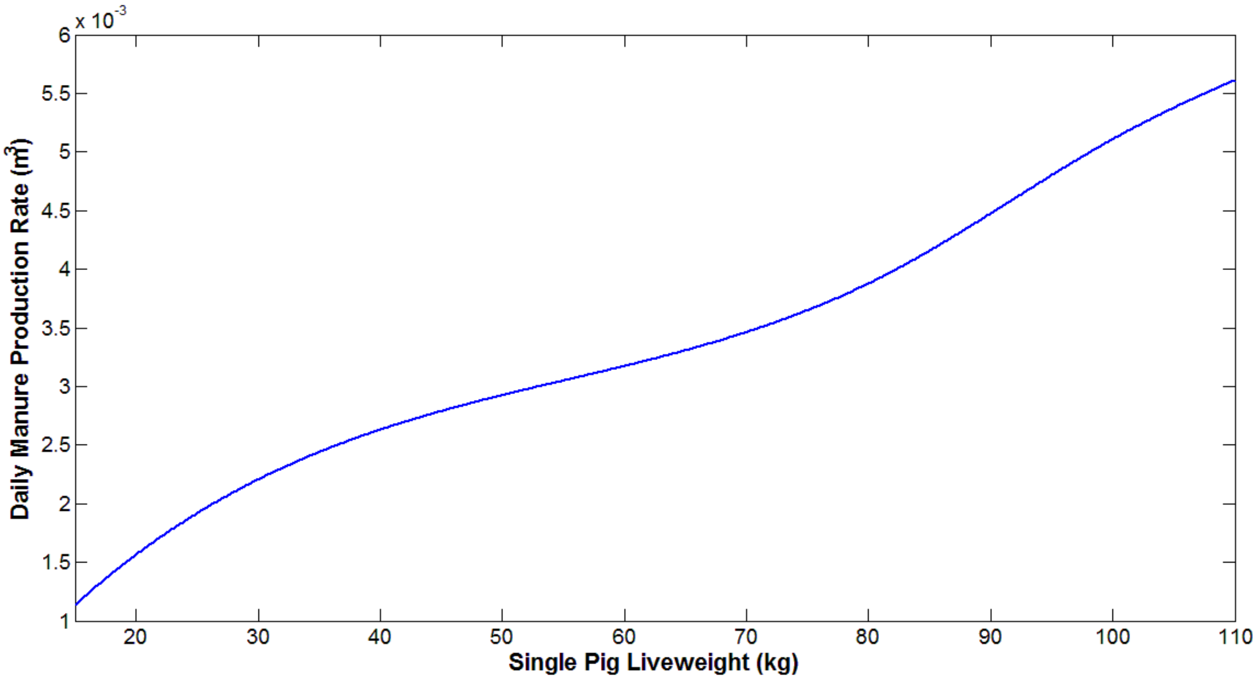

Figure 5.3 Interpolation of swine body weight and manure production rate from UIUC extension

5.2.2 Annual Crop Production Estimation

Jackson et al. (2000) calculated the nutrient balance by applying animal manure to crop land. Based on a simple calculation and crop production estimation, that approach provides farmers with a useful tool to estimate how much land is needed to recover nutrients generated by Concentrated Animal Feeding Operation (CAFO). Based on UIUC extension work, nitrogen percent losses during storage and land application are shown in table 5.1.

The current study follows the approach of Jackson et al. (2000) to estimate nitrogen consumption of land. All estimation parameters for crop land are listed in table 5.2.

Feeds for swine and effluent nitrogen from the anaerobic digestion are estimated in Chapters 3 and 4. Based on utilizing information gathered from the two subsystem models, the nitrogen recovery rate for the IFS can be estimated.

Table 5.1 Nitrogen percent losses during manure processing

Manure Storage System		
	Lower limit: short term storage, cool conditions	Higher limit: long term storage, warm conditions
Anaerobic pit	15 %	30 %
Above ground storage	10 %	30 %
Earth storage	20 %	40 %
Lagoon	70 %	85 %
Manure Land Application		
Broadcast	10 %	15 %
Incorporation	1 %	5 %
Knife or sweep injection liquid	0 %	2 %
Sprinkler irrigation liquid	15 %	40 %

Table 5.2 Assume parameters of crop production estimation

Variables	value	unit
Nitrogen requirement for soybean	0	bu/ac
Nitrogen requirement for corn	1.2	lb/bu
Corn yield	160	bu/ac
Nitrogen losses during storage	30	%
Nitrogen losses during land application	15	%

5.3 Model Inputs

This section combines simulations of all scenarios based on a white gilts group with cooling pads in commercial swine barns as described in Chapter 3.

