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Developing an agent-based model to simulate the beef cattle production and transportation in southwest Kansas

Qihui Yang [a,*], Don Gruenbacher [a], Jessica L. Heier Stamm [b], Gary L. Brase [c], Scott A. DeLoach [d], David E. Amrine [e], Caterina Scoglio [a]

[a] Department of Electrical and Computer Engineering, Kansas State University, Manhattan, KS 66506, USA
[b] Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
[c] Department of Psychological Sciences, Kansas State University, Manhattan, KS 66506, USA
[d] Department of Computer Science, Kansas State University, Manhattan, KS 66506, USA
[e] Beef Cattle Institute, College of Veterinary Medicine, Kansas State University, Manhattan, KS 66506, USA

HIGHLIGHTS

- Models the interdependent beef production system and transportation system.
- Evaluates the robustness of these interdependent systems.
- The system is robust to random failures of cattle premises or truck premises.
- The system is vulnerable to targeted shutdown of cattle premises or truck premises.
- Truck shortage in packers has the worst impact on cattle production.

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ABSTRACT

Modern beef cattle production in the U.S. is a highly specialized system that spans from cow–calf ranches, to stockers, to feedlots, to packers. The cattle production system is particularly interdependent with the transportation system, as cattle and feed need to be moved through production phases. Although this interdependence enables the economic functioning of the interdependent system, it also brings vulnerabilities to the system amplifying disease spreading and natural disaster consequences. Taking southwest Kansas as a study area, we explicitly model the beef cattle industry and the transportation industry as two independent but interconnected industries through agent-based modeling. Since cattle and truck movement data are scarce due to privacy concerns, we first generate cattle and truck movement data among production locations under normal operating conditions. We then assess the system robustness by constructing hypothetical disruptions in the cattle industry and in the transportation industry. The simulation results show that the interdependent system is robust to random failures but vulnerable to the targeted shutdown of cattle premises or truck premises. In addition, we observe that disruptions in the trucks serving packers have the worst impact on cattle production, as compared to other transportation disruptions. In disaster preparations, policymakers and system designers need to consider vulnerabilities caused by the interdependent infrastructure and pay particular attention to one of its critical components, meat packers.

* Corresponding author.
E-mail address: qihui@ksu.edu (Q. Yang).

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1. Introduction

Critical Infrastructure Systems (CIS) such as power grids and water supply systems provide reliable flows of products and services vital to the defense and security of society. They can be disrupted by technological failures such as the Northeast American power blackout in 2003, by natural hazards like hurricanes and by deliberate attacks like the cyber-attack on the Ukrainian electrical distribution system [1–3]. These disruptions are more than inconveniences; the cumulative costs from damage due to natural disaster events in the U.S. reached $306 billion in 2017 [4]. Studies have been conducted extensively on individual networks to enhance network resilience [5–8]. However, modern infrastructure systems no longer exist in isolation but have become mutually interdependent. For example, the food and agriculture sector, which accounts for roughly one-fifth of the nation's economic activity, exhibits particular interconnectedness with other CIS sectors, including transportation systems [9]. The interdependencies between CIS can cause a high systemic vulnerability within the overall U.S. economic system [10]. Disruptions of components in one system may propagate and cause elements in the other system to fail. Several studies have focused on random failures and targeted attacks on interdependent networks to enhance the network robustness [11–14]. But to our knowledge, no such exercise has been undertaken to analyze the interdependency between beef cattle production and transportation systems. Cattle production in the U.S. accounts for $67.4 billion in cash receipts, which is 18% of the total cash receipts from agricultural commodities in 2017 [15]. Thus, it is of great necessity to study the robustness of the complex cattle system. In this paper, we analyze the interdependence of the beef cattle production industry, one component of the food and agriculture sector, with the transportation industry.

The region of southwest Kansas (SW KS) provides a great context to study beef cattle production and its transportation. Kansas ranks third in the U.S., with 2,450,000 head of cattle on feed as of January 31, 2018. The beef cattle sector is the largest in the Kansas agriculture industry with 42,228 employees, and it directly contributes approximately $8.9 billion to the Kansas economy [16]. Incapacitation or destruction in either cattle production or transportation would almost certainly harm the regional economy. Disruptions in cattle production would likely undermine the profitability of regional truck companies due to underutilized capital assets and employee layoffs. On the other hand, lack of transportation services could lead to delays in cattle movement between premises.

Although the interconnectedness between these two industries has not been systematically studied, as has been done with other infrastructure systems, several studies have focused on the main factors affecting the stability of the cattle system. The cattle production system can be influenced by fluctuations in weather. For instance, drought may cause premature termination of the grazing season and force producers to market cattle early due to limited feed reserves, resulting in lower cattle production and higher mortality rates [17,18]. Additionally, disease outbreaks can cause disruptions in cattle production. Schroeder et al. [19] estimated that a foot-and-mouth disease outbreak in the central U.S. would result in the loss of as many as 7000–8000 livestock herds and 16–18 million animals. Disease transmission through cattle movement and fomites such as personnel and vehicles, have been extensively studied in recent years [20–26].

A successful beef cattle system heavily relies upon timely delivery and proper handling of cattle for transportation. Consider that the prices paid for slaughter cattle in the U.S. are influenced by age, quality grade, yield grade, and weight. Among these cattle production parameters, the USDA quality grade and cattle finishing diet have the greatest impact on beef flavor profiles [27]. Animals that deposit excesses of fat can lead to discounted prices accordingly. Loading density, trailer environment, transport duration, and the animal condition are substantially related to animal welfare, carcass and meat quality [28–30]. Transportation may be a potential stressor and decrease beef cattle welfare, resulting in substantial financial losses to the beef industry [31,32]. However, natural disasters such as heavy snowstorms and tornados may lead to disruptions in transportation infrastructure. Bai et al. [33] studied the transportation mode of meat-related industries in SW KS and provided county-level cattle transportation data, which will be used to validate our model.

Previous research reveals that the beef cattle production and transportation infrastructures are interrelated, but no study to date has evaluated the interdependence between these two industries. In this work, we will assess the robustness of the interdependent cattle production and transportation systems under different node failure conditions. Node removal is often conducted to examine the likely effects of implementing trade restrictions or vaccinations during disease outbreaks [34–36]. Similarly, we will remove cattle in simulation to mimic the loss of supply due to disease outbreaks. In scenarios depicting transportation disruptions, trucks will be removed to represent vehicle shortage caused by deliberate attacks.

Of course, understanding the interdependent cattle production and transportation systems requires the availability of movement data and cooperation among private operators. Animal movement tracking systems in Europe have contributed significantly to the analysis of livestock movements and disease spread patterns there [37–40]. However, the adoption of a traceability system is not compulsory for U.S. beef cattle operations, and producer organizations have been against such systems for confidential concerns. To address this challenge, questionnaire-based methods have been used in some studies to examine livestock movements in the U.S. [41,42]. Other studies try to estimate movement based on Interstate Certificate of Veterinary Inspection data, but these only capture the interstate movement patterns [43,44]. Therefore, this paper first generates cattle and truck movement data among production locations in normal conditions using agent-based modeling (ABM).

ABM offers a practical method to model the complex cattle system and has been widely applied to diverse areas including economics, agriculture, transportation, and healthcare [45,46]. Prior agent-based simulations regarding the beef

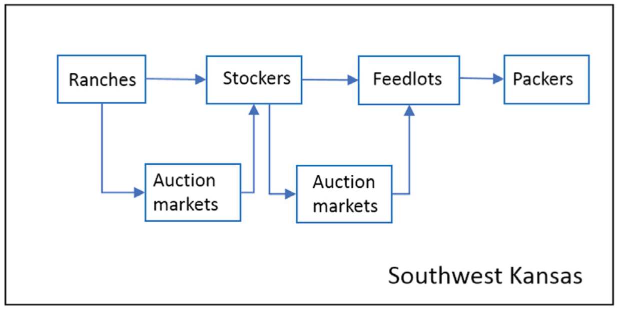


Fig. 1. Main routes of cattle movement in SW KS.

cattle industry have focused on topics of disease prediction and control measures such as analyzing the impacts of cattle movement on disease spreading patterns [47–52]. Other research has taken the cattle industry as a case study and utilized ABM as an approach to studying the policies and human decision factors in social–ecological systems, including risk management strategies in reaction to disease outbreaks, agricultural policy interventions, and market dynamics [53–59]. However, none of these models explicitly model both the cattle industry and the associated transportation industry as two distinct but interdependent industries. This paper thus adds a new element to this domain. Based on the eighty-five ABM frameworks reviewed in [60] and additional research on modeling and simulation capabilities, we selected AnyLogic as an appropriate simulation toolkit for this study.

