

Evaluating Producer Selection Policies in Intermediated Regional Food Distribution Systems: An Agent-Based Approach

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Abstract. The recent increase in demand for regionally-produced food has resulted in a need for more efficient distribution methods. To connect regional food producers and consumers, intermediated regional food supply networks have developed. The intermediary, known as a regional food hub, serves as an aggregation point for products and information and may also act as a filter to ensure that the requirements of both producers and consumers are consistently met. This paper describes an empirically-based agent-based model of a regional food network in central Iowa that is intermediated by a food hub. The model was used to test a variety of producer selection policies that could be implemented by the food hub manager to improve operations. Results indicate that policies that protect producers from competition may have negative consequences for consumer satisfaction.

1 Introduction

The modern industrial food system feeds six billion people, an accomplishment that is mainly a consequence of the increased yields resulting from inputs of synthetic fertilizers, irrigation, pesticides, new crop strains, and other technologies [1]. However, this productivity comes at a price. There are many negative externalities associated with industrial food supply chains, including toxic releases into the environment (e.g., greenhouse gases and pollution due to pesticide and nutrient runoff) and an unsustainable rate of energy and water consumption [2]. These problems stress the very inputs to the system that enable its productivity, raising concerns about relying on such a system in the long term.

By contrast, localized food systems, which reduce the number of intermediaries and geographic distance between producers and consumers, can reduce the energy and ecological costs of long-distance transportation while redistributing value along the supply chain [3]. Such systems may also enable consumers to demand greater producer accountability for ecological degradation [4]. Consumers are increasingly choosing food that is produced locally and sustainably over food from the conventional food system. Their reasons vary widely, from saving money, to wanting

to ensure food nutrition, quality, freshness, and safety, to concerns over environmental implications and the treatment of farm workers, to a desire to support the local economy and have a connection with the person who produced their food [5]. Because of this, the local food movement has grown tremendously in the past decade, with direct-to-consumer food sales in the U.S. increasing three-fold from 1992 to 2007 (from \$404 million to \$1.2 billion) [6]. Interest in supporting local food systems is also rising among policymakers, who are incorporating local foods into programs designed to reduce food insecurity, support small farmers and rural economies, encourage more healthful eating habits, and foster closer connections between farmers and consumers [7].

This increased demand has been beneficial for small- and medium-scale food producers. Traditionally, the most common market channels for these producers have been direct-to-consumer, via farmers' markets. Producers typically get better prices at farmers' market than through wholesale outlets [8], and they are ideal venues for producers who have limited quantities of a large variety of products. However, these farmers' markets are labor-intensive and are not always profitable, due to low sales volumes, competition from multiple sellers, and high transportation and marketing costs [6,9]. To avoid the challenges associated with direct-to-consumer sales, many small- and medium-scale producers would prefer to sell to larger-scale customers (e.g., grocery stores, restaurants, schools), either directly or through a distributor.

However, the structure of conventional industrial food systems is not conducive to localized distribution. In particular, the participants highly value economies of scale. Institutional buyers tend to aggregate their purchases for logistical convenience, and distributors provide them with incentives for meeting specified purchasing volumes [10]. Medium- and small-sized producers struggle to participate within this system because they lack the necessary scale to satisfy large-scale distributor volume, quality, consistency, variety, availability, and price point requirements [11]. One potential solution to this problem is the development of regional food hubs. The current USDA working definition of a food hub is "a centrally located facility with a business management structure facilitating the aggregation, storage, processing, distribution, and/or marketing of locally/regionally-produced food products" [12]. A regional food hub provides small- and medium-scale food producers an alternative to direct-to-consumer sales, in which the aggregated output of many smaller farmers is large and consistent enough to fulfill the needs of larger institutional customers. In addition to providing a market for smaller farmers, a food hub can often command higher prices than large-scale commodity distribution, because it offers customers higher value associated with regionally-produced, "identity-preserved" food [13]. This often changes the role of the small-to-medium-sized farmer from 'price-taker' to 'price-maker'. However, sufficient producer participation is critical to a regional food hub's long-term success and economic sustainability. Successful hubs are typically those that are able to gross sales of \$2 million or more (sourcing from at least 40–60 suppliers), carry a variety of different products, and provide year-round operations [12].