Because of the non-steady inflow rate, the initial state for anaerobic digestion is crucial. The current study utilizes the steady effluent state with an inflow rate of 25m^3/day, described in Chapter 4, as the initial condition of the IFS ADM1 (table 5.3). By considering tank size 575 m^3 for sludge and 57.5 m^3 for gas storage, the integrated model assumes a fluctuating feedstock inflow rate in a static tank size. Other parameters are described in Chapter 4. With the exception of parameters described in Chapters 3 and 4 for the proposed Integrated Farming System (IFS), all other parameters are listed in table 5.4. The 2010 weather information for Springfield, IL and Oklahoma City, OK were collected as described in Chapters 3 and 4.

Table 5.3 Initial state of ADM1

State no.	Variable	Value	Unit	State no.	Variable	Value	Unit
1	S_su	0.0108122	kg COD/m3	20	X_c4	0.6220355	kg COD/m3
2	S_aa	0.0048393	kg COD/m3	21	X_pro	0.5711683	kg COD/m3
3	S_fa	0.09025	kg COD/m3	22	X_ac	1.6398916	kg COD/m3
4	S_va	0.0065621	kg COD/m3	23	X_h2	1.0961955	kg COD/m3
5	S_bu	0.0138263	kg COD/m3	24	X_I	19.59845	kg COD/m3
6	S_pro	0.014907	kg COD/m3	25	S_cat	0.3368	kmole/m3
7	S_ac	26.244861	kg COD/m3	26	S_an	0.048474	kmole/m3
8	S_h2	2.18E-07	kg COD/m3	27	S_hva	0.0065465	kg COD/m3
9	S_ch4	0.0429285	kg COD/m3	28	S_hbu	0.0137962	kg COD/m3
10	S_IC	0.1709963	kg COD/m3	29	S_hpro	0.0148698	kg COD/m3
11	S_IN	0.2909569	kg COD/m3	30	S_hac	26.195068	kg COD/m3
12	S_I	7.3205007	kg COD/m3	31	S_co3	0.1602726	kmole/m3
13	X_xc	0.9527665	kg COD/m3	32	S_nh3	0.0094613	kmole/m3
14	X_ch	0.237896	kg COD/m3	33	S_gas_h2	6.69E-06	kmole/m3
15	X_pr	0.0589636	kg COD/m3	34	S_gas_ch4	1.1188619	kmole/m3
16	X_li	0.0229602	kg COD/m3	35	S_gas_co2	0.0194186	kmole/m3
17	X_su	5.2951576	kg COD/m3	36	Q_D	25	m3/d
18	X_aa	0.7428373	kg COD/m3	37	T_D	35	C
19	X_fa	0.2024616	kg COD/m3				

Table 5.4 Extended parameters for integrated farming system

Parameter	value	unit
Initial pig weight for Barn A	20.1	kg
Initial pig weight for Barn B	50.9	kg
Initial pig weight for Barn C	80.4	kg
Digester size (sludge portion)	575	m3
Digester size (gas portion)	57.5	m3

5.4 System Model Application and Discussion

This section discusses different scenarios that present the simulation results of the dynamic IFS model. Two different scenarios are discussed: an IFS system under 2010 weather conditions for Springfield, IL (section 5.4.1) and an IFS system under 2010 weather conditions for Oklahoma City, OK (section 5.4.2). Overall system nitrogen production and consumption for the two scenarios are compared in section 5.4.3.

5.4.1 IFS System under Springfield, IL Weather Conditions

Figure 5.4 shows the simulation results for overall pig weight production under weather conditions for Springfield, IL. Based on the proposed model with three commercialize scale swine barns (2400 pigs per barn) and staggered operations, market-size swine are produced continuously and provide stable swine manure as feedstock to the anaerobic digestion process.