Overall, this study aims to *generate simulated data of cattle movement in southwest Kansas* and *analyze the interdependence between the beef cattle production and the transportation infrastructure.* Guided by the Organization Model for Adaptive Computational Systems (OMACS) framework, we develop an agent-based model that builds the business operations of both the beef cattle industry and the associated transportation services. This model is employed to generate cattle movement data among premises under normal conditions and then to assess the system robustness under different node failure conditions. The outcome of this study will significantly raise awareness of vulnerabilities in the interconnected cattle/transportation system and benefit existing disaster preparedness. The next section illustrates our approach to develop the model and assess the system robustness.

2. Materials and methods

In this section, we first introduce the operating principles of the beef cattle industry and the transportation industry. Assumptions are made based on prior research and field studies. Then we illustrate the model design guided by OMACS framework. In the end, implementation details in AnyLogic are briefly described.

2.1. Conceptual model of the interdependent system

Besides the literature review above, we consulted beef cattle experts and did field studies in a local auction market and a finishing feedlot. According to the main findings from these activities, the operation processes and assumptions are summarized as the following.

2.1.1. Operating principles and model assumptions of the beef cattle industry

In the agent-based model, the beef cattle system mainly consists of four components: packer, live production, entry point, and auction market. In reality, cattle are traded through physical sale barns, video auctions or internet. Auction markets in the following refer to the physical sale barns and are seen as aggregated points for cattle movement. Cattle trading among premises is a complex process, which is determined by many factors such as good relationships and prices. In our model, market conditions are assumed to be stable, and price fluctuations are not included for simplification reasons. Therefore, the buyers randomly select sellers to purchase cattle, and operators in each production stage make decisions to move cattle mainly based on the animals' weight. The major cattle movement routes inside SW KS are depicted in Fig. 1. Calves raised in ranches are sold to stockers either through direct sales or auction markets. Similarly, feedlot operators source cattle either directly from stockers or through auction markets.

Packer. The beef slaughter industry in the U.S. is heavily concentrated, with only four firms in KS accounting for more than 80% of the total beef slaughter capacity [18]. As consistent with [33], all the cattle fed in SW KS are assumed to be slaughtered in the four major packers in SW KS. Despite the influence from market conditions, the demand for finished cattle remains relatively constant throughout the year. Each packer operates close to full capacity and slaughters, on average, 6000 head of cattle per day. From Monday through Friday, the entering meat process lasts for 16 h per day, and the cleaning process goes on in the remaining 8 h. Buyers from the packers randomly select feedlots to purchase cattle weekly. In 2005, there were 2,539,280 cattle transported from outside SW KS and 3,721,050 finished cattle transported

Table 1
Transportation flows and percentages of total transport activity.

Transportation flows			Percentages of total transport activity			
Origin	Destination	Type	Owned by producers	Rent from fleets	Owned by packers	From entry points
Ranch	Stocker	Via auction market	10%	90%	–	–
		Via direct sales	90%	10%	–	–
Stocker	Feedlot	Via auction market	10%	90%	–	–
		Via direct sales	90%	10%	–	–
Feedlot	Packer	Via direct sales	–	–	100%	–
Entry point	Packer	Via direct sales	–	–	100%	–
Entry point	Producer	Via direct sales	–	–	–	100%

from inside SW KS to the packers [33]. Based on this, we assume that each packer purchase 59% of its cattle from within SW KS and the rest from outside SW KS.

Live production. The live production locations are cattle premises inside SW KS, namely cow–calf ranches, stockers and feedlots. The latter two categories are referred to as "starter feedlot" and "finishing feedlot" in [33]. Cattle producers usually purchase cattle on a weekly basis based on their inventory and cattle flow requirements. They continue buying the available supply of animals until they achieve their maximum size. If the supply inside SW KS cannot provide enough cattle, the producers will purchase cattle from outside SW KS. More specifically, when the available cattle supply within SW KS is below the producer's demand multiplied by the presumed percentage of animals coming from within SW KS (see below), the producer will purchase more cattle from outside SW KS to compensate this shortage. In this way, producers' needs will always be satisfied. In particular, we assume:

- For a feedlot, around 10–15% of its cattle are purchased from within SW KS, and the remaining 85–90% are sourced from outside the region. The average daily gain is uniformly distributed between 2.6–3.3 pounds per day for heifers and 3–4 pounds per day for steers. Once heifers and steers achieve 1250 pounds and 1350 pounds respectively, they will be moved to the packers. At the model initialization, the ratio between heifer and steer is set at 0.6:0.4.
- For a stocker, about 50% of calves originate from SW KS, and the rest come from outside. Both heifers and steers grow at a rate of 2 pounds per day, and they are moved to feedlots for backgrounding once they achieve 650 pounds. At the model initialization, the ratio between heifer and steer is 0.6:0.4.
- For a ranch, cattle gain 1.67 pounds per day, and the finishing weight is 450 pounds. Cows are equally likely to give birth to a heifer or steer calf. Based on the ideal distribution of pregnancy for cow–calf herds in [61], it is assumed that most calves are born in March and April in the model. 60% of the herd gives birth in the first 21-day interval, 23% in the second 21-day interval, and 7% in the third 21-day interval. Additionally, 5% of calves are born outside this 63-day period. 5% of cows fail to become pregnant and therefore they will not give birth to calves. At the model initialization, only cows are set in the ranches.

Entry point. Since there are also cattle coming from outside SW KS, we put 12 entry points on the system boundaries which are located on the major highways into and out of SW KS, as in [33]. Cattle and trucks are placed at these entry points to represent those cattle or trucks coming from outside SW KS into the region. The following assumptions are made for the cattle from outside SW KS. (1) Transporting finished cattle from outside SW KS to the packers: 70% of the cattle come from the south, and 10% of cattle come from each of the north, east, and west directions [33]; (2) Transporting feeder cattle from outside SW KS to the feedlots: 30% of the cattle come from each of the north, south, and east directions, and 10% of the cattle come from the west [33]; (3) Transporting calves from outside SW KS to stockers: same as the feedlots; (4) No calves are coming from outside SW KS to the ranches in SW KS; (5) Cattle are evenly distributed among those entry points in the same direction.

2.1.2. Operating principles and model assumptions of the transportation industry

In reality, cattle movements among premises are highly dynamic and depend on a multitude of factors such as space availability, cattle weight and feed availability. For simplicity, we assume the ratios of total transport activity for each type of transportation flows as in Table 1. After producers (ranch, stocker or feedlot) finish trading cattle, the buyer side will transport the cattle either using its trucks or renting from truck companies. More specifically, 90% of cattle movements through direct sales between producers are via producers' trucks, while the remaining 10% are via trucks from fleets. In comparison, cattle movements via auction market between producers have the opposite percentages of total transport activity. Overall, 34% of the operations purchase cattle from the auction markets [62]. Entry points representing truck premises outside SW KS, use their trucks to move cattle from outside to the region. Packers use their trucks to ship cattle from both inside and outside SW KS.

In the model, vehicles owned by cattle producers are of small capacity, while all the rest are of large size. A large truck can accommodate on average 45 finished cattle or can hold 75 feeder cattle [33]. By similar calculations, it is assumed that small vehicles can carry 38 feeder cattle or 75 calves.

Livestock transportation is subject to federal and state regulations governing drivers' hours of service [63], as well as animal welfare requirements. Thus, we assume that each truck driver must complete a route within a 14 h duty period

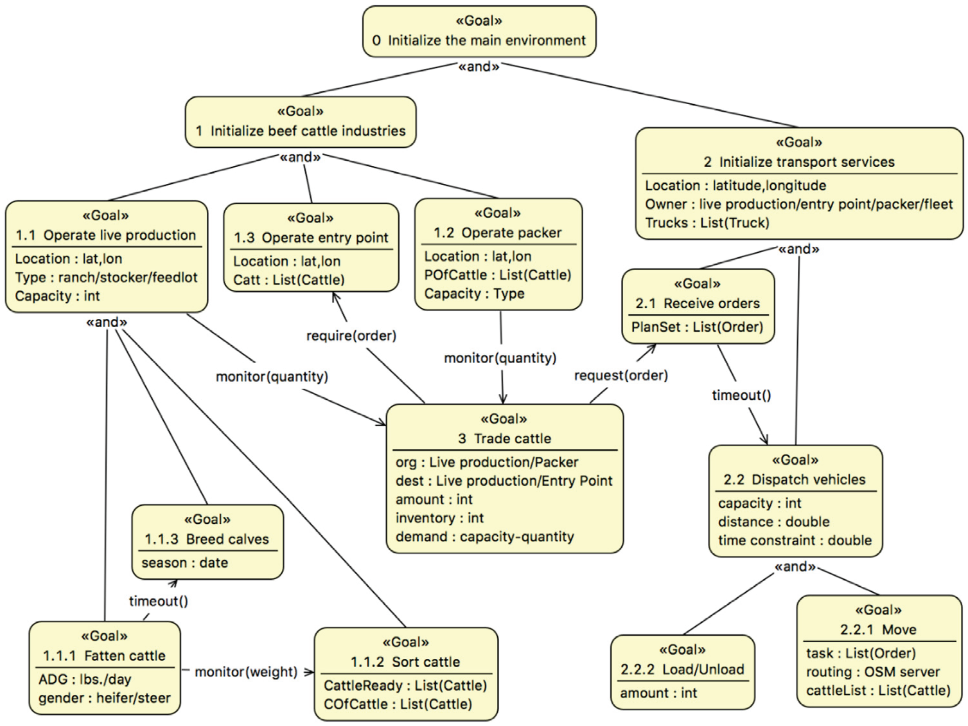


Fig. 2. Goal model of the system.

and must rest for ten consecutive hours before going back on duty. Based on this, vehicle dispatch algorithm is designed to minimize the number of vehicles dispatched and total distance traveled while obeying duty time limits. More details can be found in the supplemental information (see Appendix A).

