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A vector-borne contamination model to assess food-borne outbreak intervention strategies

Jessye Talley[a], Lauren B. Davis[b,*], Benjamin Morin[c], Liping Liu[d]

[a] Department of Industrial & Systems Engineering, Morgan State University, 1700 East Cold Spring Lane Baltimore, MD 21251, USA
[b] Department of Industrial & Systems Engineering, North Carolina Agricultural & Technical State University, 1601 East Market St. Greensboro, NC 27411, USA
[c] Department of Mathematics and Statistics, Vassar College, 124 Raymond Avenue, Box 257, Poughkeepsie, NY 12604, USA
[d] Department of Mathematics, North Carolina Agricultural & Technical State University, 1601 East Market St. Greensboro, NC 27411, USA

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ABSTRACT

Food-borne illness occurs through the consumption of food that has been tainted at some point in the food supply chain. While most contamination is accidental, there is some evidence of intentional food adulteration. This study explores the relationship between food safety practices and consumer behavior in a two-stage food supply chain. We use a vector-borne model to represent the spread of contaminated food through the supply chain. Based on our computational study,we determine the number of consumers that become ill as a result of a contamination event, describe the effect of consumer consumption and purchase behavior on the spread of food-borne illness, and evaluate the effects of various intervention strategies on consumer illness.

1. Introduction

Food-borne illness affects one in six consumers annually within the United States often resulting in hospitalizations and deaths [1]. These illnesses are caused by toxins or pathogens that enter the body through contaminated food or beverages. Food contamination can occur either with intent to harm or unintentionally based on human error. There are three categories of contaminants that cause food outbreaks: (1) bacterial, (2) chemical, and (3) physical. Bacterial contaminants (e.g salmonella or E.coli) are the most common; these are present when workers do not handle food properly, when food is set at dangerous temperatures that allow toxins to grow, and when consumers lack food preparation skills. Chemical contaminants (e.g ethylene glycol) are found in everyday products that may be readily available for purchase or can be introduced during growth of the food product (i.e. on farm). Physical contaminants (e.g. metal parts or insects) are found during the production phase when food products are packaged. Since there are multiple ways contamination can occur, it is important to track contamination events within the food supply chain in order to prevent consumer risks.

Many cases of food contamination occur during the production, distribution and consumer stages. Table 1 provides examples of contamination at each stage [2–4] focusing on a select release location, agent, and food product. The release location ranges from a processing plant to an actual distribution channel such as a restaurant. According to the Centers for Disease Control (CDC), between 2009 and 2010, approximately 48% of outbreaks were linked to food consumption at restaurants,

* Corresponding author.
E-mail addresses: jessye.bemleytalley@morgan.edu (J. Talley), lbdavis@ncat.edu (L.B. Davis), bmorin@vassar.edu (B. Morin), lliu@ncat.edu (L. Liu).

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Table 1
Food contamination at different supply chain stages.

Year	Stage	Release location	Agent	Food product type
1996	Production	Processing plant	Various	Meat
1994	Distribution	Tanker truck	Salmonella	Ice cream
1984	Consumer	Restaurant	Salmonella	Salad

whereas 21% occurred at an individual's home. These agents were mostly bacterial; however, chemical contamination can occur. Each of these scenarios demonstrate how the supply chain is vulnerable to leaving consumers at risk for becoming ill, promoting the need for mitigation or intervention strategies.

It is important to have strategies and tools that keep products safe when purchased by the end consumer as the food supply chain continues to grow globally. Intervention strategies allow companies to control the spread of contaminated products to the consumer. Many companies use a recall process for food contamination events that allows food organizations to determine both the cause of the toxin and how many people have already developed symptoms due to ingestion of the product. However, the guidelines indicating the best time to implement this strategy are not clearly defined.

This paper proposes a methodology for determining the number of consumer illnesses and contaminated food products at both the manufacturer and retailer. Specifically we consider a dairy food (i.e. milk) product that is processed at the manufacturer and sent to grocery stores. We use a deterministic vector-borne model in order to illustrate the progression of the human and food population through different supply chain stages given a food contamination event. We implement a set of controls showing the effects of the recall and inspection processes and perform sensitivity analysis to demonstrate the effects of purchasing and consumption behavior on the human and food populations. Food safety and food defense stakeholders can gain the following insights from this model: (1) track the amount of safe and contaminated food products that are produced and sent to a distribution channel; (2) quantify the number of consumers who become ill after purchasing a contaminated food product; and (3) understand the effects of intervention strategies on the production and distribution phase during a contamination event. The results from this model shows the impact of consumer behavior, specifically consumption and purchasing in relation to the number of customer illnesses which gives insight into the best control strategy to use during a contamination event.

The remainder of this paper is organized as follows. Section 2 discusses the literature related to models quantifying risk and consequences associated with the consumer, showing the contribution of this study. Section 3 provides the methodologies used to model the interaction of the consumer with contaminated food. Section 4 summarizes the parameters and data used for the experimental design. Section 5 provides results for the vector-borne model. Section 6 gives conclusions and directions for future work.

2. Literature review

We examine the existing literature from two perspectives. First, we discuss prior studies in food supply chain risk management with emphasis on models quantifying the risk of food-borne outbreaks and evaluating the efficacy of various interventions at the manufacturing stage of the supply chain. Second, we discuss a summary of epidemic and compartment models in order to provide the proper context and background for our model as well as position our research contribution.

2.1. Food supply chains

2.1.1. Supply chain structure

The food supply chain literature focuses on certain characteristics such as quality, safety, efficiency, food products, and food processes [5]. Chebolu-Subramanian and Gaukler [6] propose an analytical model (which is validated through simulation) to study the origins and modes of detection for contamination on various food supply chain designs where illness has already occurred. Chen et al. [7] consider a decentralized and centralized supply chain structure that models quality control using various sampling strategies. These strategies allow them to determine the total supply chain costs. Buchanan and Appel [8] discuss the integration of analysis and mathematical models in order to enhance the information used by risk managers when meeting regulatory requirements for food safety and defense. As food supply chains gain more stakeholders and grow globally there is a need for increased product safety and security [9].

2.1.2. Interventions

The food protection plan lists intervention as one of its core elements. Interventions refers to inspections, sampling, and surveillance within the supply chain. Many researchers develop models that focus on control strategies related to public health measures for diseases and food. These models are briefly described in the subsequent paragraph.

Liu and Wein [10] develop a differential equation model that implements antibiotic residue testing for trucks after an outbreak occurs. With testing, the number of people affected is reduced to half for one strategy. The other strategy when used in isolation prevents even more people from becoming ill. Liu and Wein [11] consider detection after a certain amount