

NPB FINAL RESEARCH GRANT REPORT FORMAT

As a requirement of each research grant, a final report detailing the project results must be provided to the National Pork Board. Please write the industry summary with the producer in mind. The remaining content of the report can be written for a scientific audience. ALL final reports must be submitted in the following format or the report will be returned for correction. PLEASE DO NOT INCLUDE ANY TYPE OF COVER PAGE.

Project Title and NPB project identification number Creating a sustainability index for the United States swine industry through stochastic modeling (#21-101)

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Industry Summary:

Random variation is a natural component of biological systems but is difficult to quantify and account for in the programs that are typically used to formulate swine diets and make production decisions. On the growing-finishing swine farm, variation may arise from pig characteristics (e.g., sex differences, ranges in pig body weight, varying efficiencies of digestion and nutrient utilization, etc.), feed characteristics (e.g., feed ingredient nutrient composition, quality of feed mixing or pelleting, diet formulations that fail to match nutrient requirements, etc.), environmental conditions (primarily, temperature above or below the pig's thermoneutral zone changing feeding behavior and growth), and management factors (e.g., stocking density, marketing techniques, etc.). Clearly, randomness stemming from these variables has potential to influence the productivity of the herd or profitability of a farm operation. However, these sources of randomness are complex and wide ranging and their impacts upon the system are difficult to disentangle.

The objective of this project was to develop a system to incorporate stochastic (i.e., random) elements into the equations currently utilized in *Nutrient Requirements of Swine* (NRC, 2012), the reference authority of swine nutrition. To accomplish this, we developed an agent-based model to simulate the complex factors that influence pig growth and production performance. Traditional models consider the swine herd in the aggregate and base calculations off the average performance of the herd. Accordingly, these equations are rigid and inflexible because they overlook the individual differences between individual animals. On the other hand, agent-based models provide an opportunity to improve upon these equations because each pig is treated as an autonomous agent with unique behavior, thereby allowing for simulation of the random variations in growth, nutrient use, and responses to environmental conditions.

The agent-based model was built using the NetLogo modeling environment, a program designed for detailed simulations. Pigs in the model were represented individually and operated according to defined rules. In this case, the rules are the mechanistic equations of the existing NRC (2012). Therefore, pig performance in nutrient partitioning, nutrient requirements, and growth could be simulated and observed. Simulations were run at the default settings (growing from approximately 45 pounds to 285 pounds) and accounted for environmental changes outside of the pig's ideal range. Model terms and the variation in these terms can be customized by each user to simulate their unique production scenarios or to address the question they seek to answer. Indeed, a major benefit of the agent-based model is the ability to simulate real-world

scenarios without the associated costs or risks, thereby allowing producers to evaluate different management strategies quickly and effectively.

The major outcome of this effort for pork producers is that agent-based modeling offers a valuable tool for improving the efficiency and sustainability of swine production. This tool allows swine producers and swine industry decision makers to test different management approaches and feeding strategies in a virtual environment, thereby reducing the risks of implementing new practices immediately upon the farm. The ability to customize the model with farm-specific data, such as feed composition or barn conditions, means that producers can tailor it to fit their needs and improve upon their decision-making on their operations. The model is intentionally written to allow for continued evolution. As the model progresses, future integrations with feed optimization and sustainability metrics will help producers to achieve better economic and environmental outcomes. In sum, the model has the potential to drive innovation in swine production and to help producers to manage resources more effectively to keep pace with industry demands.

Key Findings:

- Agent-based modeling offers detailed simulation of individual pig behavior, growth trajectories, and nutrient partitioning, thereby providing insights into the variability and underlying mechanisms driving nutrient requirements and use on the swine farm and the untangling of complex situations that drive nutrient flow through a system.
- Agent-based modeling offers a risk-free platform for testing scenarios and optimizing production performance without incurring the costs and risks associated with real-world experimentation.
- The modular structure of the agent-based model allows for regular updates with new data or user inputs to ensure continued relevance in the industry.
- Transitioning the model to web-based applications will make it more user friendly, and hosting it in logical locations, such as the National Animal Nutrition Program, could enhance versatility by integrating with existing resources including feed composition libraries.

Keywords:

Agent-based Modeling; Feed efficiency; Nutrient utilization; Sustainability; Stochasticity

Scientific Abstract:

Nutrient requirements of growing-finishing pigs are influenced by a complex interplay of factors, including feed intake, metabolism, and environmental conditions. To better understand these dynamics, a comprehensive agent-based model (ABM) was developed and implemented to simulate the growth performance and nutrient requirements of growing-finishing pigs. The ABM was built upon the principles and mechanistic equations from *Nutrient Requirements of Swine* (NRC, 2012), providing a detailed representation of individual pig behavior and interactions within their environment. The model consisted of pig agents capable of movement, feed consumption, nutrient metabolism, and growth based on their nutritional balance status. The proposed ABM was developed using NetLogo, allowing for the dynamic simulation of feed intake, metabolism, and growth processes of pigs with stochasticity included via a triangular distribution function. Key variables, such as body weight gain, starting and finishing weights, pig sexes, and environmental conditions are incorporated into the model; outputs were calibrated using results of pig growth rates and feed conversion ratios from the NRC (2012) computer model to ensure accuracy and reliability. Hence, the ABM is a comprehensive computer framework for simulating and understanding the complex dynamics governing the growth and development of pigs. Further, program-generated result reports of pig outputs allow users to account for and analyze individual variations among the agents (pigs) of the simulation to enhance the model's applicability and utility in practical swine production settings. The model accurately estimates foundational parameters of pigs' biological growth,

including body weight, feed intake, metabolizable energy (ME) intake, maintenance ME requirements, protein deposition (Pd), and lipid deposition (Ld). In addition, the daily requirements such as amino acid, calcium (Ca), and phosphorus (P) requirements were calculated separately for each pig. For purpose of model validation, the growth of pigs of three different sexes (barrow, gilt, and entire male) from 20 kg to 130 kg was simulated. As expected, barrows experienced the least daily protein deposition, the greatest daily lipid deposition, and the greatest time to market weight (i.e., date of pig attainment of the rule to exit the simulation). Daily lipid deposition reached a peak of roughly 409 g/day, 359 g/day, and 314 g/day in barrows, gilts, and intact males, respectively. The results of this project are anticipated to impact the enhancement of feeding and management strategies within commercial swine production systems, leading to greater production efficiency and sustainability in the pork sector. This method has potential to help swine producers and decision makers to not only quantify but also improve feed efficiency while minimizing feed waste and nutrient excretion, resulting in more sustainable practices in swine production that support environmental stewardship and profitable pig production.