2.2. Model design

In this section, we illustrate the model design using OMACS framework. Packer, live production, fleet and entry point agents are all in possessions of trucks and are referred to as *truck premises*. Meanwhile, live production and entry point agents are suppliers of cattle and are indicated as *cattle premises.*

The OMACS framework is proposed to guide multi-agent system design, and its fundamental concepts include agents, goals, and roles [64]. Our model consists of two organizations at the highest level of conception, i.e., the cattle production process and the transportation process. Constructed in agentTool III developed in [65], Fig. 2 presents the goal classes that drive the system and the parameters related to these goals. Each goal is labeled as G_i, using the following notation. The top goal consists of two sub-organization goals, i.e., *initialize the beef cattle industry* (G_1) and *initialize transport services* (G_2). The top goal indicates that agents need to be appropriately created and located based on the GIS map at model setup.

In the cattle industry organization, G_1 is decomposed to three leaf goals ($G_{1.1}$, $G_{1.2}$, $G_{1.3}$) that are assigned to live production, packer and entry point agents, respectively. The sub-goal of $G_{1.1}$, *fatten the cattle* ($G_{1.1.1}$) is the only goal that initially exists, and the rest are triggered by events. When the system starts, $G_{1.1.1}$ is applied to all live production agents, in which cattle weight is based on the average daily gain. Meanwhile, a timeout-event is periodically triggered so that producers periodically sort those cattle above the finishing weight into groups, which are ready to be shipped ($G_{1.1.2}$). Cows in ranches are assigned with $G_{1.1.3}$ *breed the cattle,* which is triggered once a year. G_3 *trade cattle* is a complex goal assigned to live production and packer agents. They periodically count their cattle inventory and will start to purchase cattle once the inventory falls below the capacity (an event is raised to trigger G_3).

In the transportation organization, truck premises need to achieve goals of $G_{2.1}$ *receive orders* and $G_{2.2}$ *dispatch vehicles*. At idle state, the vehicles are placed at the truck premises. After the cattle trade ends (G_3), an event will be triggered to send requests for transport services, which will be received by the truck premises agent ($G_{2.1}$). A time-out event will be triggered so that the truck premises conducts the vehicle dispatch algorithm and sends the trajectory commands to the vehicles ($G_{2.2}$) on the second day. Upon receiving the messages, the truck starts to move to each order's origin to pick up cattle and unload the cattle at the destination ($G_{2.2.1}$ and $G_{2.2.2}$).

OMACS goals are achieved by agents playing specific roles within the corresponding organization. Table 2 shows the agent types, the capabilities required and the corresponding roles. For example, the cattle playing the role of heifers give birth to calves each year. Table 3 details the interactions between agents or roles.

Table 2
Agent types, capability and roles.

Agent types	Capability possessed	Playable roles
Cattle	Give birth; Grow.	Heifer; Steer.
Truck	Move along the road; Transport cattle; Communication.	Truck.
Fleet	Execute algorithms; Communication.	Truck premises.
Live production	Accommodate cattle; Trade cattle; Communication; Sort cattle periodically.	Cattle premises (ranch, stocker or feedlot); Truck premises.
Packer	Accommodate cattle; Trade cattle; Execute algorithms; Enter meat process; Communication.	Order buyer; Entrance of meat process; Truck premises.
Entry point	Accommodate cattle; Execute algorithms; Communication.	Cattle premises; Truck premises.
Order	Record the origin, destination and the amount of cattle.	Messages in trade process; Tasks of the trucks.

Table 3
Interacting agents and rules.

Interacting agents		Rules
Truck	Cattle	Trucks transport cattle according to the amount specified in the order.
	Packer	The packer sends orders to its trucks according to the vehicle dispatch algorithm.
	Fleet	Fleet company sends a sequence of orders to its trucks on the second day of receiving orders.
	Entry point	Entry point agent dispatches trucks on the second day of receiving orders.
	Live production	Live production agent dispatches vehicles on the second day after the trade ends.
Live production	Live production	Producers communicate with each other at random during a week to trade cattle.
Live production	Packer	Packers and Live producers (feedlots) trade cattle on each Friday morning.
Live production	Entry point	Live producers (feedlots or stockers) purchase cattle from entry points
Packer	Entry point	Packers purchase cattle from the entry points weekly.

Table 4
Summary input statistics.

	Ranch	Stocker	Feedlot	Total
Number of farms	18	50	233	301
Cattle Inventory	14,050	79,768	2,819,189	2,913,007

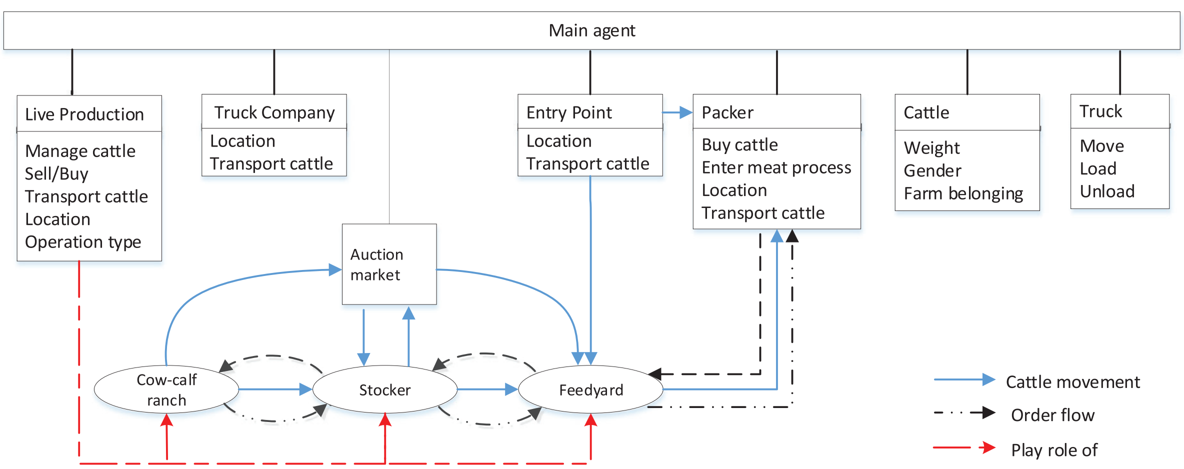


Fig. 3. Simulator structure.

2.3. Model implementation

The model was developed in AnyLogic 8 University 8.3.3, with all functions written in Java. The model structure is depicted in Fig. 3, and the implementation details are briefly introduced as the following.

The interdependent system includes a total of 301 live production locations, four major packers and 12 entry points for cattle and trucks from outside SW KS. Statistics of the model input are summarized in Table 4.

The main agent builds the environment that the other agents share. At the model initialization, it creates and locates the agents within a GIS map based on the latitude and longitude of the model input data (Fig. 4). The routes are requested from *OpenStreetMap* server provided by AnyLogic and set with the shortest path method. The live production agents are assigned one of the three industry roles: ranch, stocker, or feedlot based on the input data. Cattle agents are assigned