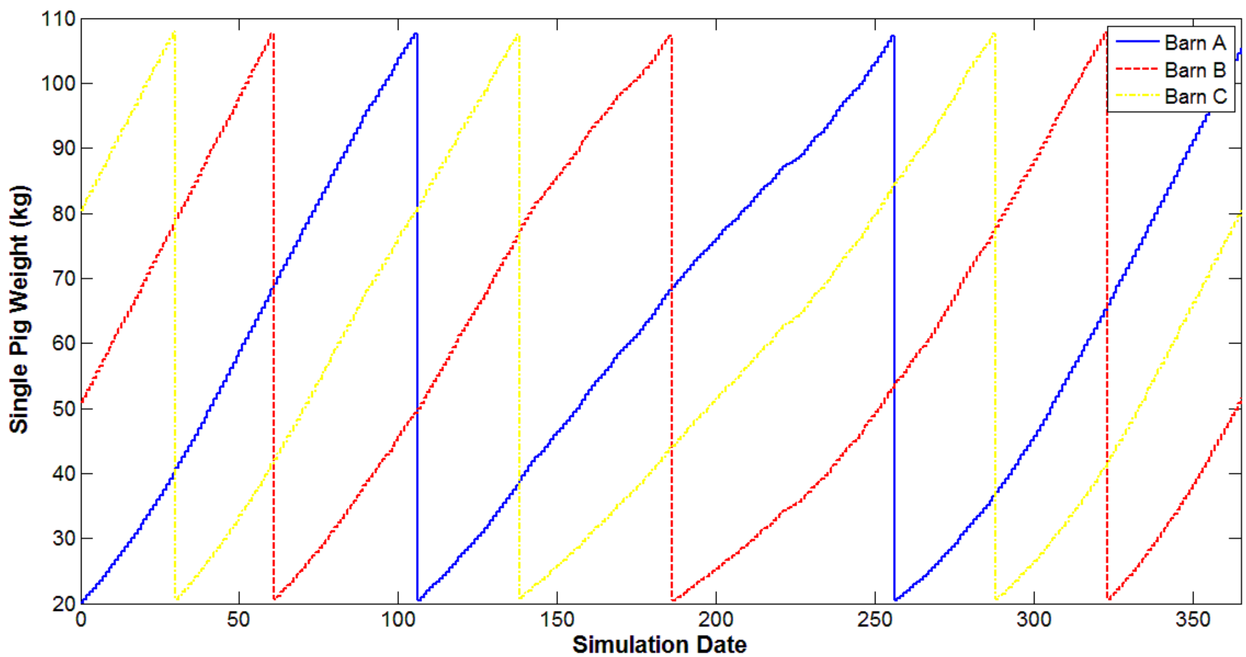

Figure 5.4 Total swine body weight production over virtual experiment year

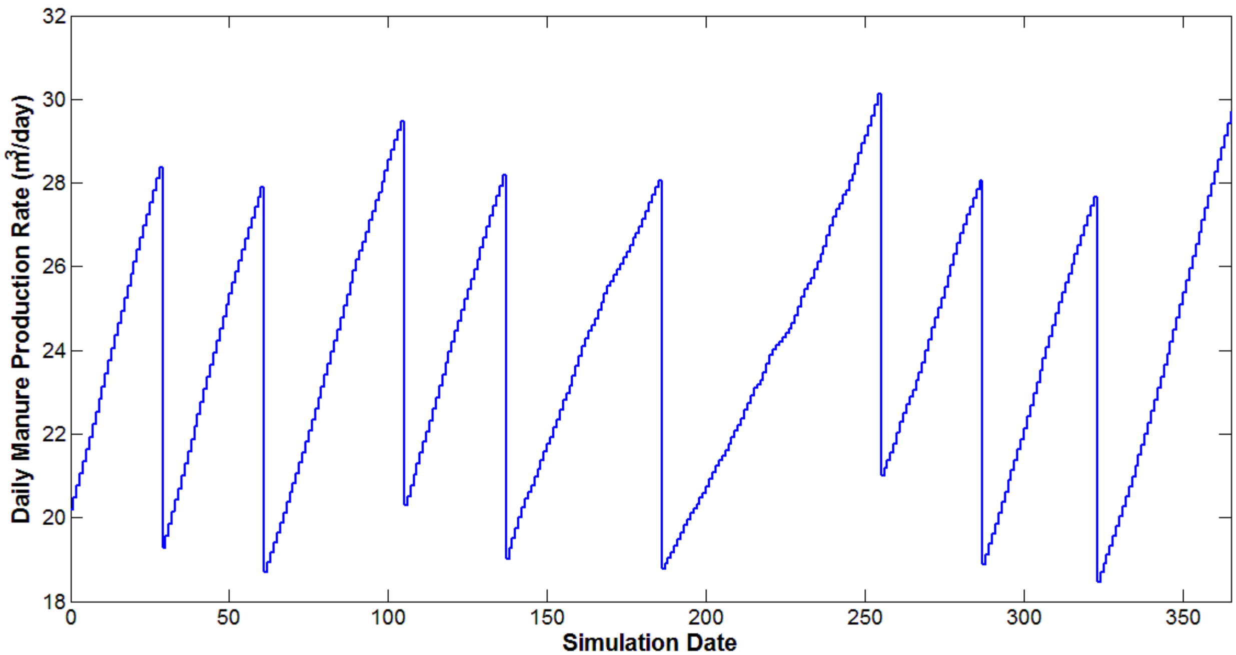

Figure 5.5 Manure production rate over simulation year

As shown in figure 5.5, manure production fluctuates from around 18 m^3/day to 30 m^3/day, which means that HRT fluctuates from 32 days to 20 days with the fix-sized digester. The methane production rate is affected by HRT as shown in figure 5.6. The main reason for the fluctuation is that higher HRT (lower influent rate) has a higher methane production rate per inflow rate and lower HRT (higher influent rate) has a lower methane production rate per inflow rate.