Introduction:

Increasing global population and global demand for pork coupled with consumer and regulatory demands for sustainable meat production will require the US swine industry to adopt technology-supported production practices. Precision livestock technologies have the potential to enhance several aspects of swine production such as animal feed utilization, health monitoring, and environmental interactions (Benjamin and Yik, 2019). Proper swine nutrition is essential to support feed efficient growth (Patience et al., 2015) and is a key opportunity area for technological integration to support sustainable swine production. Feed is the primary cost of a swine production system, and appropriate nutritional management holds great potential to mitigate environmental impacts of swine production through efficient nutrient utilization (Yang et al., 2023).

Swine nutrition is a complex system with multiple variables, including quality of feed inputs, biological characteristics of nutrient digestibility and utilization, and manure production. Pigs require a balanced diet, and the animal's nutritional requirements vary depending on animal age, sex, body weight, stage of production, and environmental and management conditions (Patience et al., 2015). Effectively capturing and accounting for the multivariate interactions of the dynamic swine nutrition system requires technological tools that can represent individual entities (e.g., pigs) and connect their relationships with other variables of the system.

Various modeling paradigms can be employed to develop decision-support tools for agricultural systems (Tedeschi, 2019; 2023). Traditionally, swine nutrition relied on generalized feeding recommendations that provide average requirements for differing stages of growth and production, such as those provided in *Nutrient Requirements of Swine* (NRC, 2012). While these guidelines offer an excellent starting point, they may fail to account for individual variation within a herd, leading to the potential for over- or under-feeding of specific nutrients (Patience et al., 2015). Mechanistic models simulate the complex physiological processes involved in swine nutrition by quantifying the underlying biological mechanisms that govern nutrient metabolism, absorption and utilization (Bastianelli et al., 1996; Bastianelli and Sauvant, 1997; Pomar et al., 2003). By incorporating detailed physiological data, mechanistic models provide a more comprehensive understanding of the factors influencing swine performance. However, these models can be complex, resource-intensive, and rigid. More recently, mathematical models have been used to optimize feed formulations and feeding strategies. Nutrient optimization models incorporate the nutrient requirements of pigs, feed composition, and other production factors to identify the most efficient and cost-effective solutions. Researchers have considered linear programming, nonlinear programming, and multi-objective optimization techniques to develop optimal feeding strategies (Woods, 2018; Soleimani et al., 2021). These approaches have demonstrated the potential to improve feed efficiency, reduce nutrient excretion, and enhance overall productivity. Nonetheless, such models require robust data inputs and may fail to account for the dynamic nature of animal behavior and environmental variation.

Stochastic models are becoming increasingly pragmatic to account for the randomness inherent in natural systems, and agent-based modeling (ABM) is a powerful tool that provides the flexibility needed to support the multiple stochastic elements of a livestock production system (Kaniyamattam and Tedeschi, 2023). Agent-based models operate on two defining principles: first, that agents of the system operate according to user-defined rules (e.g., mechanistic equations) that reflect specific elements of the system the model is designed to emulate; and second, that agents have memory, such that previous outcomes influence current events in a dynamic sequence. Therefore, ABM allows for the simulation of individual animal behaviors and interactions within a herd, capturing the heterogeneity that exists in swine production. By integrating the strengths of existing models, ABM can account for variation in several inputs and can simulate the interactions between pigs, feed intake, nutrient usage, and environmental factors while still providing a comprehensive and adaptable framework for nutrition management (Boumans et al., 2018). This approach also allows for simulation (i.e. *in silico* experimentation) of various management scenarios or feeding strategies to provide insight

towards optimizing efficient, sustainable, and profitable production practices (Akintan et al., 2024). Finally, when agronomic conditions are considered (e.g., feed ingredient quality and composition, fertilizer value of manure, etc.), ABMs may encompass multiple downstream elements to provide life cycle assessments of the simulated system (Bayram et al., 2023). Therefore, an ABM-decision system provides complete details of the farm at the individual agent (pig) level and allows researchers, producers, and stakeholders to manage and predict outcomes of various strategies to make informed decisions.

The project aimed to develop an ABM-based approach to simulate and study growing-finishing pig production systems. The dynamics of the swine nutrition system for growing-finishing pigs has been simulated by integrating mathematical and statistical models based on the principles and equations in the *Nutrient Requirements of Swine* (NRC, 2012). Practically, the deterministic equations of the NRC (2012) serve as the rules by which individual agents operate within the ABM; the rules of the model, therefore, may be easily updated if or when more precise information of pig biology becomes available. By integrating the components of the NRC (2012) into an ABM, we created a realistic, scientifically sound, and customizable simulation environment that captures the complex interactions between nutrient intake, metabolism, and growth performance in pigs.

Objectives:

The objective of the study was to incorporate stochastic modeling into the NRC (2012). The current *Nutrient Requirements of Swine* reference text is limited in the ability to provide optimal nutrient recommendations to swine nutritionists and pork producers due to its reliance on deterministic modeling that ignores natural variation. Hence, through the incorporation of stochastic modeling, which allows for dynamic inclusion of non-fixed variables, the model may provide pork producers greater customization of nutrient usage to their operations.

Materials & Methods:

Agent-Based Model Selection and Development

The project developed and implemented an ABM integrated with the NRC (2012) model to simulate the nutrient requirements and growth performance of growing-finishing pigs by incorporating all relevant parameters for pig growth and nutrition while utilizing the principles of agent-based modeling. The ABM was chosen to capture the complex and dynamic behaviors of individual pigs, as well as their interactions with their environment. In the simulation, each pig is represented as an autonomous agent with a unique set of attributes that govern its growth and development over time. This micro-level representation allows for a more realistic and comprehensive simulation of the underlying biological processes and of the evaluation of potential management strategies.