To gain an increased understanding of the preferences, drivers, attributes, and behaviors of food hub participants, as well as the factors that encourage/discourage consumers and producers to participate in the system over time, an empirical investigation of an intermediated regional food system in central Iowa was performed.

The food hub in this system operates as an online grocery store: in a distribution cycle, each producer-member uploads information about his available products onto a website. This information is shared with consumer-members, who select and purchase items from the website. Producers then deliver these items to a central distribution center, where products are sorted for transport to various secondary distribution sites throughout central Iowa. Consumers then travel to the site nearest to them to pick up their orders. To remain economically viable, the food hub charges its members a fee for this service. However, supporting small-scale Iowa producers is also a critical component of the hub's mission. Therefore, the food hub manager encourages small producers to participate, although this increases the number of transactions the hub must broker. The manager is also mindful of the number of producers in each product category, with an aim toward avoiding too much competition and unsustainable prices. The food hub also tries to promote greater consumer access to regional food by seeking to provide a range of price points. There are often tradeoffs between supporting producer and consumer members, which can be challenging for the food hub to successfully manage.

Twenty-two consumer-members of this food hub were interviewed to ascertain the reasons that they shopped for food through the hub. For each of 14 different values, consumers responded on a 5-point Likert scale to describe the level of importance of each of the values in determining their participation with the food hub. Their responses to these were statistically analyzed (using cluster analysis) to enable categorization of consumers into four different personas: Locavores, Pragmatists, Frugalists, and Idealists. These personas and other data obtained from the study were used to inform the development of an agent-based model (ABM) of the system and to serve as inputs to the model. The model was used to demonstrate the value of representing the consumers as persona-based agents, as described in [14].

This paper describes a revised version of the ABM, in which a food hub manager agent acts as a centralized control for the system. This version of the model can be used to explore the impacts of different management strategies on the food hub's performance. In particular, the Iowa food hub manager would like to know what types of supplier selection policies he should employ (if any). The manager's current policy is to allow any producer in Iowa who wishes to sell food through the food hub to do so. The manager then relies on the consumers to determine whether a producer may continue to participate: if a producer's prices are too high, or if their products are of poor quality, or if there is insufficient demand for their product, they will make few sales. Such producers will typically either try to improve their offerings, or they will cancel their membership. Thus, producer selection at the food hub is a decentralized process, in which the overall makeup of food hub's producers at any point in time is an emergent property resulting from competition among the producers.

However, the food hub manager suspects that if he intervenes via appropriate producer selection policies, he may be able to increase his consumers' satisfaction by only allowing in those producers that are most likely to meet their needs. He may also be able to improve the well-being of his producers by preventing an oversupply of any given type of food, thereby keeping competition among producers reasonable and prices sufficiently high. The question addressed in this paper is: what producer selection policies should the manager implement to best support the food hub's objectives?

2 Model Description

In this section, the agents that inhabit the empirically-based ABM of the central Iowa regional food system (producers, consumers, food hub manager) are described, and an overview of the model and its constituent sub-models is provided.

2.1 Agents

Producer agents are characterized by eleven parameters, each of which governs how the agent is evaluated by consumers and/or how it makes its decisions. Table 1 lists these parameters and the possible values they can take on. The values that are assigned to a producer for each of these parameters represent innate characteristics that are fixed throughout the duration of the simulation run.

Table 1. The eleven parameters/values that characterize producer agents.

Producer Parameter	Possible Values
Maximum Production Capacity	50 units/cycle
	100 units/cycle
	150 units/cycle
Remaining Inventory Threshold	70%
	80%
	90%
Price	low
	medium
	high
Ease Of Food Preparation	low
	medium
	high
Food Nutritional Content	low
	medium
	high
Food Freshness Issues	1% chance
	5% chance
Distance From Food Hub	≤ 20 miles
	20-40 miles
	> 40 miles
Reliability Issues	1% chance
	5% chance
Production Practices	insufficient information
	conventional
	chemical-free
	certified organic
Food Safety Issues	0.1% chance
	0.5% chance
Treatment Of Animals	no certification
	certified humane

Consumer agents are described by three parameters: their persona, their demand category, and their food familiarity level. Based on the results of the interviews with food hub consumer members, the probability of the generation of a consumer agent having a given persona in the model was 54%, 23%, 5%, and 18% for being Locavores, Pragmatists, Frugalists, and Idealists, respectively. The average Likert value from the human subject data was established for each of the 14 values for each of the four personas. Each of these values was scaled from 0 to 1, where 1 indicates a strong preference for the given value, and 0 indicates very little interest in that particular value. These values are given in Table 2.