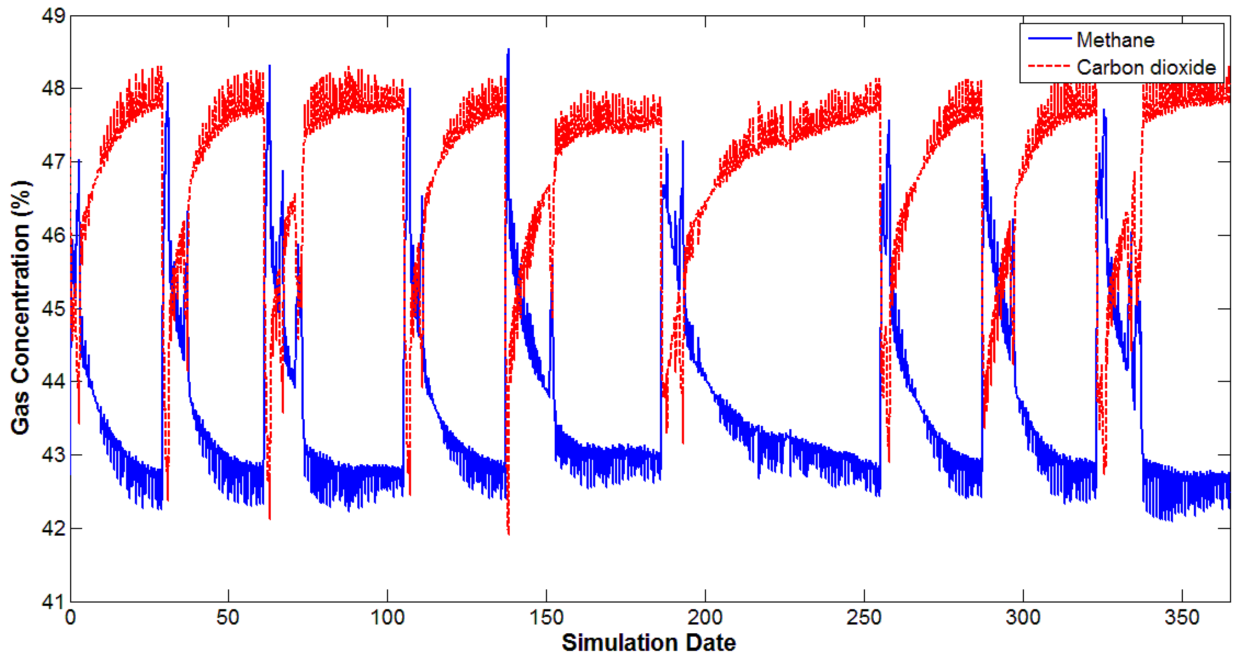

Figure 5.6 Methane and carbon dioxide concentration in biogas under Springfield weather conditions

The current study chose the CHP unit for this proposal based on the methane production rate and estimated total heat/power production. Heat production is more efficient when direct heaters are used to process biogas as fuel compared to the CHP unit; therefore, the current study proposes to implement only one CHP and to utilize excess biogas directly to the heater. The current study utilizes one Vitoblock BM-55/88 CHP unit (table 4.6) and the excess methane to generate heat and power as described in section 4.4.