Integration of NRC (2012) Information Within the Agent Based Model

The integration of the NRC (2012) key information and guidelines within the agent-based model was achieved through the following key steps.

1. Identification of relevant equations and relationships

The first step involved the review of the NRC (2012) publication to identify the key equations, parameters, and relationships that govern the growth, body composition, energy requirements, and tissue partitioning of pigs. This included equations for calculating critical body parameters: protein deposition (Pd), lipid deposition (Ld), ash, and water content, as well as the impact of environmental and management factors on pig energy requirements and feed intake, such as stocking density or ambient temperature above or below the pig's thermoneutral zone (**Table 1, Table 2, and Table 3**).

2. Translation of NRC (2012) concepts into agent-based modeling constructs

The identified NRC (2012) guidelines and equations were next translated into the agent-based modeling framework within the NetLogo environment (Northwestern University; Evanston, IL). This involved defining the individual pig agents, their attributes, and the dynamic behaviors that would affect the changes in these attributes over time. The simulation model was designed to replicate the growth and development of each pig agent based on NRC-derived equations and relationships.

3. Inclusion of sex-specific characteristics

The simulation model incorporates three distinct sexes of growing-finishing pigs: gilts, barrows, and entire males (boars). Each sex is represented in the model by a separate agent type, thereby enabling simulation of their unique growth and production characteristics, as well as potential sex-specific responses to various feeding and management practices. Although entire males are seldomly grown with barrows and gilts on production farms, their inclusion in NRC (2012) materials prompts their inclusion in this model; further, the uniqueness of the boar's growth characteristics compared to barrows and gilts provides opportunity for model validation. Therefore, the ABM model captures the sex-specific differences in factors such as protein deposition, lipid deposition, and energy requirements as specified in the reference text guidelines.

4. Defining the spatial structure and environmental factors

The simulated environment was divided into discrete patches, each with attributes representing the user's desired logic or intention (i.e., pens within a barn, barns within a farm site, or farms within a geographic area; **Figure 1**). This attribute allows monitoring of the influence of environmental conditions. It also allows users the ability to incorporate changes in temperature and housing which can affect pig energy requirements or feed intake or impose constraints or limitations on pig resources or space.

5. Comprehensive attribute representation

The pigs were represented with a comprehensive set of attributes, including weight, body composition (body protein mass [BPM], body lipid mass [BLM], ash, and water), feed intake, and requirements of energy, amino acids, vitamins, and minerals. The dynamic changes in these attributes over time were simulated using the equations and relationships specified in the NRC (2012) guidelines, allowing for a detailed representation of the individual pig and herd growth and production performance.

Model Calculations, Parameters and Calibration

The comprehensive ABM developed for this project details representation of key mechanisms and calculations in simulating body metabolism, nutrient requirements, and growth performance of growing-finishing pigs. To consider the micro-level components of the system, equations from the NRC (2012) were used as rules of the agent-based model to govern agent (pig) behavior, growth, and environmental interactions and to calculate body composition change iteratively (i.e., daily), where i and j represent the day of feeding and the pig's ID, respectively (**Table 1**, **Table 2**, and **Table 3**). Briefly, the empty body weight and tissue composition of a pig at a user-defined starting weight is calculated. From this, metabolizable energy intake, feed intake (using user-defined input of the energy density of feed), and growth potential of body tissues (e.g., protein, lipid) are calculated with adjustments for pig sex and environment. Stochasticity is included in the model with a triangular distribution function, a simplification of the probability distribution function, in which the outcome is randomly generated from a range of the maximum, minimum, and most likely outcomes. The new body weight is then derived, and the process is repeated iteratively until the pig meets the user-defined criteria for existing the system (i.e., marketing from the barn). At each day, updated nutritional requirements (amino acids, vitamins, and minerals) are calculated to reflect the animal's new body composition and growth potential.

Implementation of the ABM was carried out using NetLogo (Wilensky, 1999), an agent-based modeling platform known for its versatility and capability to simulate dynamic and complex systems. The program consisted of individual growing-finishing pig agents that were capable of movement, interaction with their environment, feed consumption, nutrient metabolism, and growth based on prior performance, current body composition, and present nutritional requirements. The interface of the simulation environment includes a virtual representation of pigs within their pen and toggle features for users to define specifics of the simulation (**Table 4**). The program has the option for the user to specify the absence or presence (and if present, the severity) of ambient temperature and housing constraints. Similarly, the metabolizable energy content of the feed and the percent feed wastage were programmed at default settings (3,300 Kcal / kg and 5%, respectively) but also with options for user specification.

In the default model settings, individual pigs begin with a starting weight of 20 kg and are fed iteratively until reaching a final market weight of 130 kg (**Figure 2**). The model was developed to account for differing nutritional requirements of three sexes: gilts, barrows, and entire males. Therefore, body weight gain and nutrient requirements are updated daily according to hardcoded rules of the ABM and user-defined settings. The algorithms dictating the daily processes at the farm level and at the pig level are provided in **Figure 3** and **Figure 4**, respectively. These algorithms outline the step-by-step process of the simulation, beginning with the initialization of the environment and the global parameters. It then iterates through a predefined number of steps, during which it gathers information about each pig, assesses their status based on various metrics (e.g., body weight and environmental conditions), and then determines their next actions within the barn. The algorithm also incorporates mechanisms for updating the pigs' internal states and removing pigs that reach user-defined exit criteria (i.e., market weight). Finally, it records

essential outputs and generates reports and visualizations to facilitate user analysis of the simulation results. Outputs of the ABM were validated by comparison with outputs from the NRC (2012) Excel spreadsheet computer model.

Results:

The comprehensive ABM developed for the project successfully simulates the nutrient requirements and growth performance of growing pigs as compared to outputs of the existing NRC (2012) computer model. The ABM model was able to depict the complex interactions between pigs, feed intake, and environmental factors and provide an accurate and dynamic representation of swine growth performance.