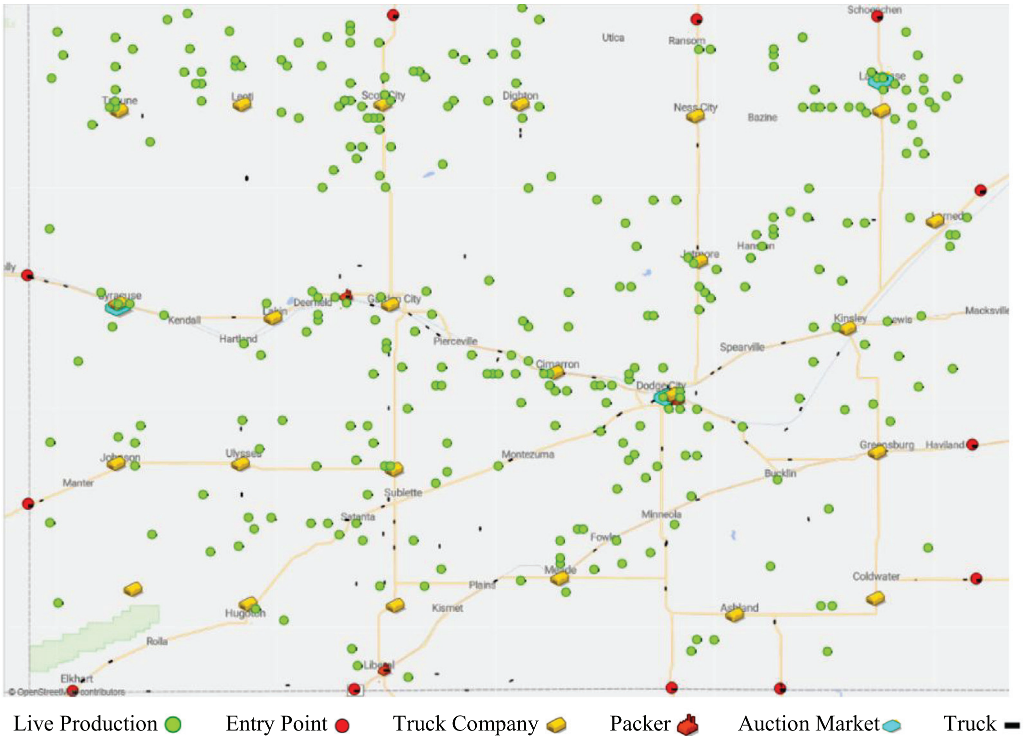


Fig. 4. Animation on GIS map.

Table 5
Summary of key variables.

Agent	Variable name	Description
Live production	CofCattle	List of cattle not ready to be sold.
	CattleReady	List of cattle ready to be sold to the next place.
	FSTrucks	List of light trucks belonging to this live production agent.
	PlanSet	List of orders to be fulfilled by the trucks.
Packer	PofCattle	List of cattle physically stay in the packer.
	FBTrucks	List of large trucks belonging to this packer.
	PlanSet	List of orders to be fulfilled by the trucks.
Entry point	Feeders/Finished	List of feeder cattle or finished cattle from outside SW KS.
	PlanSet	List of orders to be fulfilled by the trucks.
	Trucks	List of large trucks from outside SW KS.

with a weight parameter uniformly distributed between a minimum and a maximum value and located at their cattle premises.

The live production agents periodically check whether the cattle achieve the finishing weight and sort them into the group ready to be shipped. On a weekly basis, they communicate with other live production agents and entry point agents to purchase cattle. On the second day after the trade ends, cattle are transported to the next production stage. Packer agents purchase cattle from feedlots within SW KS and entry points each week. The order agent consists of the number of cattle, origin, and destination. Each cattle agent gains weight based on growth rate determined by its gender and owner (i.e., type of live production agent it belongs to). Heifers in cow–calf ranches breed new calves according to the predetermined fertility rate. The variables deemed necessary for readers to understand the model are shown in Table 5.

The model's time scale is based on dates, generating data from Jan 1st 12:00:00 AM-Dec 31st 11:59:59 PM. For the simulation experiment, the maximum available memory is set as "Custom 56320 Mb". With "Virtual time mode" selected, the model runs at its maximum speed, and there is no mapping from AnyLogic model time to the real time. "Fixed seed" option is selected for the random number generation, making the results reproducible.

2.4. Experimental design

Two experiments were performed to assess the system robustness in response to disruptions in the beef cattle industry and the transportation industry. In the first experiment, the removal of trucks refers to the unavailability of vehicles caused by deliberate attacks. In the second experiment, cattle premises are removed to mimic the loss of cattle supply caused by interventions such as trade restrictions or culling during disease outbreaks. For example, the removal of entry point agents considers the possible case, in which cattle are found to be infected outside SW KS and the markets in SW KS are subsequently closed to cattle from that side of the boundary.

During cattle trade, a cattle buyer randomly selects producers to purchase cattle. To model this process, we use a pseudorandom number generator in AnyLogic to generate a sequence of numbers, which are the indexes of the cattle premises. Please note that the sequence of numbers is not truly random and is determined by the seed. Therefore, "fixed seed" option is selected in the simulation setup so that the model will always produce the same results as long as all the other settings remain unchanged. Accordingly, we only run the model once to obtain the results for each simulation scenario. Aside from the removal of the premises, all other parameters remain unchanged for comparison purposes.

A truck premises agent and the population of all the truck premises are denoted as g and $\mathcal{G}$ respectively to explain the simulation process. Truck premises are categorized by agent class, and the population in the kth category is indicated as $\mathcal{G}_k$, where $k = 0, \ldots, 3$ refer to packer, farm, fleet or entry point respectively. g_i^k is the ith truck premises agent in the kth truck premises category. The fraction of unavailable trucks over all the vehicles is denoted by p.

2.4.1. Disruptions in the transportation industry

To reflect the impact of transportation disruptions on the cattle industry, we defined an indicator, the fraction of demand met, as follows:

$$\text{Fraction of demand met (\%)} = \mathcal{A}/\mathcal{P} \tag{1}$$

where $\mathcal{A}$ and $\mathcal{P}$ are the total headcount of cattle actually moved and expected to be moved regarding all cattle premises respectively.

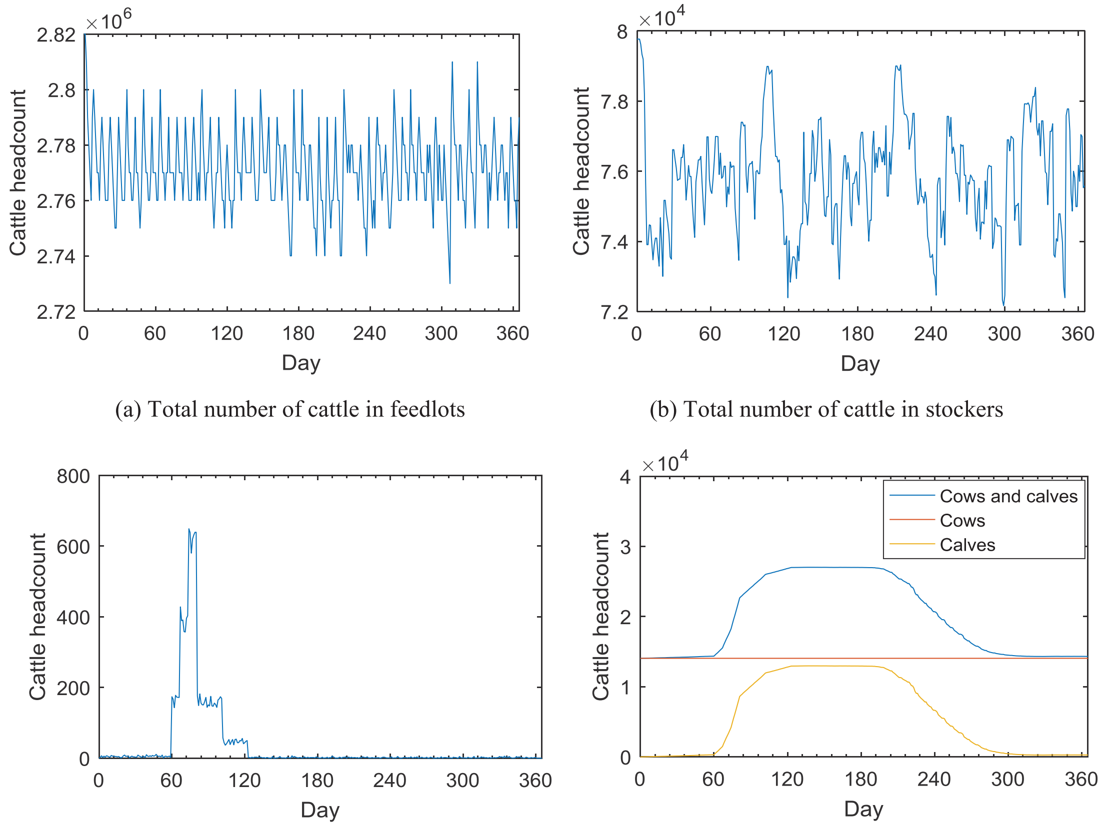
Each truck premises agent dispatches vehicles using Algorithm A1 (see Appendix A) with input *PlanSet*, a list of orders to be delivered. Facing vehicle shortage problems, the truck premise agent would fail to complete assigning all orders in *PlanSet.* As a result, those orders fulfilled will be placed in the *ActualSet*, and the remaining orders are left at *PlanSet*. Those cattle which need to be moved by the remaining orders are seen as cattle losses, since they will not reach their destination on time. The remaining orders and the new orders coming in will be mixed in *PlanSet* and processed by Algorithm A1 on the next day.