To examine electricity and heating requirements/production for the proposed IFS model, overall heat/power consumption and heat/power production by the CHP unit under Springfield weather conditions are compared as shown in figures 5.7 and 5.8. Figure 5.7 demonstrates that with the proposed operation, the total heat production is not sufficient to maintain indoor air temperature under extreme winter conditions. However, it is possible to reduce the heat requirements by managing the growing schedule of the three different barns and raising building thermal resistance to reduce the heat requirements. A CHP unit generates more electricity than required by an IFS system as shown in figure 5.8. The excess power generated by the CHP unit can be directed other subsystems that may be added in the future.

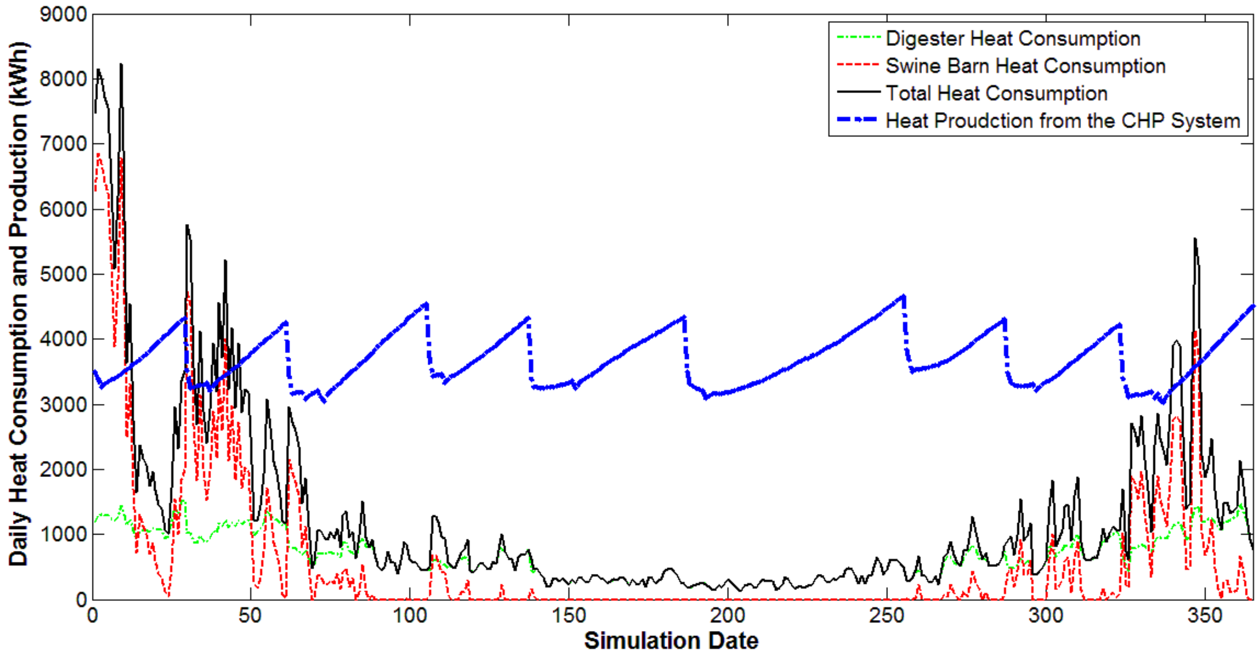

Figure 5.7 Heat requirement and production of the IFS under Springfield weather condition with one CHP unit.