For demonstration purposes and validation of the default settings of the model, pigs of three different sexes (barrow, gilt, and entire male) were grown from 20 kg to 130 kg. Expected and known differences in growth performance of barrows, gilts and boars were observed. Daily body weight gain and body weight on each individual day are represented in **Figure 5a** and **Figure 5b**, respectively. As expected, barrows experienced the least daily protein deposition (**Figure 5c**) and the greatest daily lipid deposition (**Figure 5d**). At 130 kg market weight (i.e., pig attainment of the rule to exit the simulation), daily lipid deposition reached a peak of roughly 409 g/day, 359 g/day, and 314 g/day in barrows, gilts, and boars, respectively. Additionally, barrows showed the greatest daily metabolizable energy intake and requirements (**Figure 6a** and **Figure 6b**, respectively) and the greatest daily feed intake (**Figure 7**). Finally, nutritional requirements may be updated daily when body composition and growth potential are known. The requirement of several nutrients, including standardized ileal digestible amino acids, standardized total tract digestible phosphorus, and several minerals and vitamins, are provided in **Table 5**.

Discussion:

Agent-based modeling provides a powerful tool for simulating, understanding, and predicting the complex interactions that influence the growth and production performance of swine. This approach allows for a more nuanced and detailed representation of the factors affecting pig growth and performance, moving beyond the aggregate-level models traditionally used to capture individual agent variation and dynamic responses to management and environmental factors.

One of the key strengths of the ABM is the ability to simulate individual pig behavior and dynamic nutrient partitioning. By representing pigs as autonomous agents with their own unique characteristics and responses to the environment, the model can capture the variability in growth trajectories and nutrient utilization that is often overlooked in traditional approaches. This level of detail may be particularly valuable for swine industry decision makers, as the model has the power to provide insight into underlying mechanisms driving nutrient use and utilization in a production setting.

In addition to simulating individual pig behavior, the model also enables the assessment of various environmental stressors (e.g., ambient temperature outside of the pig's thermoneutral zone) and management strategies. This is particularly relevant in the context of modern swine production, in which factors such as housing conditions and feeding strategies have significant impact on the efficiency, profitability, and sustainability of a farm. By incorporating these factors into the model, researchers and industry professionals may easily and rapidly simulate multiple scenarios to identify the largest costs and opportunities. Indeed, the virtual nature of the ABM provides a risk-free and expense-free environment for producers, scientists, nutritionists, consultants, and students to test multiple scenarios and interventions. For example, the pig growth performance and nutrient requirement results reported herein were derived from a simulation of pigs growing from 20 kg to 130 kg. These default settings are appropriate for model demonstration but would fail to represent the variation of natural conditions. It is well known that animal growth and farm profit are influenced by pig-specific factors, such as birth weight and weaning weight (Cabrera et al., 2010; Fix et al., 2010), and marketing decisions such as sorting at pig removal to market (Cheng et al., 2017; Zhou and Bohrer, 2019). The ABM's capabilities to simulate individual pigs (for example, to test the impact of increasing standard deviation of pig body weight at barn stocking on farm nutrient use) and user customizations (for example, to evaluate the effect of different strategies to remove pigs from a barn at marketing) make this program the ideal experimental software to allow for exploration and evaluation of innovative ideas and management practices without incurring the costs and risks associated with real-world experimentation. By providing a platform for *in silico* experiments, the model may even accelerate the pace of innovation in pig production while facilitating rapid evaluation of new ideas and technologies that drive continuous improvement.

No model is ever perfect but must be continuously improved to reflect updated conditions. The ABM was built with a modular design to enhance the utility and adaptability. In fact, by breaking down the model into discrete components that can be easily modified or expanded, the model managers may regularly and easily update the material with new empirical data, revised

mechanistic equations, or with additional modules to address user needs or questions. This flexibility helps to ensure that the model will remain relevant and up to date in a rapidly evolving field. Future developments of the model will enhance the value that it provides to swine producers. Primarily, the model should integrate with existing databases or models. Integration with pig performance data could allow for better refinement of the stochastic elements of the model and a truer representation of modern pig farms. Additionally, integration with existing feed optimization models would allow for exploration of feeding strategies and better quantification of sustainability metrics. In the version outlined in this report, the model assumes that the pig's nutrient requirements are perfectly met on each day; in reality, that would not be feasible. Instead, pigs are commonly fed in phases with diets formulated to meet the average requirement of the population. This strategy is effective but would not be as efficient as the results represented herein (Pomar et al., 2014). Accordingly, user inputs of diet specifications would allow the incorporation of several important considerations, such as feed ingredient digestibility, instances and severity of under- and over-feeding, and nutrient excretion in manure. Further, when nutrient parameters are defined by a user, nutrient flow through a system may be quantified. This would similarly allow assessment of economic performance alongside the environmental impacts. By integrating life cycle assessments and feed optimization models within the system, we can complete multiple evaluations to identify the most cost-effective strategies that minimize ecological impacts.

The ABM was developed within NetLogo modeling environment. This is a free and robust program that is used by students and professionals worldwide, yet it has several limitations. While NetLogo is effective for the initial coding and programming, it is not likely to be the most user-friendly system because it is not easily hosted on a website. Transitioning the model into the Python coding language will facilitate web-based applications. The question then becomes – where to host the model? Multiple options are available, including the Pork Checkoff website (<https://pork.org/>) and National Animal Nutrition Program (NANP; <https://animalnutrition.org/>). The NANP, supported by the USDA National Institute of Food and Agriculture, among other partners, may be a logical selection, as it already maintains a robust database of animal nutrition models, and contains a feed composition library. Integration with the feed composition library would be useful for users to reference dietary features and to incorporate variation of feed ingredient composition into the integrated nutrient optimization models.