Table 2. Consumer agent persona preference values for food hub and producer parameters.

Value Persona	Variety	Buy Convenience	Price	Preparation Convenience	Nutrition	Freshness	Familiarity	Novelty	Distance	Relationship	Reliability	Production	Safety	Treatment Of Animals
Locavore	.700	.700	.633	.367	.917	1.0	.650	.467	1.0	.717	.817	.950	.983	.917
Pragmatist	.720	.680	.560	.640	.840	.880	.480	.560	.720	.480	.560	.720	1.0	.800
Frugalist	.200	.600	1.0	.600	1.0	.800	.800	.400	1.0	.600	.800	.800	.600	.400
Idealist	1.0	.860	.700	.750	1.0	1.0	.650	.850	1.0	.950	.950	1.0	1.0	1.0

Consumer agents are also characterized by a utility value, which is a measure of the consumer's satisfaction at any point in time. The higher a consumer's overall utility value is, the more likely he is to engage in commerce with the food hub in a given cycle, which influences his membership status. Utility values are scaled from zero to one, with zero being the least-preferred value and one the most-preferred. The direction of preference for these utility distributions tends to be intuitive – consumers prefer low prices, highly nutritious/fresh/safe food, etc.

The model also contains a single food hub manager agent that assesses relative supply and demand levels at the end of each distribution cycle. He can then use this information to determine whether or not to allow new producer agents to become members of the hub.

2.2 Model Overview

The model contains producer and consumer agents that trade six different categories of food, using the food hub as an intermediary. Each producer agent produces and sells one of the six product categories to consumers through the food hub. Each time the model generates a producer agent, there is a fixed probability that the agent will be assigned to particular category (e.g., there is a 25% chance that it will be a meat producer), based on historical data from a real-life food hub. It is assumed that a producer agent may only provide items in a single category, which is typically case in the real regional food system and supported by the producers interviews.

Each simulated time-step represents a distribution cycle by the food hub, which occurs approximately every two weeks throughout the year, for a total of 22 cycles

per year. Producers and consumers can be in one of three different membership states with respect to the food hub: non-member, member, or canceled member. Agent interactions are confined to producer-consumer transactions. It is assumed that consumers do not interact with one another directly, and neither do producers.

The model consists of five major sub-models: initialization, consumer purchase decisions, consumer evaluation and status update, producer evaluation and status update, and food hub membership update. The initialization sub-model is only run once, at the start of each simulation run. The other four sub-models are executed sequentially in every time-step.

Initialization. The model is initialized with 30 producer agents, each of which is assigned parameter values based on the probabilities determined from the interviews data, system data, and assumptions. Each producer is initialized with 100% of its yield available for sale through the food hub. 50 consumer agents are created, each of which is assigned a demand category (i.e., low, medium, high), a food familiarity category, and a persona. Each consumer's producer ratings matrix is initialized with producer attribute values for each of the producer agents in the model. Consumer overall utility is initialized to 1.00 (the maximum value), and food hub membership status for all consumers and producers is set to "member".

Consumer Purchase Decisions. Each consumer who is currently a food hub member checks its overall utility value: if the value is greater than 0.70, then the consumer decides to participate in purchasing; if the value is less than 0.70, the probability that the consumer decides to participate corresponds to its utility value. If it decides to purchase from the food hub, it is assumed that it will try to fill as much as its demand as possible via the food hub. Consumers who have decided to participate are selected in random order to make their purchases from participating producers. Each consumer first assesses its demand in each product category. Then, it seeks out producers that have inventory available in each product category. As a consumer successfully purchases items from producers in each cycle, the consumer's demand for that item is reduced. It is assumed that demand that goes unfilled by the food hub will be filled by other exogenous sources (i.e., there is no demand backlog from one time-step to the next). After a consumer completes a transaction with a producer, it will update the parameter values in its producer ratings vector for that producer. If the consumer is unable to find any producers with inventory in a product category, its overall utility will be reduced by 0.05, and it will move on to the next category. If the consumer finds a producer(s) with inventory, but this inventory is insufficient to completely fill its demand, its utility will be reduced by 0.01. If the consumer's demand is completely satisfied, its utility will increase by 0.01.