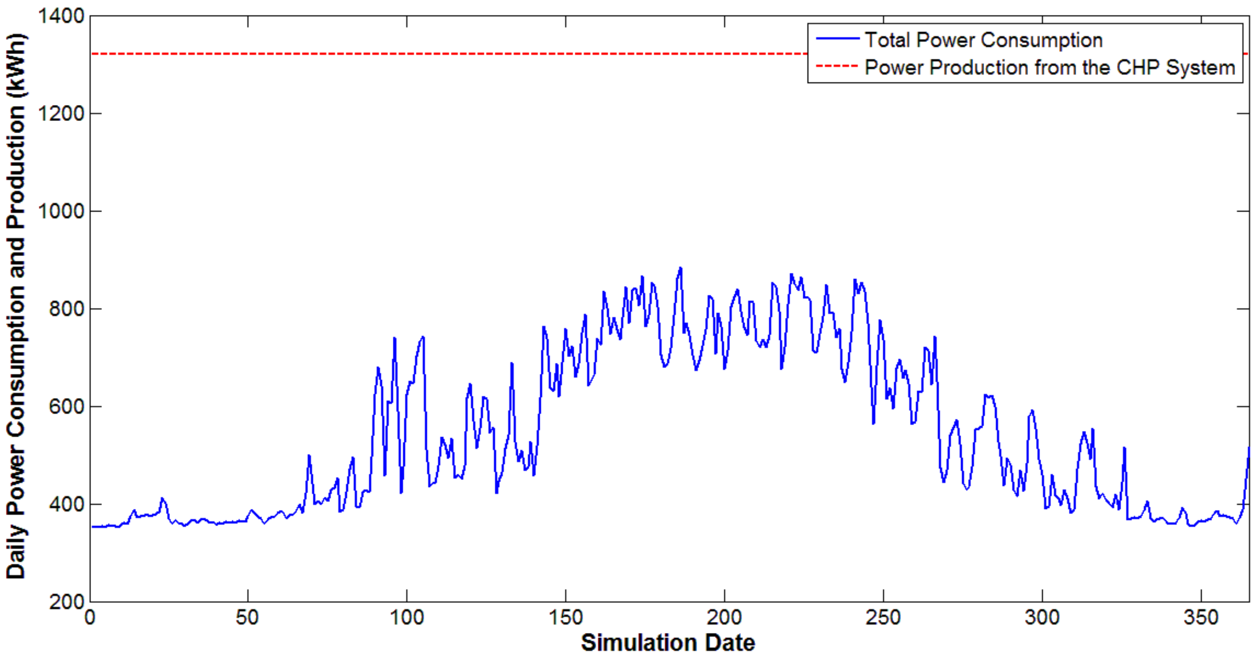

Figure 5.8 Electricity power requirement and power production of the IFS under Springfield weather conditions with one CHP unit

5.4.2 IFS system under Oklahoma City Weather Conditions

Figures 5.9 and 5.10 show overall energy consumption and production portfolios under Oklahoma weather conditions. Since the overall heat requirements under weather conditions in Oklahoma City are relatively smaller than in Springfield, the current study chose two Vitoblock BM-55/88 CHP units to generate more electricity. Figure 5.9 shows that heat production is sufficient for the integrated system under both summer and winter conditions. Moreover, the two CHP units in the integrated system produce more power that can be connected to the grid for other usages as shown in figure 5.10.