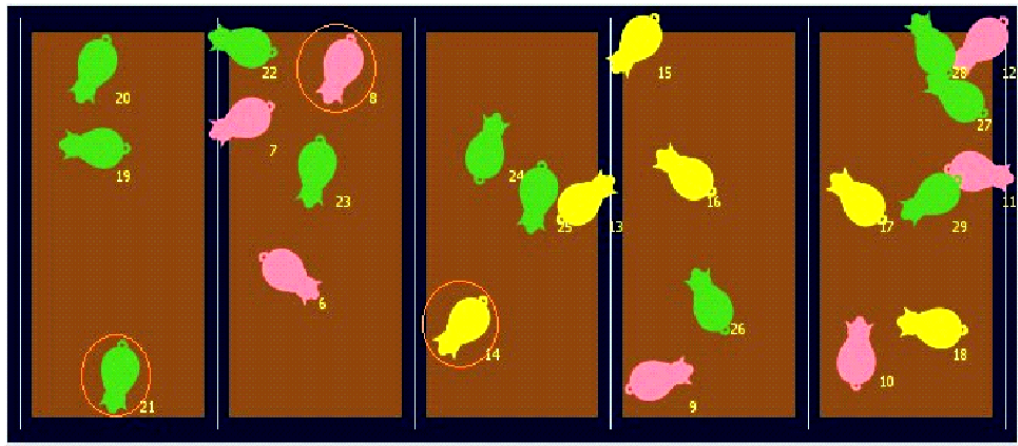
In conclusion, the ABM described in this report can serve as a crucial tool to guide the swine production industry toward continued profitability and sustainability. The work aligns with several industry priorities of resource stewardship and environmental conservation, and ultimately contributes to the establishment and preservation of a resilient and responsible agricultural system capable of meeting the needs of a growing global population. In this context, the ABM can facilitate continuous improvement within the industry, support informed decision making, and drive the development of innovative solutions to the challenges faced by modern pig production.

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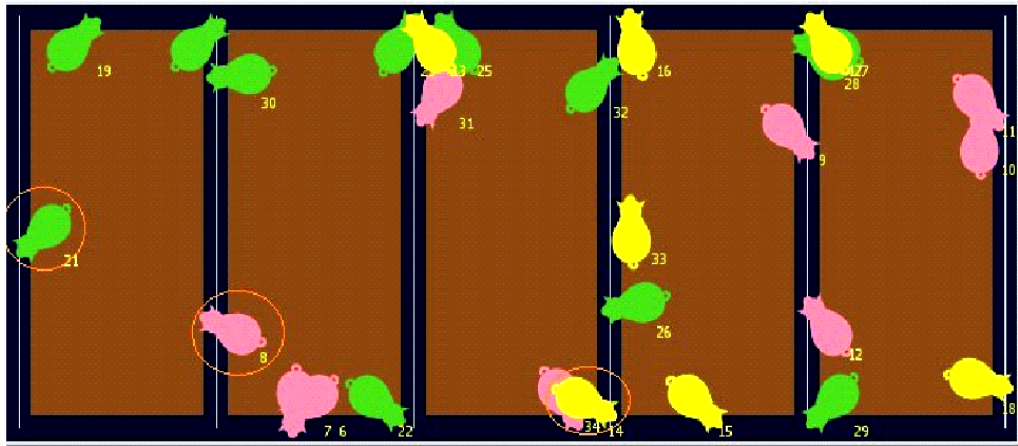
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Figure 1. The interface of independent agents and their environment on the 1st day (a) and the 82nd day (b) of the simulation program. The different colors of the circled agents represent the three sexes included in the program: barrows, gilts, and entire males.



(a)



(b)

Figure 2. Flowchart representation of the iterative framework of feeding pigs and updating nutrient requirements based on prior performance from model initiation (stocking of the barn) to finishing (market weight). In the default settings, pigs are stocked in the barn at 20 kg and the model operates until marketing at 130 kg.

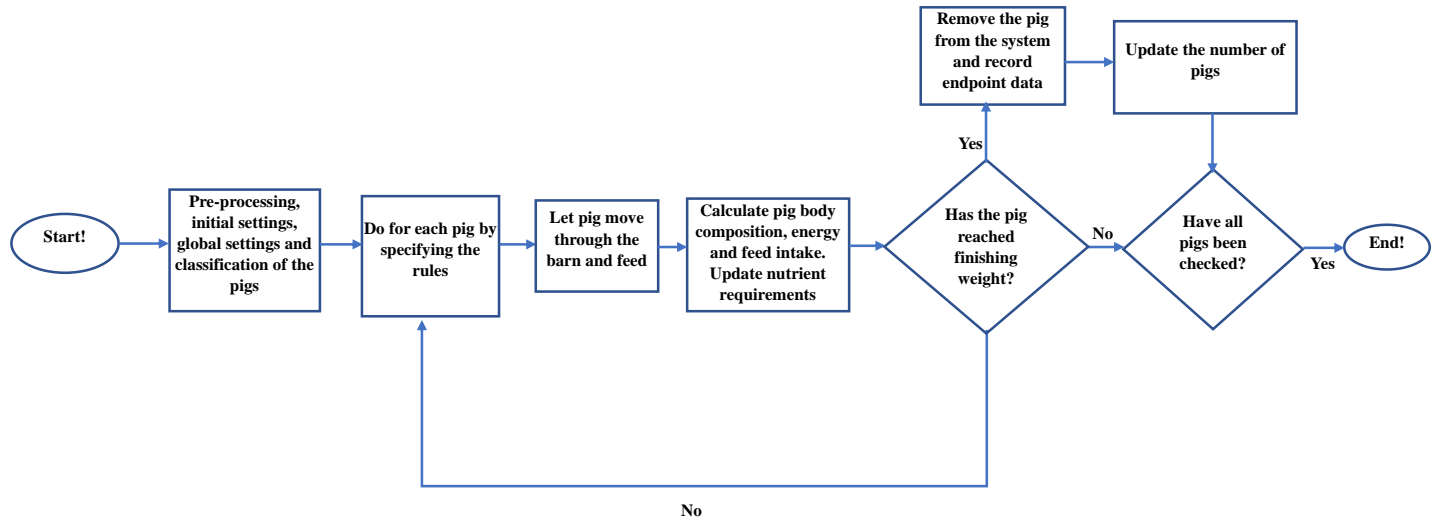


Figure 3. A pseudocode representing the simulation process of agents within a farm.

Start Procedure:

Initialize the simulation

Set the number of time steps

Set up the simulation environment

Set up global parameters

Define the necessary data and parameters

Loop: for all *time steps* do:

for all *pigs* do:

Gather pig's information

Assess the pig's status (e.g., body weight, Pd, Ld, etc.)