The consumer will then assess each of the available producers with respect to its values, using the producer ratings vectors. It then ranks each of these producers by the total value it provides him. It then selects the producer with the highest rank and purchases either enough of the producer's inventory to fill its demand or all of the producer's inventory (whichever is larger). If it has any unfilled demand, it will move on to the next ranked producer and will purchase as much as available/needed from him, and so on. After each interaction with a producer, the consumer will update its producer ratings vector for that producer. The consumer will continue this process for each of the remaining five product categories.

Consumer Evaluation and Status Update. After all consumer agents are finished purchasing food, each consumer will evaluate its overall utility with the food hub, which is based on its previous transactions. If a consumer's overall utility falls below a threshold value of 0.10 (out of 1.00), or if the consumer observes that it has participated with the food hub fewer than four times out of the previous eleven distribution cycles, it will change its membership status to "canceled member" and will no longer participate in transactions with the food hub.

Producer Evaluation and Status Update. A producer makes one key decision in each distribution cycle: what percentage of its production capacity to sell to consumers via the food hub. Throughout the simulation, the percentage of production capacity that a producer allocates to the food hub (rather than to other market channels, such as farmers' markets) may vary over time, according to how well the producer's products have sold through the food hub in previous distribution cycles. This update defines the producer's degree of participation with the food hub and depends on the producer's upper threshold for unsold inventory ratios. The unsold inventory ratio is simply the amount of inventory (in food units) that a producer has left at the end of a cycle, divided by the total number of units that it offered to consumers through the food hub at the beginning of the cycle. If this ratio is equal to zero (i.e., it sold the entire available inventory), then in the next cycle the producer will increase its offerings by 10% (up to its capacity). If this ratio is greater than the producer's upper threshold for unsold inventory, it will calculate a weighted average of the ratio of number of items sold to capacity, over the three most recent cycles and will change the percentage of capacity that it offers through the food hub in the next time-step to that average value. If the ratio is greater than zero but less than the upper threshold value, the number of units that the producer offers through the food hub in the next time-step will remain unchanged. It is assumed that if a producer's participation drops to less than 10% of its capacity at any point in time, that producer will no longer participate with the food hub for the duration of the simulation run (i.e., its status will become "canceled member").

Food Hub Membership Update. In each cycle, new producer and consumer agents are generated and are initialized as members of the food hub. It is assumed that new consumer agents are created at a constant rate of two consumers per cycle. A new producer agent is created in every other cycle, on average. These rates approximate the actual rates at which new producer and consumer members joined the real-life food hub, based on food hub historical data.

3 Experimentation and Results

To assess the value of implementing various different producer selection policies, the food hub manager agent may choose to intervene during the "Food Hub Membership Update" sub-model execution. To execute a given selection policy, when a producer agent is created and attempts to join the food hub, the manager will determine the producer's attributes, assess how well these attributes fit the needs of the food hub and its consumers, and based on this assessment, decides whether or not to allow the producer to join the food hub.

3.1 Experimental Scenarios

Five different experimental scenarios were run to test the impact of having the food hub manager intervene in the selection of producers:

1. *No centralized management of supplier selection*: This scenario represents the status quo – any producers who wish to join the food hub are allowed to join.
2. *Supplier selection – balancing supply and demand*: In this scenario, when a producer attempts to join the food hub, the manager will assess total system supply and demand levels from the previous distribution cycle for the candidate producer's product type. If the supply of that food type in the previous cycle was less than 120% of the demand (allowing for future growth), then the manager will allow the producer to join; otherwise, the producer is removed from the system.
3. *Supplier selection – accounting for producer size*: In this scenario, the manager evaluates a producer in terms of system supply and demand (as in Scenario 2), but he makes exceptions for small-sized producers. That is, if a small dairy producer requests membership, even if the food hub's supply of dairy items from other producers is already much greater than existing demand, the manager will make an exception to the policy and will allow that producer to join. This policy reflects the food hub's socially-responsible imperative to support small-scale regional producers.
4. *Supplier selection – accounting for producer price level*: This scenario is similar to Scenario 3, but here the manager will make an exception for producers who are at a low price level; i.e., such producers will be allowed to join even if supply-demand ratio of their food type is greater than 120%. This scenario does not reflect current practices at the Iowa food hub but serves as a "what-if" experiment to determine what would happen to the system if the food hub decided to place a greater emphasis on improving access for low-income consumers.
5. *Supplier selection – accounting for producer size and price*: This scenario combines Scenarios 2, 3, and 4, such that the manager's selection policy is very generous – he will only restrict producer membership if the candidate producer is medium/high size and/or price and the supply for that producer's product type is greater than 120% of demand.