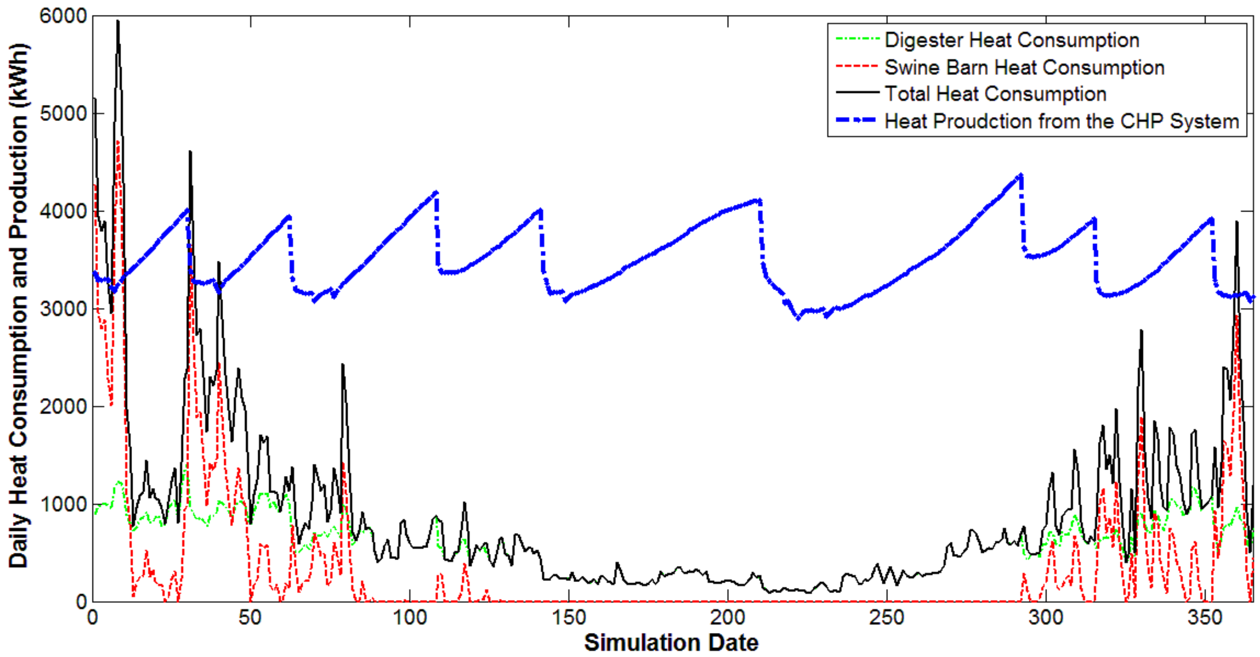

Figure 5.9 Heat requirement and production of the system under Oklahoma City weather conditions with two CHP unit

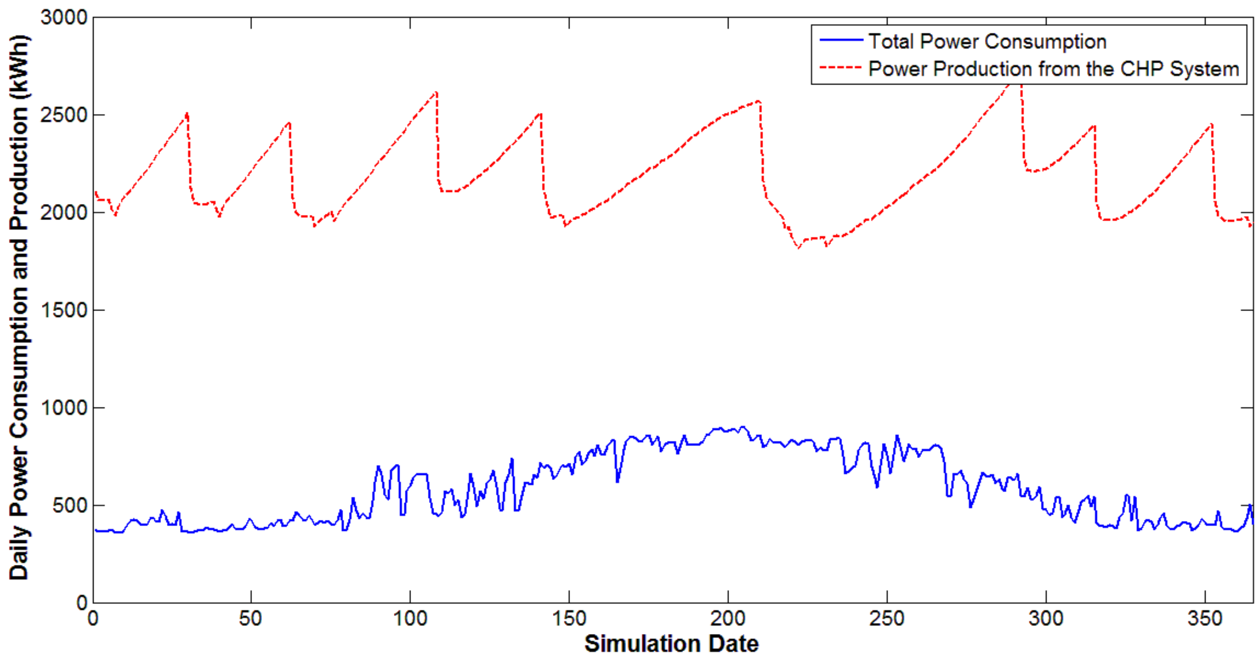

Figure 5.10 Electricity power requirement and power production of the system under Oklahoma City weather conditions with two CHP units

5.4.3 Overall System Nitrogen Production and Consumption in Oklahoma City and Springfield

Table 5.5 shows the estimated overall nitrogen production by the anaerobic digester and estimates crop (Soybean and Corn) production under two scenarios. Swine feed consumption is also listed in table 5.5 and compared with crop production estimations. The swine manure in the proposed IFS system recovers 20.1% of nitrogen for swine feed requirement under 2010 Springfield weather conditions compared to 21.3% recovery under 2010 Oklahoma City weather conditions. Due to greater intake of nitrogen (swine feed) than production (market-size swine) in the swine production system, nitrogen deficiency is expected. Although the current calculations do not consider carryover nitrogen from the previous year's legume crop or fertilizer, the results provide a direction for system design.