The main agent executes Algorithm 1 on a daily basis to calculate $\mathcal{A}$, $\mathcal{P}$ and the total cattle loss $\mathcal{L}$. We first compute $\mathcal{P}^k$ by summing up the amount of cattle specified in *order* agents of *PlanSet* from $\mathcal{G}_k$, which are all truck premises in the kth truck premises category. Then, $\mathcal{P}$ is the summation of $\mathcal{P}^k$ for all truck premise categories from the first day to the last day (simulation stop time). Similarly, the summation of the cattle quantities specified in *ActualSet* is $\mathcal{A}$. Alternatively, we can count the number of cattle unloaded every time a truck arrives at the destination. Both methods are conducted in the experiment and yield the same results.

Algorithm 1 Compute the *fraction of demand met*

Input: $g_i^k \in \mathcal{G}_k$ which has *PlanSet* and *ActualSet*
$\mathcal{P}^{t-1}$, $\mathcal{A}^{t-1}$, $\mathcal{L}^{t-1}$ from previous day

function calcFDM( )
  $\mathcal{A} \leftarrow \mathcal{A}^{t-1}$, $\mathcal{P} \leftarrow \mathcal{P}^{t-1}$, $\mathcal{L} \leftarrow \mathcal{L}^{t-1}$
  for (int k=0; k<4; k++)
    $\mathcal{P}_k \leftarrow 0$, $\mathcal{A}_k \leftarrow 0$, $\mathcal{L}_k \leftarrow 0$
    for each $g_i^k \in \mathcal{G}_k$
      $p_i^k \leftarrow 0$, $a_i^k \leftarrow 0$
      for each order in $g_i^k.PlanSet$
        $p_i^k \leftarrow p_i^k + order.amount$
      end for
      for each $order \in g_i^k.ActualSet$
        $a_i^k \leftarrow a_i^k + order.amount$
      end for
      $\mathcal{P}_k \leftarrow \mathcal{P}_k + p_i^k$, $\mathcal{A}_k \leftarrow \mathcal{A}_k + a_i^k$
    end for
    $\mathcal{L}_k \leftarrow \mathcal{P}_k - \mathcal{A}_k$
    $\mathcal{P} \leftarrow \mathcal{P} + \mathcal{P}_k$, $\mathcal{A} \leftarrow \mathcal{A} + \mathcal{A}_k$, $\mathcal{L} \leftarrow \mathcal{L} + \mathcal{L}_k$
  end for
  $\mathcal{A}^t \leftarrow \mathcal{A}$, $\mathcal{P}^t \leftarrow \mathcal{P}$, $\mathcal{L}^t \leftarrow \mathcal{L}$
  return $\mathcal{P}^t$, $\mathcal{A}^t$, $\mathcal{L}^t$
end function



(a) Total number of cattle in feedlots
(b) Total number of cattle in stockers
(c) Total number of new calves born daily in ranches
(d) Total number of cattle in ranches

Fig. 5. Statistics of cattle in each production stage within SW KS over a 365-day period.

2.4.2. Disruptions in the cattle industry

The product of headcount and distance are calculated as an indicator for the adverse effects caused by disruptions in cattle industry with the following steps.

Step 1. Live production and entry point agents are removed based on either random or targeted strategy. In target removal strategy, we progressively remove nodes, one after another, in the decreasing order of specific criteria.

Step 2. When the truck t fulfills an order j, the miles traveled (round trip) d_j and the headcount of cattle carried during this trip n_j are recorded.

Step 3. Calculate the travel distance of all cattle in the system, *headcount* × *distance* of the system, which is $\sum_{t\in\mathcal{T}} n_j \cdot d_j$.

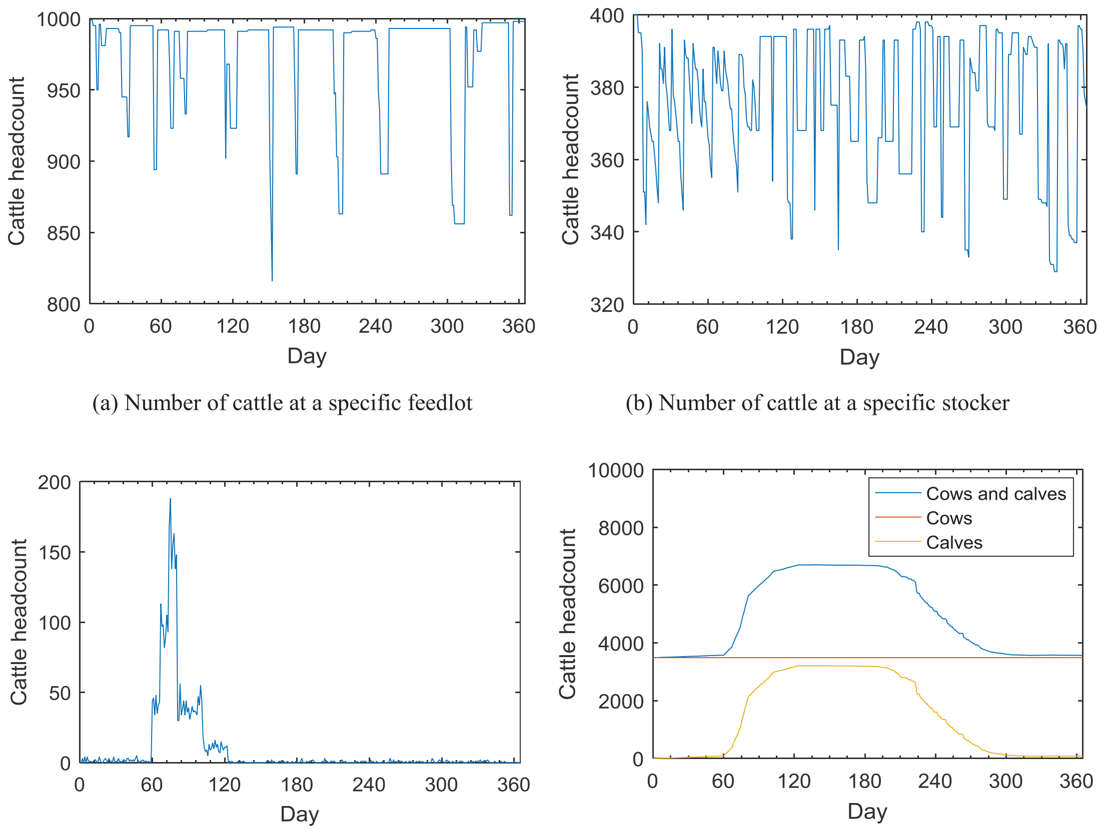
The next section will describe the simulation results and implications.

3. Results and discussion

In this section, we present results regarding the simulated data generated from the agent-based model. We then evaluate results regarding the system robustness to disruptions in the cattle production and transportation industries.

3.1. Data generation under normal condition

We present the visualization of cattle quantity from the perspective of each producer category and individual cattle premises as follows. Results regarding the total number of cattle located in feedlots, stockers, and ranches within SW KS over a year are shown in Figs. 5(a)–(d). In Fig. 5(a), the total number of cattle living in feedlots fluctuates weekly. Packers ship cattle out of feedlots from Monday to Friday, causing the number of cattle in feedlots to decrease. Next, feedlots buy animals from stockers to return to capacity. When the new cattle arrive, the number of cattle in feedlots increases accordingly. In comparison, the number of cattle in stockers fluctuates with a smaller amplitude in Fig. 5(b). The number of new calves born daily is shown in Fig. 5(c). In Fig. 5(d), the number of cows in the ranches stays stable while the number of calves increases in March and April because of the new births. The new calves remain in the ranches for several months and are then moved to stockers for backgrounding in fall. Therefore, the curve starts to decrease around August.



(a) Number of cattle at a specific feedlot

(b) Number of cattle at a specific stocker

(c) Number of calves born daily at a specific ranch

(d) Number of cattle at a specific ranch

Fig. 6. Sample plots of cattle quantity in individual producer locations within SW KS over a 365-day period.

Over the annual period, all premises are consistently part of the trade network. With the constant weekly nature of the market chain, there is little variation between the seasons. Births of calves in ranches are seasonal, but the ranches' total capacity constitutes only 0.48% of the total capacity of all live production sites in SW KS according to our input data. Therefore, the model is not strongly affected by seasonality.

Cattle quantities of particular premises in each producer category over time result in similar patterns. Thus, we randomly select one producer agent from each group and present its cattle quantity over a year in Fig. 6.

The model output contains details describing every truck and cattle movement among premises, e.g., truck id, cattle id, origin, destination, date. Individual truck movement data are aggregated at county-level and summarized in the supplemental information (see Appendix A). The county-level distribution of cattle movement is a bit different from those results in [33], because our model's input data are slightly different from that of Bai et al. [33] due to the data cleaning process regarding the longitude and latitude. Additionally, Bai et al. only consider feedlots in SW KS and assume that all the feeder cattle are coming from outside the study area. However, results in both methods are within a similar range. Comparisons with the simulated data generated from the model and simulated data published by Bai et al. [33] are shown in Table 6.