100 replications were run for each of the five scenarios. The length of each replication was 110 time-steps (i.e., distribution cycles), which represents five years of system operation at 22 distribution cycles per year. The food hub manager has two primary objectives: maximizing food hub revenues while providing support and economic opportunities for regional producers. To reflect this, the following six output metrics were captured at the end of each time-step:

- Total food units sold through the food hub
- Total number of consumer agents participating
- Total number of producer agents participating
- Average "age" of participating producer and consumer agents
- Average producer size level
- Average producer price level

3.2 Results

The model output for each of the five experimental scenarios was analyzed statistically to measure the impact of the various supplier selection strategies on the output metrics of interest. The results of this analysis are divided into two overall categories: consumer metrics and producer metrics.

Figure 1 shows a 95% confidence interval plot on the mean values of total units sold at the end of 110 time-steps for each experimental scenario (where the labels on each interval correspond to the scenario number). The interval plots for the total number of participating consumer agents and the average consumer age in the final time-step have a very similar appearance to Figure 1. Although the average number of food units sold and the average number of participating consumers decreased when the food hub manager implemented a supplier selection policy based on balancing supply and demand (Scenario 2), the difference was not statistically significant from the status quo (Scenario 1). The average number of units sold was highest for the two selection policies that controlled for supply and demand but made exceptions for small-sized producers (Scenarios 3 and 5), but again, the difference was not statistically significant. The only significant difference that was observed was when comparing the size-based policies with the price-based policy: the price-based policy (Scenario 4) resulted in the lowest average volume of commerce, number of participating consumers, and consumer length of participation (i.e., “age”).

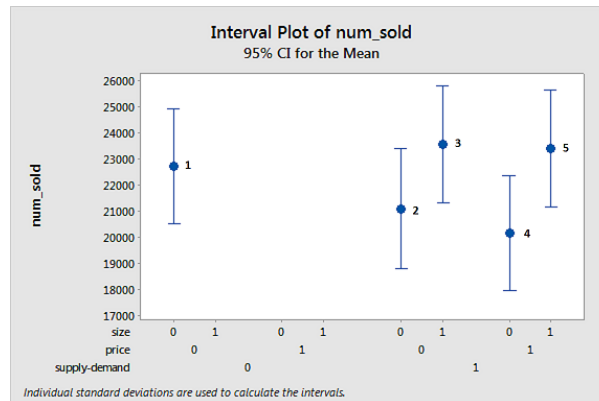


Fig. 1. 95% confidence interval plot on the mean total number of food units sold after 110 distribution cycles for each of the five experimental scenarios.

As Figure 2 shows, the average number of producers in the system at the end of a replication is significantly lower for Scenarios 2 and 4 than for Scenarios 1, 3, and 5. Figure 3 shows that the status quo (Scenario 1) yields the lowest average producer time in system (i.e., “age”), while the strictest selection policy (Scenario 2) results in the highest average value. Figure 4 indicates that, unsurprisingly, a price-based selection policy results in a significantly lower average producer price level. Interestingly, Scenario 1 yields the next lowest price level, without relying on any explicit pricing controls.

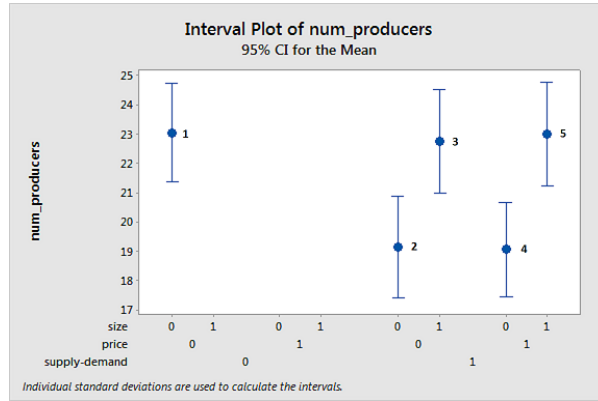


Fig. 2. Interval plot of the mean number of producers in the final time-step for each scenario.