While the nutrient recovery rate is higher under Oklahoma weather conditions, the swine production rate is lower. The higher nitrogen recovery rate under 2010 Springfield weather conditions shows that less swine feed is needed to produce market-size swine.

Table 5.5 Nitrogen balance for AD effluent and swine feed under Springfield weather conditions over a 12-month period

Parameter	Springfield	Oklahoma City	Unit
Nitrogen produced by AD	34550	34206	kg
Nitrogen can be utilized by plant	20557	20353	kg
Corn requirement as swine feed	4783783	4453947	kg
Nitrogen requirement for the corn requirement	102509	95442	kg
Nitrogen recovery rate	20.1	21.3	%

The current study implicitly includes energy and nutrient (nitrogen) inputs that support the proposed integrated farming system. This model assumes no nitrogen needs for soybean production as reported by Jackson et al. (2000); therefore, legume nitrogen fixation is considered a significant source for nitrogen in the proposed IFS system.

CHAPTER 6 CONCLUSION AND FUTURE RESEARCH

6.1 Conclusion

The current study develops and proposes an Integrated Farming System (IFS) model that simulates the swine production process, the anaerobic digestion (AD) process, and Combined Heat and Power (CHP) production. The IFS model shows two scenarios based on 2010 weather conditions in Springfield, IL and Oklahoma City, OK. The scenarios present different system heat/power requirement portfolios, swine growth performance, and system nutrient recovery rates for the two locations.

A trade-off between heat and electricity power production was found by the current study. While utilizing biogas directly as fuel for heaters provides higher heat production efficiency, the CHP unit is capable of producing electricity with lower heat production efficiency. If the system demands more heat than CHP production provides, then the direct utilization of biogas as fuel for heaters may also be considered to support the overall system heat requirement.

With lower average ambient temperatures in Springfield, IL compared to those in Oklahoma City, OK, the total IFS heat requirement is higher. Therefore, implementation of single CHP unit with an additional heater to utilize excess biogas as fuel is proposed by this IFS model to produce sufficient power and more heat when the heat requirement is higher under colder climate conditions. Engineers and farmers can add more CHP units to generate more electricity but new technologies may be needed to meet greater heat requirements in winter.

The IFS model proposed by the current study in the Oklahoma City scenario has a lower overall heat requirement and a higher power requirement compared to the proposed IFS model in the Springfield scenario. There is no need to utilize biogas directly as fuel for a heater to support the system heat requirements. Instead, it is feasible to feed all biogas to the CHP units to produce more electricity.

A higher feed-to-gain ratio resulting from heat stress under summer conditions is presented by the proposed IFS model. The model and farm experiments show that in summer conditions variations in swine growth performance depend on different operation strategies and efficiency of cooling systems.

Overall system nitrogen recovery efficiency is affected by swine growth performance. The nutrient recovery rate is higher in Oklahoma City compared to that in Springfield. Less nitrogen in swine feed is transformed to market-size swine with higher feed-to-gain ratio; therefore, a cropping system requires less nitrogen input to support swine production.

The dynamic IFS model proposed by the current study provides engineers and researchers with a tool that is useful for designing operation strategies and estimating the impact of technologies on an IFS system. Without the expense of conducting in-farm experiments, the proposed model provides estimations of energy production and consumption portfolios through simulations of a virtual farming system design that presents parameters to be considered before an actual system is constructed.

6.2 Future Research

Further studies are needed to investigate the development of a manure excretion model that connects intake diet, pig body weight, and environmental factors to provide a more accurate estimation for an extended integrated system. Based on a stronger connection between swine manure and diet, engineers and researchers can then study the IFS consumption/production portfolio as affected by diet design.

Future studies are also needed to investigate the development of models for different types of animal and plant production systems. For example, an algae production system needs to be considered due to its high production and nutrient usage rate.

Also, future research needs to be directed toward optimization based on utilization of results presented by this proposed integrated model. For example, economic analysis and total energy/nutrient analysis are two interesting topics for investigation of optimization.

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