3.2. Evaluation of system robustness under disaster conditions

In this section, system robustness to disruptions in the beef cattle industry and transportation industry are measured under different scenarios. Since the model results under normal conditions show little variation across seasons, subsequent analysis was conducted just for the first two weeks of the year.

3.2.1. Disruptions in the transportation industry

Removal of trucks over the system. Different removal strategies of truck premises are summarized in Table 7. For full implementation details, see Appendix A. In Fig. 7, all the random strategies result in a similar response pattern, revealing the robustness of the network. For example, 61.1% to 76.5% of the demand can be still met when 50% of trucks become unavailable. In comparison, targeted removal based on a decreasing order of truck quantity owned by each truck premises

Table 6
Key statistics over a year.

Statistics	Simulated data in Bai et al. [33]	Author's simulated data	Difference	Conformity
Total number of finished cattle from feedlots inside SW KS to the packer	3,721,050 head	3,694,270 head	0.72%	Yes
Number of cattle coming from outside SW KS to packers	Total: 2,539,280 head; South: 1,777,496 head; North/East/West: 253,928 head	Total: 2,569,225 head; South: 1,798,282 head; North/East/West: 256,868 head	Total: 1.18% South: 1.17% North/East/West: 1.16%	Yes
Packer annual kill capacity	6,260,330 head	6,263,495 head	0.05%	Yes
Truck miles traveled for transporting cattle from inside SW KS to packers	13,456,956 miles	10,749,558.7 miles	-	–
Truck miles traveled for transporting cattle from outside SW KS to packers	10,438,844 miles	10,314,759.3 miles	1.19%	Yes
Truck miles traveled for transporting cattle (inside and outside SW KS) to packers	23,895,800 miles	21,064,318 miles	-	–

Table 7
Summary of removal strategies.

Strategy	Description
Random strategy-each premises	For each truck premises agent g_i^k with n_i^k trucks, randomly remove $p \cdot n_i^k$ trucks. In total, $\sum_{g\in\mathcal{G}} p \cdot n_i^k$ trucks are removed, where $\mathcal{G}$ refer to all truck premises agents.
Random strategy-over the system	Randomly remove $p \sum_{g\in\mathcal{G}} n_i^k$ trucks from the whole system.
Random strategy-each premises category	For each category k, randomly remove $p \sum_{g\in\mathcal{G}_k} n_i^k$ trucks. In total, remove $\sum_{k=0}^{3} p \sum_{g\in\mathcal{G}_k} n_i^k$.
Targeted strategy-over the system	In the whole system, intentionally remove $p \sum_{g\in\mathcal{G}} n_i^k$ trucks based on truck premises ranked by number of trucks, from high to low.

leads to a notably faster drop in the fraction of demand met. Among the truck premises, packers possess the largest numbers of trucks. Thus, their trucks will be removed first under the targeted strategy. Packers utilize their vehicles to pick up cattle both from inside and outside SW KS. Once packers lose all their trucks, they are unable to pull cattle from feedlots. Consequently, feedlots will always be at full capacity and will not request cattle from other premises. Similarly, stockers will not purchase animals from other suppliers as well. Therefore, the system's transportation flow quickly stops when the fraction of trucks unavailable reaches around 14%, which is the ratio of the number of packers' vehicles over total truck quantity in the system.

Removal of trucks over each truck premises category. Here we analyze the system robustness with the removal of trucks belonging to each truck premises sector. We continue removing those trucks from the truck premises based on their truck quantity, from high to low, until the number of vehicles removed reaches the product of p and the total truck quantity in the system (see Fig. 8).

In Fig. 8, both the red curves change abruptly compared with others, indicating that disruptions in the packer sector affect the cattle movement most. Packers are the most demanding truck premises located at the top of the supply chain, making the coupled system more fragile. When 10% of the total truck population is removed under a targeted strategy on packers, the demand met is reduced by about 90%. In comparison, random removal of trucks from the packer sector seems to be slightly less impactful and converges with the targeted strategy at around 14%, which is the maximum portion of all trucks that the packer sector owns. It is worth noting that, although the total trucks from producers constitute around 55% of all trucks in the system, complete removal of the producers' trucks only decreases the fraction of transportation demand met by about 15%. This is probably because there are many feedlots, allowing a relatively robust network.

These findings highlight that packers and regional boundaries represent crucial components of truck industry resiliency. Packers are the premises with the largest number of trucks, followed by the entry points. To mitigate the effects of deliberate transportation attacks on the cattle industry, truck premises should become more resilient by distributing vehicles within a larger geographical area. In the model, we did not consider sharing trucks among different truck premises. Such coordination among truck premises may help decrease the effects of transportation disruptions on cattle production during disasters. For example, if all the trucks become unavailable at a packer, other neighbors' trucks could

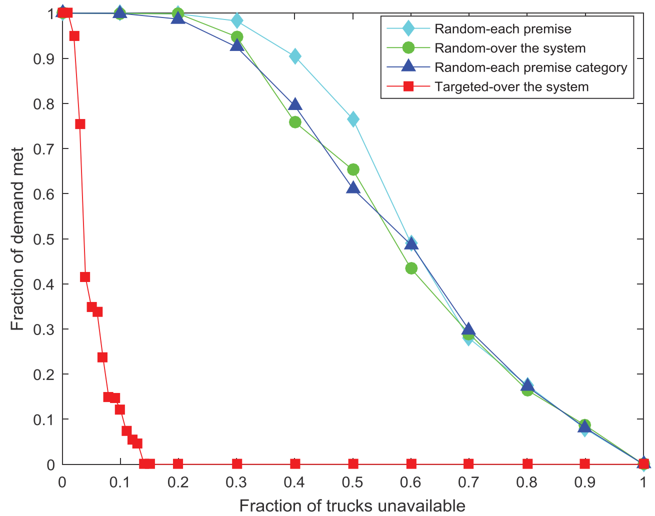


Fig. 7. Fraction of demand met over the fraction of trucks removed from the transportation industry under different removal strategies in a two-week period.

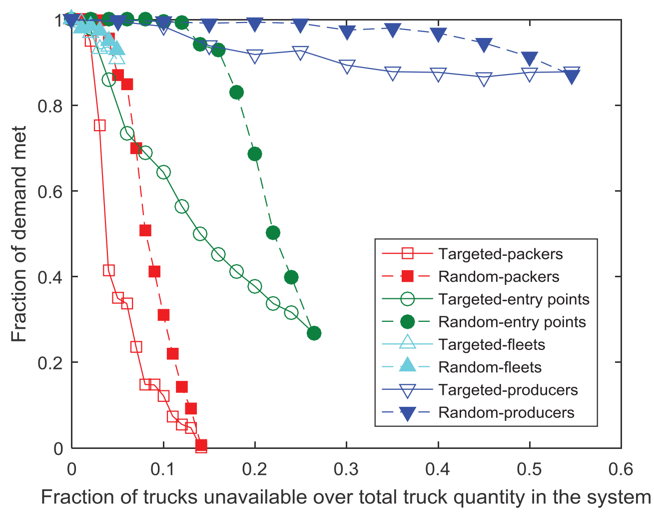


Fig. 8. Fraction of demand met over the fraction of trucks removed in transportation industry under strategies differentiated on sectors in a two-week period.

transport cattle and fulfill its production needs. In this way, cattle production could possibly last for a more extended period when there are disruptions.

3.2.2. Disruptions in the cattle industry

The simulation results of cattle industry disruptions are shown in Fig. 9, in which *headcount* $\times$ *distance* is normalized based on its value under normal conditions. The results show that the intentional removal of cattle premises changes more sharply compared with the random strategy. During the trade, producers randomly select from the rest of the premises to purchase animals. Arbitrary node removal causes cattle movement in the system to be redistributed, but the system stays relatively robust and self-adaptive. For example, when 50% of cattle premises become unavailable, *headcount* $\times$ *distance* is still around 65%. For targeted strategies based on cattle capacity or the number of cattle ready, large producers and entry point agents were removed first. Large cattle suppliers need more transportation services, and once they are removed the distance cattle travel decreases quickly. Targeted removal based on out-degree, which is the number of animals moved out of that premises in a period, does not decrease as much as other targeted strategies after $p = 10\%$. This appears to be because some large-capacity producers did not sell cattle in this period and are not removed at the beginning, so they maintain the functioning of the transportation industry until they are removed in the end. Two conclusions may be drawn from these findings to help ensure truck premises' profitability and buffer against possible losses caused by dependence

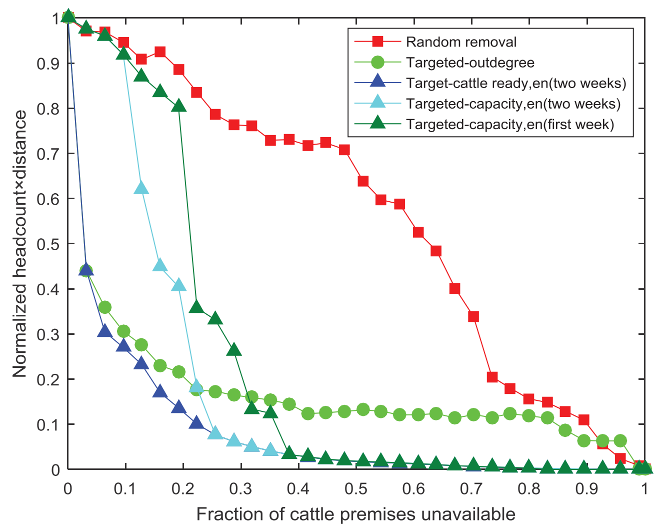


Fig. 9. Normalized product of headcount and distance of transportation industry on the fraction of cattle premises removed in a two-week period.

on the cattle industry. Regarding disease outbreaks, more focus can be put on communicating control measures for large cattle producers in SW KS and inspection on the regional boundary. In addition, large-capacity producers may distribute their cattle to multiple locations to help enhance the system robustness against targeted attacks.