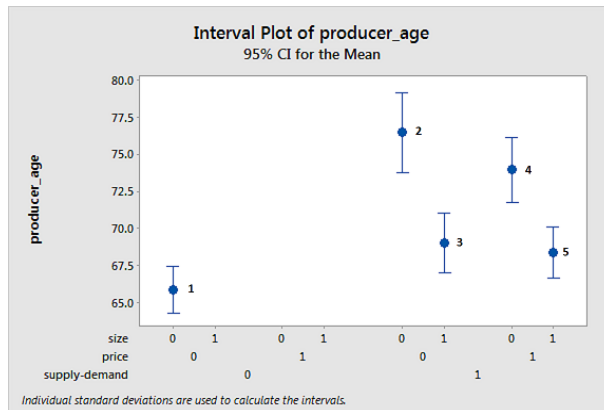


Fig. 3. Interval plot of the average producer age in the final time-step for each scenario.

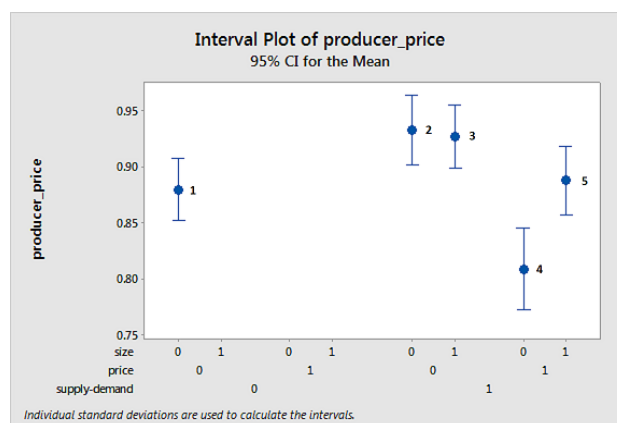


Fig. 4. Interval plot of the average producer price level in the final time-step for each scenario.

4 Discussion

The results of these experiments suggest that the food hub manager can manage his supply base in any way he chooses, and it won't affect consumer participation significantly, although implementing a selection policy that controls for supply and demand but makes exceptions for low-price producers (Scenario 4) leads to slightly lower consumer participation. This reflects the real-life food hub consumers' general price insensitivity, as well as the real-life producers' pricing attributes – most of them are not low-cost producers. However, selection policies do have a significant impact on the producer metrics. When the manager selects producers based on overall supply-demand ratios and does not make exceptions for small-sized producers, there are fewer producers in the system, and these producers stay in the system longer.

The most interesting outcome of these experiments involves the tradeoff between protecting producers and meeting the needs of the consumers. Comparing the status quo (Scenario 1) with the unmodified supply-demand selection policy (Scenario 2), the average values for both the price and size categories across all producers is lower in the no-management scenario, which is a result that is preferred by consumers. Scenario 1 also has a greater average number of participating producers, indicating that the food hub is “sharing the wealth” over a greater number of producers. However, the average length of participation per producer is much higher in Scenario 2. These results suggest that the food hub manager's loyalty to currently participating producers protects them from healthy competition and prohibits consumer preferences from being expressed (i.e., lower prices and more and smaller producers). The food hub manager must decide if, in his efforts to support producers, he wants to fully support a few producers, or partially support many producers and allow for some competition among them. Although the modification to the selection policy to encourage small-sized producers (Scenario 3) does indeed reduce the average participating producer size and slightly increases consumer participation and average producer participation length, these gains are so small that the food hub manager should question whether it is worthwhile implementing such a policy, particularly because the total number of participating producers is no greater than in the no-management scenario.

5 Conclusion

This paper described an empirically-based ABM of an intermediated regional food system in central Iowa, in which system success relies upon the achievement of potentially conflicting social and economic objectives and the careful balance of meeting both producer and consumer requirements. The experiments described in this paper show how ABM can be used to capture the effects of different producer selection policies on regional food hub consumer and producer participation. The results of these experiments suggest that centralized control via management policies can lead to desired outcomes, but such policies can also have unintended (and sometimes undesirable) consequences for system behavior.

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