Observe the environmental conditions (e.g., temperature, housing)

Determine the pig's actions

Move pig through the barn

Interact pig with the environment (e.g., consume feed)

Update the pig's internal state based on the actions taken and its individual parameters

if *weight* \geq *final weight*:

Remove the pig from the farm

Update the number of pigs

end if

end for

Update the environmental conditions if needed (e.g., temperature, humidity)

Record the simulation outputs (e.g., weight gain, body depositions, body requirements)

end for

Generate reports and visualizations as needed

End

Figure 4. A pseudocode representing the feeding procedures and calculations for all pigs operating within the ABM system.

Start Feeding Procedure:

Set initial parameters

for all pig categories (*gilts*, *barrows*, *entire males*) **do:**

for all pigs in the category **do:**

if pig category is *gilts*:

 Call *Feed-g* (feeding procedure for gilts)

else if pig category is *barrows*:

 Call *Feed-b* (feeding procedure for barrows)

else:

 Call *Feed-m* (feeding procedure for entire males)

end if

Common steps for all pig categories

 Calculate pig's weight gain

 Update the pig's weight

 Calculate the pig's body Composition (e.g. Pd, Ld, Ash, Water, etc.)

 Update pig's energy intake and feed intake

 Update nutrient requirements (e.g. amino acids, minerals, and vitamins)

if *feeding ractopamine*:

 Call *Feed-Rac*

end if

if weight \geq sell-weight:

 Set final-weight as weight

 Calculate fat-free-lean

 Remove pig

 Update the number of pigs

end if

end for

end for

End

Figure 5. Comparison of body composition performance curves for individual pigs including gilts, barrows, and entire males by daily body weight gain (a), body weight (b), protein deposition (Pd; c), and lipid deposition (Ld; d) from 20 kg to 130 kg.

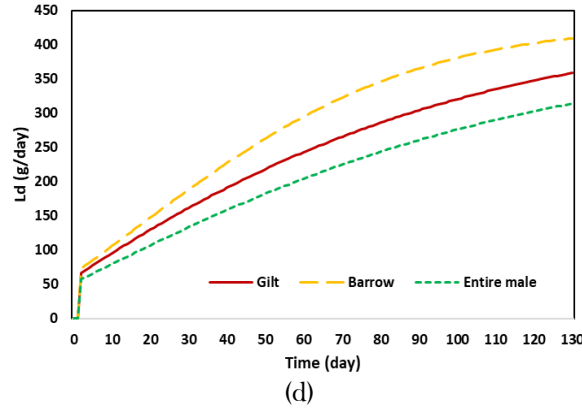
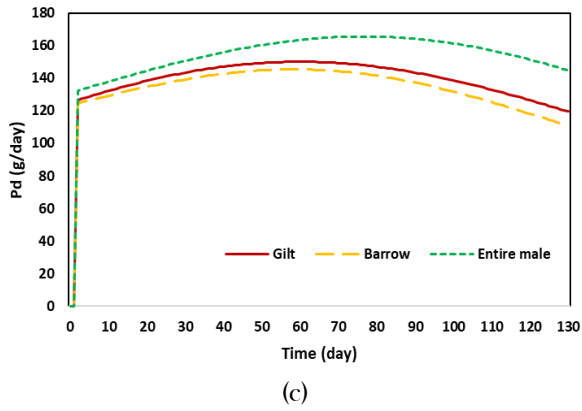
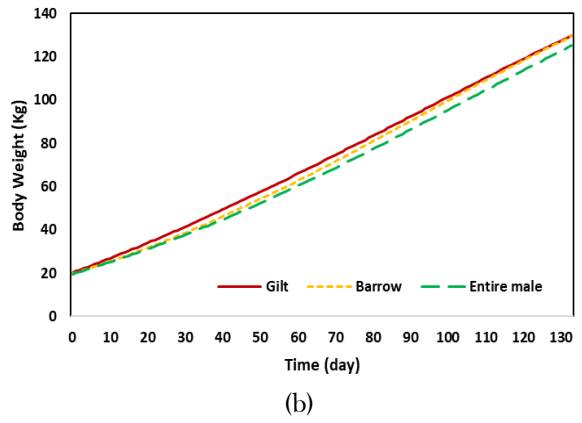
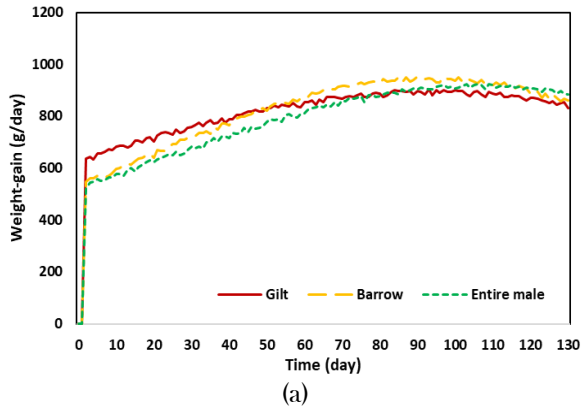


Figure 6. Comparison of daily metabolizable energy intake (a) and daily metabolizable energy requirement (b) curves for individual gilts, barrows, and entire males from 20 kg to 130 kg.

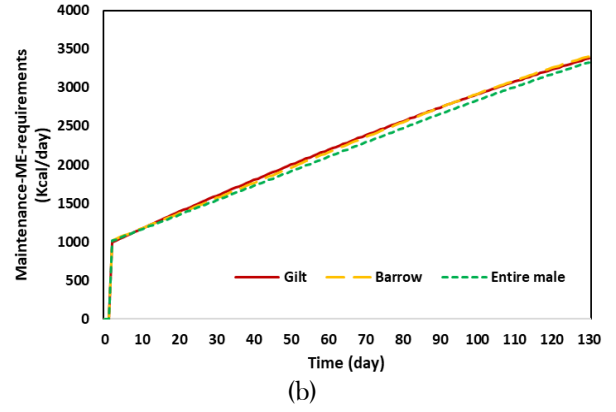
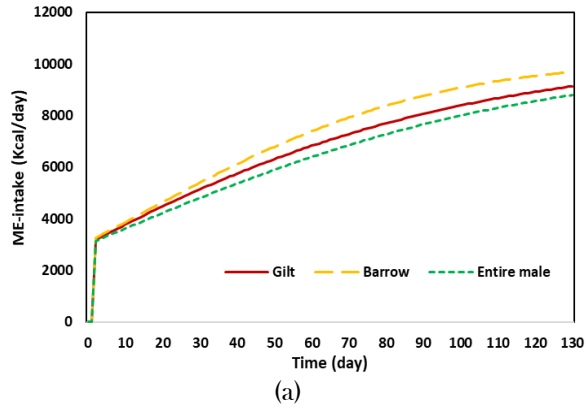


Figure 7: Average daily feed intake for gilts, barrows, and entire males from 20 kg to 130 kg.