4. Conclusion and future work

Most previous studies regarding the beef cattle industry have focused on operation mechanisms and disease preventions. To our knowledge, this paper is the first to explicitly model both the cattle industry and transportation services as two distinct but interdependent industries. The model, built in AnyLogic, generates cattle and truck movement data among premises based on regular business operating principles and assumed conditions. The data is fine-grained in both time and space, capturing each cattle and truck movement with a labeled id. Due to privacy issues, cattle and truck movement data for SW KS are only available in [33] to the authors' knowledge. The cattle and truck movement data generated from the agent-based model are aggregated at county-level, which are within a similar range of the county-level data in [33]. We proceeded to evaluate the interdependent network robustness under disaster conditions. Our results show that the interconnected system is relatively stable against disruptions in either the beef cattle industry or the transportation industry under random failure strategies. For targeted strategies, packers are identified as critical elements of the truck system, since a shortage of packer trucks was shown to inflict the worst impact on the system. In addition, truck premises, especially those that require a larger number of vehicles, need to ensure that they take proper measures to have access to additional trucks in case of deliberate attacks. In this way, the negative effects of vehicle shortage on the cattle production system can be mitigated. However, the best approach to provide additional trucks with a greater diversity in physical locations requires more investigation.

In conclusion, the interdependence between the cattle industry and transportation industry creates vulnerability to the system. The locations and natures of these vulnerabilities need to be fully considered by system planners for making better decisions on disaster preparedness. Due to the complexity of the cattle supply chain, the current model is a simplification of reality, but it does include the most significant elements of cattle production and transportation. In the model, the cattle birth distribution is assumed based on the literature [61], and future data collection efforts may focus on obtaining better cattle birth data. Furthermore, subject-matter experts we consulted during the field studies, estimated the percentages for various transportation routes, which might be different for other U.S. regions. For example, for movements from ranches to stockers, in Table 1, they estimated that 10% of cattle are transported using producers' vehicles while the rest 90% of cattle are moved via vehicles rent from fleet companies. Moreover, this model is extensible, with the ability to add more complexity and functionality to focus on particular issues such as disease simulations. More features will be incorporated in the model in the future work, such as human decision making factors, to analyze their impact on the resilience of the interdependent cattle and transportation system.

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Appendix A. Supplementary data

Describes algorithms used during simulation and simulated data aggregated at county-level.
Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physa.2019.04.092.

References

[1] B. Liscouski, W. Elliot, Final report on the august 14, 2003 blackout in the united states and canada: causes and recommendations, in: A Report to US Department of Energy, vol. 40, 2004, p. 86.
[2] S. Wang, L. Hong, X. Chen, Vulnerability analysis of interdependent infrastructure systems: A methodological framework, Physica A 391 (11) (2012) 3323–3335.
[3] D.U. Case, Analysis of The Cyber Attack on The Ukrainian Power Grid, Electricity Information Sharing and Analysis Center, E-ISAC, 2016.
[4] NCEI, Billion-Dollar Weather and Climate Disasters: Overview, 2017, Available from: https://www.ncdc.noaa.gov/billions/.
[5] R. Albert, H. Jeong, A.-L. Barabási, Error and attack tolerance of complex networks, Nature 406 (6794) (2000) 378–382.
[6] S. Pahwa, M. Youssef, P. Schumm, C. Scoglio, N. Schulz, Optimal intentional islanding to enhance the robustness of power grid networks, Physica A 392 (17) (2013) 3741–3754.
[7] A. Sydney, C. Scoglio, D. Gruenbacher, Optimizing algebraic connectivity by edge rewiring, Appl. Math. Comput. 219 (10) (2013) 5465–5479.
[8] X.F. Wang, J. Xu, Cascading failures in coupled map lattices, Phys. Rev. E 70 (2004) 056113.
[9] Department of Homeland Security, Critical Infrastructure Sectors, 2018, Available from: https://www.dhs.gov/critical-infrastructure-sectors.
[10] S.S. Chopra, V. Khanna, Interconnectedness and interdependencies of critical infrastructures in the US economy: Implications for resilience, Physica A 436 (2015) 865–877.
[11] S.V. Buldyrev, R. Parshani, G. Paul, H.E. Stanley, S. Havlin, Catastrophic cascade of failures in interdependent networks, Nature 464 (2010) 1025.
[12] X. Huang, J. Gao, S.V. Buldyrev, S. Havlin, H.E. Stanley, Robustness of interdependent networks under targeted attack, Phys. Rev. E 83 (2011) 065101.
[13] F. Tan, Y. Xia, W. Zhang, X. Jin, Cascading failures of loads in interconnected networks under intentional attack, Europhys. Lett. 102 (2013) 28009.
[14] L. Tang, K. Jing, J. He, H.E. Stanley, Complex interdependent supply chain networks: Cascading failure and robustness, Physica A 443 (2016) 58–69.
[15] Cash receipts by selected commodity, US Department of Agriculture Economic Research Service, 2019, Available from: https://data.ers.usda.gov/reports.aspx?ID=17832,
[16] Kansas Department of Agriculture, Estimated Economic Impact of Agriculture, Food, and Food Processing Sectors, 2017.
[17] K.E. Craft, R. Mahmood, S.A. King, G. Goodrich, J. Yan, Droughts of the twentieth and early twenty-first centuries: Influences on the production of beef and forage in Kentucky, USA, Sci. Total Environ. 577 (2017) 122–135.
[18] J.S. Drouillard, Current situation and future trends for beef production in the United States of America—A review, Asian-Australas. J. Animal Sci. 31 (2018) 1007.
[19] T.C. Schroeder, D.L. Pendell, M.W. Sanderson, S. Mcreynolds, Economic impact of alternative FMD emergency vaccination strategies in the midwestern United States, J. Agric. Appl. Econ. 47 (2015) 47–76.
[20] M. Gilbert, A. Mitchell, D. Bourn, J. Mawdsley, R. Clifton-Hadley, W. Wint, Cattle movements and bovine tuberculosis in Great Britain, Nature 435 (2005) 491.
[21] C.M. Scoglio, C. Bosca, M.H. Riad, F.D. Sahneh, S.C. Britch, L.W. Cohnstaedt, K.J. Linthicum, Biologically informed individual-based network model for Rift Valley fever in the US and evaluation of mitigation strategies, PLoS One 11 (2016) e0162759.
[22] K.L. VanderWaal, C. Picasso, E.A. Enns, M.E. Craft, J. Alvarez, F. Fernandez, A. Gil, A. Perez, S. Wells, Network analysis of cattle movements in Uruguay: Quantifying heterogeneity for risk-based disease surveillance and control, Prev. Vet. Med. 123 (2016) 12–22.
[23] G. Rossi, G.A. De Leo, S. Pongolini, S. Natalini, S. Vincenzi, L. Bolzoni, Epidemiological modelling for the assessment of bovine tuberculosis surveillance in the dairy farm network in Emilia-Romagna (Italy), Epidemics 11 (2015) 62–70.
[24] G. Rossi, R.L. Smith, S. Pongolini, L. Bolzoni, Modelling farm-to-farm disease transmission through personnel movements: From visits to contacts, and back, Sci. Rep. 7 (2017) 2375.
[25] M. Nöremark, J. Frössling, S.S. Lewerin, A survey of visitors on Swedish livestock farms with reference to the spread of animal diseases, BMC Vet. Res. 9 (2013) 184.
[26] A. Ortiz-Pelaez, D. Pfeiffer, R. Soares-Magalhaes, F. Guitian, Use of social network analysis to characterize the pattern of animal movements in the initial phases of the 2001 foot and mouth disease (FMD) epidemic in the UK, Prev. Vet. Med. 76 (2006) 40–55.
[27] T. O'Quinn, D. Woerner, T. Engle, P. Chapman, J. Legako, J. Brooks, K. Belk, J. Tatum, Identifying consumer preferences for specific beef flavor characteristics in relation to cattle production and postmortem processing parameters, Meat Sci. 112 (2016) 90–102.
[28] T. Grandin, Recommended Animal Handling Guidelines & Audit Guide: A Systematic Approach to Animal Welfare, AMI Foundation, 2010.
[29] K. Schwartzkopf-Genswein, L. Faucitano, S. Dadgar, P. Shand, L. González, T. Crowe, Road transport of cattle swine and poultry in North America and its impact on animal welfare, carcass and meat quality: A review, Meat Sci. 92 (2012) 227–243.
[30] G. Miranda-De La Lama, M. Villarroel, G. María, Livestock transport from the perspective of the pre-slaughter logistic chain: A review, Meat Sci. 98 (2014) 9–20.
[31] A. Barham, B. Barham, A. Johnson, D. Allen, J. Blanton Jr, M. Miller, Effects of the transportation of beef cattle from the feedyard to the packing plant on prevalence levels of Escherichia coli O157 and Salmonella spp, J. Food Prot. 65 (2002) 280–283.
[32] S.M. Huertas, A.D. Gil, J.M. Piaggio, F.J.C.M. Van Eerdenburg, Transportation of beef cattle to slaughterhouses and how this relates to animal welfare and carcase bruising in an extensive production system, Animal Welf. 19 (2010) 281–285.
[33] Y. Bai, P.C. Oslund, T.E. Mulinazzi, S. Tamara, C. Liu, M.M. Barnaby, C.E. Atkins, Transportation logistics and economics of the processed meat and related industries in Southwest Kansas, in: Final Report for Kansas Department of Transportation Research Project KU-06-3, 2007.
[34] P. Motta, T. Porphyre, I. Handel, S.M. Hamman, V.N. Ngwa, V. Tanya, K. Morgan, R. Christley, B.M. Barend, Implications of the cattle trade network in Cameroon for regional disease prevention and control, Sci. Rep. 7 (2017) 43932, https://doi.org/10.1038/srep43932.
[35] M.J. Jeger, M. Pautasso, O. Holdenrieder, M.W. Shaw, Modelling disease spread and control in networks: Implications for plant sciences, New Phytol. 174 (2007) 279–297.
[36] I.Z. Kiss, D.M. Green, R.R. Kao, The network of sheep movements within Great Britain: Network properties and their implications for infectious disease spread, J. R. Soc. Interface 3 (2006) 669–677.
[37] P. Bajardi, A. Barrat, L. Savini, V. Colizza, Optimizing surveillance for livestock disease spreading through animal movements, J. R. Soc. Interface 9 (2012) 2814–2825.

[38] M.L. Brennan, R. Kemp, R.M. Christley, Direct and indirect contacts between cattle farms in north-west England, Prev. Vet. Med. 84 (2008) 242–260.
[39] P. Bajardi, A. Barrat, F. Natale, L. Savini, V. Colizza, Dynamical patterns of cattle trade movements, PLoS One 6 (2011) e19869.
[40] G. Rossi, G.A. De Leo, S. Pongolini, S. Natalini, L. Zarenghi, M. Ricchi, L. Bolzoni, The potential role of direct and indirect contacts on infection spread in dairy farm networks, PLoS Comput. Biol. 13 (2017) e1005301.
[41] T.W. Bates, M.C. Thurmond, T.E. Carpenter, Direct and indirect contact rates among beef, dairy, goat, sheep, and swine herds in three California counties, with reference to control of potential foot-and-mouth disease transmission, Am. J. Vet. Res. 62 (2001) 1121–1129.
[42] B.J. Dominguez, Characterization of livestock herds in extensive agricultural settings in southwest texas, (Doctoral Dissertation), Texas A & M University, 2010.
[43] M.G. Buhnerkempe, D.A. Grear, K. Portacci, R.S. Miller, J.E. Lombard, C.T. Webb, A national-scale picture of US cattle movements obtained from interstate certificate of veterinary inspection data, Prev. Vet. Med. 112 (2013) 318–329.
[44] E.E. Gorsich, A.D. Luis, M.G. Buhnerkempe, D.A. Grear, K. Portacci, R.S. Miller, C.T. Webb, Mapping US cattle shipment networks: Spatial and temporal patterns of trade communities from 2009 to 2011, Prev. Vet. Med. 134 (2016) 82–91.
[45] E. Bonabeau, Agent-based modeling: Methods and techniques for simulating human systems, Proc. Natl. Acad. Sci. 99 (2002) 7280–7287.
[46] A. Marvuglia, S. Rege, T.N. Gutierrez, L. Vanni, D. Stilmant, E. Benetto, A return on experience from the application of agent-based simulations coupled with life cycle assessment to model agricultural processes, J. Clean. Prod. 142 (2017) 1539–1551.
[47] J. Robins, S. Bogen, A. Francis, A. Westhoek, A. Kanarek, S. Lenhart, S. Eda, Agent-based model for Johne's disease dynamics in a dairy herd, Vet. Res. 46 (2015) 68.
[48] E. Dion, L. VanSchalkwyk, E.F. Lambin, The landscape epidemiology of foot-and-mouth disease in South Africa: A spatially explicit multi-agent simulation, Ecol. Model. 222 (2011) 2059–2072.
[49] H. Kim, N. Xiao, M. Moritz, R. Garabed, L.W. Pomeroy, Simulating the transmission of foot-and-mouth disease among mobile herds in the far north region, Cameroon, J. Artif. Soc. Soc. Simul. 19 (2016).
[50] C.W. Ross, R.J. Glass, J. Harger, S.H. Conrad, A.A. Zagonel, W.E. Beyeler, M. Finley, Development of an agent-based epidemiological model of beef cattle, in: The 19th International Conference of the System Dynamics Society, 2011.
[51] A. Moustakas, M.R. Evans, Coupling models of cattle and farms with models of badgers for predicting the dynamics of bovine tuberculosis (TB), Stoch. Environ. Res. Risk Assess. 29 (2015) 623–635.
[52] H. Liu, P. Schumm, A. Lyubinin, C. Scoglio, Epirur_cattle: A spatially explicit agent-based simulator of beef cattle movements, Procedia Comput. Sci. 9 (2012) 857–865.
[53] S. Rasch, T. Heckelei, R. Oomen, C. Naumann, Cooperation and collapse in a communal livestock production SES model–a case from South Africa, Environ. Model. Softw. 75 (2016) 402–413.
[54] A.M. Bate, G. Jones, A. Kleczkowski, R. Naylor, J. Timmis, P.C. White, J. Touza, Livestock disease management for trading across different regulatory regimes, EcoHealth (2018) 1–15, https://doi.org/10.1007/s10393-018-1312-y.
[55] M. Schouten, T. Verwaart, W. Heijman, Comparing two sensitivity analysis approaches for two scenarios with a spatially explicit rural agent-based model, Environ. Model. Softw. 54 (2014) 196–210.
[56] A. Romera, S. Morris, J. Hodgson, W. Stirling, S. Woodward, A model for simulating rule-based management of cow–calf systems, Comput. Electron. Agric. 42 (2004) 67–86.
[57] C.A. Aktipis, L. Cronk, R. de Aguiar, Risk-pooling and herd survival: An agent-based model of a Maasai gift-giving system, Human Ecol. 39 (2011) 131–140.
[58] M. Schouten, P. Opdam, N. Polman, E. Westerhof, Resilience-based governance in rural landscapes: Experiments with agri-environment schemes using a spatially explicit agent-based model, Land Use Policy 30 (2013) 934–943.
[59] K.E. Jablonski, R.B. Boone, P.J. Meiman, An agent-based model of cattle grazing toxic Geyer's larkspur, PLoS One 13 (2018) e0194450.
[60] S. Abar, G.K. Theodoropoulos, P. Lemarinier, G.M. O'Hare, Agent based modelling and simulation tools: A review of the state-of-art software, Comput. Sci. Rev. 24 (2017) 13–33.
[61] R.L. Larson, B.J. White, Reproductive systems for North American beef cattle herds, Vet. Clin. : Food Animal Pract. 32 (2016) 249–266.
[62] Beef Feedlot Industry Manual, The Foreign Animal Disease Preparedness and Response Plan, United States Department of Agriculture, Animal and Plant Health Inspection Service, Center for Food Security and Public Health, 2011.
[63] Federal Motor Carrier Safety Administration, Summary of Hours of Service Regulations, 2017.
[64] S.A. DeLoach, J.C. Garcia-Ojeda, O-MaSE: A customisable approach to designing and building complex, adaptive multi-agent systems, Int. J. Agent-Oriented Softw. Eng. 4 (2010) 244–280.
[65] S.A. DeLoach, OMACS: A framework for adaptive, complex systems, in: Handbook of Research on Multi-Agent Systems: Semantics and Dynamics of Organizational Models, IGI Global, 2009, pp. 76–104.