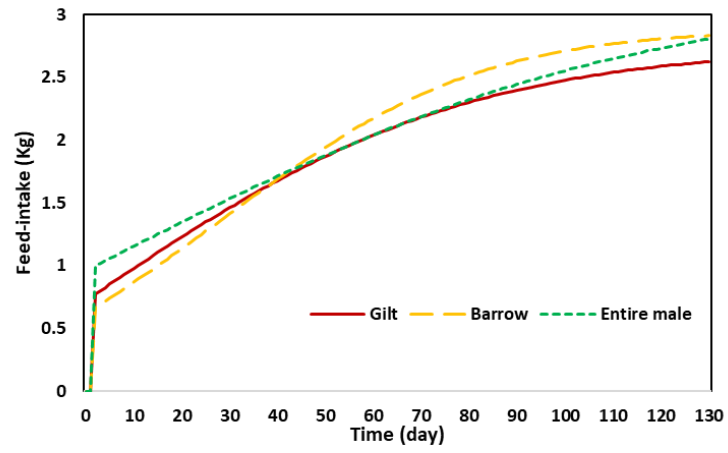


Table 1. Equations from the NRC (2012) utilized to calculate pig body weight composition and daily growth. Equations are numbered according to their use in the ABM, not according to their reference number in the NRC (2012).

Parameter	Description	Equation	Equation number
<i>BWG</i>	Body weight gain	$BWG_{ij} = 485.17 + 8.8503 \times BW_{(i-1)j} - 0.0477 \times BW_{(i-1)j}^2$	(1-1)
<i>BW</i>	Body weight	$BW_{ij} = BW_{(i-1)j} + BWG_{ij}$	(1-2)
<i>EBW</i>	Empty body weight	$EBW_{ij} (kg) = BP_{ij} + BL_{ij} + Wat_{ij} + Ash_{ij}$	(1-3)
<i>Wat</i>	Whole-body water mass	$Wat_{ij} (kg) = (4.322 + (0.0044 \times Pd_{maxj})) \times P_{ij}^{0.855}$	(1-4)
<i>Ash</i>	Whole-body ash mass	$Ash_{ij} (kg) = 0.189 \times BP_{ij}$	(1-5)
<i>Gutf</i>	Gut fill	$Gutf_{ij} (kg) = 0.277 \times BW_{0j}^{0.612}$	(1-6)
<i>PBT</i>	Probe backfat thickness	$PBT_{ij} (mm) = -5 + \frac{12.3 \times BL_{ij}}{BP_{ij}} + (0.13 \times BP_{ij})$	(1-7)
<i>Pd</i>	Protein deposition	$Pd_{ij} (g/d) = (a) \times [b + (c \times BW_{ij}) + (d \times BW_{ij}^2) + (e \times BW_{ij}^3)]$	(1-8)
<i>BP</i>	Whole-body protein deposition	$BP_{ij} = BP_{(i-1)j} + Pd_{ij}$	(1-9)
<i>Ld</i>	Lipid deposition	$Ld_{ij} (g/d) = \frac{(ME_{intij} - maintenME_{ij} - Pd_{ij} \times 10.6)}{12.5}$	(1-10)
<i>BL</i>	Whole-body lipid deposition	$BL_{ij} = BL_{(i-1)j} + Ld_{ij}$	(1-11)

* *i*: The day under feeding; *j*: Pig's ID

** For gilts: $a = 137$, $b = 0.7066$, $c = 0.013289$, $d = -1.3120 \times 10^{-4}$, $e = 2.8627 \times 10^{-7}$;

For barrows: $a = 133$, $b = 0.7078$, $c = 0.013764$, $d = -1.4211 \times 10^{-4}$, $e = 3.2698 \times 10^{-7}$;

For entire males: $a = 151$, $b = 0.6558$, $c = 0.012740$, $d = -1.0390 \times 10^{-4}$, $e = 1.64001 \times 10^{-7}$

Table 2. Equations from the NRC (2012) utilized to calculate energy intake and feed intake. Equations are numbered according to their use in the ABM, not according to their reference number in the NRC (2012).

Parameter	Description	Equation	Equation number
<i>MEint</i>	Metabolizable energy intake	$MEint_{ij} (kcal/d) = a \times \{1 - \exp[-\exp(b) \times BW_{ij}^c]\}$	(2-1)
<i>Feedint</i>	Feed intake	$Feedint_{ij} = 1.053 \times \left(\frac{MEint_{ij}}{ME \text{ content}}\right)$	(2-2)
<i>LCT</i>	Lower critical temperature	$LCT_{ij} (^{\circ}C) = 17.9 - 0.0375 \times BW_{ij}$	(2-3)
<i>Minspace</i>	Minimum space for maximum ME intake	$Minspace_{ij} (m^2/pig) = 0.0336 \times BW_{ij}^{0.667}$	(2-4)
<i>Maxfeedint</i>	Maximum daily feed intake	$Maxfeedint_{ij} (g/d) = (111 \times BW_{ij}^{0.803})[1 + (LCT_{ij} - T) \times 0.025]$	(2-5)
<i>StdmME</i>	Standard maintenance ME requirements	$StdmME_{ij} (kcal/day) = 197 \times BW_{ij}^{0.60}$	(2-6)
<i>MEtherm</i>	ME requirements for thermogenesis	$MEtherm_{ij} (kcal/d) = 0.07425 \times (LCT_{ij} - T) \times StdmME_{ij}$	(2-7)
<i>mME</i>	Maintenance ME requirements	$mME_{ij} (kcal/d) = StdmME_{ij} + MEtherm_{ij} + adj$	(2-8)

* *i*: The day under feeding; *j*: Pig's ID

** Gilts: *a* = 10967, *b* = - 3.803, *c* = 0.9072; Barrows: *a* = 10447, *b* = - 4.283, *c* = 1.0843; Entire males: *a* = 10638, *b* = - 3.803, *c* = 0.9072

*** *T*: Environment temperature, °C

**** *adj*: ME requirements for increased activity or genotype adjustment

Table 3. Equations from the NRC (2012) utilized to calculate nutrient requirements Equations are numbered according to their use in the ABM, not according to their reference number in the NRC (2012).

Parameter	Description	Equation	Equation number
$GITLys$	Basal endogenous GIT lysine losses	$GITLys_{ij} = 1.1 \times 4.17 \times 10^{-4} \times Feed\ dry\ matter \times Feedint_{ij}$	(3-1)
$ILys$	Integument lysine losses	$ILys_{ij} = 0.0045 \times BW_{ij}^{0.75}$	(3-2)
$SIDLys1$	SID lysine requirements for GIT plus integument losses	$SIDLys1_{ij} = \frac{GITLys_{ij} + ILys_{ij}}{0.75 + 0.002 \times (maxPd_{ij} - 147.7)}$	(3-3)
$SIDLys2$	SID lysine requirements for Pd	$SIDLys2_{ij} = \frac{(0.071 \times Pd_{ij}) \times (1.0547 + 0.002215 \times BW_{ij})}{0.75 + 0.002 \times (maxPd_{ij} - 147.7)}$	(3-4)
$SIDLys$	Total SID lysine requirements	$SIDLys_{ij} = SIDLys1_{ij} = SIDLys2_{ij}$	(3-5)
P	Body Phosphorus mass	$P_{ij} = 1.1613 + 26.012 \times BP_{ij} + (0.2299 \times BP_{ij}^2)$	(3-6)
$FDint$	Feed dry matter intake	$FDint_{ij} = Feed\ dry\ matter \times Feedint_{ij}$	(3-7)
$STTDP$	STTD P requirements	$STTDP_{ij} = 0.85 \times \left[\frac{(max\ P\ retention)}{0.77} + (0.19 \times FDint_{ij}) + (0.007 \times BW_{ij}) \right]$	(3-8)
Ca	Total Ca requirements	$Ca_{ij} = 2.15 \times STTDP_{ij}$	(3-9)
$Mineral$	Mineral requirements	$Mineral_{ijk} = p + q \times \ln(BW_{ij})$	(3-10)
$Vitamin$	Vitamin requirements	$Vitamin_{ijk} = m + n \times \ln(BW_{ij})$	(3-11)

* i : The day under feeding; j : Pig's ID

** k : Type of mineral or vitamin

*** p, q : Minerals' constant coefficients

**** m, n : Vitamins' constant coefficients

Table 4. Model parameter default settings and user options to customize the system

Parameter	Amount	Customizable
Number of pig housing units (pens, barns, or farms)	5	Yes
Number of sexes	3 (gilt, barrow, entire male)	Yes
Run time	140 days	Yes
Initial weight	20 Kg	Yes
Final weight	130 Kg	Yes
ME content	3300 Kcal	Yes
% Feed wastage	5%	Yes
% Diet fermentable fiber in feed content	10.5%	Yes
% Feed dry matter	88%	Yes
Environmental temperature	20 °C	Yes
Ractopamine level	20 mg/Kg	Yes
Starting weight for feeding ractopamine	78 Kg	Yes

Table 5. Estimation of standardized ileal digestible (SID) amino acids, standardized total tract digestible phosphorous (STTD P), total calcium, and several vitamins and minerals in individual gilts, barrows, and entire males on day 130 of the simulated feeding period.

	Gilt	Barrow	Entire male	
Body Weight (Kg)	126.55	127.99	123.55	
SID Lysine (g/d)	17.65	17.31	19.47	
SID amino acids (requirements relative to lysine); (g/d)				% of SID Lysine
Arginine	8.06	7.91	8.90	45.7
Histidine	6.06	5.95	6.70	34.4
Isoleucine	9.21	9.03	10.16	52.2
Leucine	17.76	17.43	19.61	100.7
Methionine	5.09	5.00	5.62	28.9
Methionine + cysteine	9.95	9.76	10.98	56.4
Phenylalanine	10.53	10.33	11.62	59.7
Phenylalanine + tyrosine	16.55	16.24	18.27	93.8
Threonine	10.64	10.44	11.74	60.3
Tryptophan	3.01	2.96	3.33	17.1
Valine	11.45	11.23	12.64	64.9
N	37.90	37.19	41.83	214.8
Phosphorus and calcium requirements; (g/d)				
STTD P	5.34	5.08	6.22	
Total Ca	11.49	10.92	13.38	
Mineral requirements				
Sodium (g/d)	2.92	2.94	2.9	
Chlorine (g/d)	2.31	2.32	2.29	
Magnesium	1.15	1.16	1.14	

Potassium (g/d)	4.75	4.76	4.73
Copper (mg/d)	8.46	8.48	8.41
Iodine (mg/d)	0.40	0.40	0.40
Iron (mg/d)	111.34	111.52	110.96
Manganese (mg/d)	5.79	5.82	5.74
Selenium (mg/d)	0.41	0.42	0.41
Zinc (mg/d)	140.96	141.45	139.91

Vitamin requirements

Vitamin A (IU/d)	3767.85	3784.44	3732.48
Vitamin D3 (IU/d)	434.76	436.67	430.68
Vitamin E (IU/d)	31.88	32.02	31.58
Vitamin K (mg)	1.44	1.45	1.43
Biotin (mg/d)	0.14	0.14	0.14
Choline (g/d)	0.86	0.87	0.86
Folacin (mg/d)	0.86	0.87	0.86
Niacin (mg/d)	86.95	87.33	86.13
Pantothenic acid (mg/d)	19.89	19.96	19.73
Riboflavin (mg/d)	5.59	5.61	5.56
Thiamin (mg/d)	2.89	2.91	2.87
Vitamin B6	2.89	2.91	2.87
Vitamin B12	12.51	12.50	12.53