2013

Are We Sick Yet: Assessing Consumer Mortality From Food Contamination In Multiple Distribution Channels

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ARE WE SICK YET: Assessing Consumer Mortality from Food Contamination in Multiple Distribution Channels

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department: Industrial & Systems Engineering

Major: Industrial & Systems Engineering

Major Professor: Dr. Lauren Davis

Greensboro, North Carolina

2013

School of Graduate Studies
North Carolina Agricultural and Technical State University
This is to certify that the Master's Thesis of

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has met the thesis requirements of
North Carolina Agricultural and Technical State University

Greensboro, North Carolina
2013

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Dedication

This work is dedicated to all of the families that make me who I am: Ware, Teasley, Thomas, & Williams. To my immediate family: William, Barbara, & Ashley Teasley. To the friends that have become my family which includes the love of my life, Melvin Heggie II. To the many individuals that have been dedicated to my educational success and personal development throughout my lifetime. To my fellow students that have encouraged me on this journey. I appreciate the work that has been done in my favor by the almighty God, to whom I will continue to serve in all things.

Acknowledgements

I would like to express my sincere gratitude to my advisor Dr. Lauren Davis for her continued support, guidance, patience and most of all her high expectations. Her influence has been indispensable to my growth and development. In addition to my advisor, I would also like to acknowledge my committee members: Dr. Stephanie Luster-Teasley and Dr. Alan Erera. I certainly value your insight and appreciate your expertise. The National Center for Food Protection and Defense should be recognized for their dedication to food safety and their support of student research.

The material is based on work supported by the U.S. Department of Homeland Security under the Summer Research Team for Minority Serving Institutions and the National Center for Food Protection and Defense. Disclaimer: the views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies either expressed or implied of the U.S. Department of Homeland Security.

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Abstract

According to the Center for Disease Control approximately 48 million people get sick from food-borne illnesses per year. In 2011, about 80% of illnesses were triggered by unspecified agents transmitted through food. Food contaminations put customers at risk and can be detrimental to the economy since customers rely on the fact that the food system is reliable and resilient. This research aims to compare the vulnerabilities of three food supply chain distribution channels: food retail, food service and food manufacturing. Distribution channels are the last nodes in the supply chain and they dictate how many people interact with contaminated products. This study will evaluate how many people are exposed to illness from an intentional chemical contamination. A discrete time Markov Chain with rewards model is developed to estimate the number of individuals to become ill given a successful attack on the food system. The model incorporates information on purchasing behavior, product shelf life, and the relationship between individual contaminant consumption and illness. Preliminary results show that more customers are expected to experience illness when purchasing from food retail and food service locations. However, food manufacturing has the shortest time frame for imposing an intervention to prevent further illness.

The proposed research has the potential to provide insight into timely interventions and influence how intervention policies would need to be tailored to each distribution channel in the event that a chemical contamination occurs.

CHAPTER 1

Introduction

1.1 Background

Americans unconsciously depend on the fact that the United States food system is reliable and robust. To ensure the safety of individuals, the integrity of the food system must be protected and defended against detrimental outbreaks. Food protection is aimed at reducing the exposure to potential risks such as natural hazards, human errors or system failures in the food system. Food defense is intended to reduce the impact of an attack on the system. The Department of Homeland Security has introduced several programs to protect and defend the national food system. One such program is the National Center for Food Protection and Defense which has several research and education program goals. The first goal is to reduce the potential for contamination at any point along a food supply chain. In the event that an outbreak occurs, the second goal is to alleviate potential public health concerns, economic disruption, and business loss.

One immediate health concern is the amount of people who become ill and possibly die from food contamination. An estimated 48 million people get sick from food poisoning every year according to a report released by the Centers for Disease Control in December of 2010 (Winerman, 2012). In 2011, 47.8 million foodborne illnesses, hospitalizations, and deaths occurred. The report also indicates that about 20 percent of the foodborne illnesses in the United States are caused by “known pathogens” such as Salmonella and E. coli. However, 80 percent of cases are related to “unspecified agents”.

1.2 Motivation

Known or unknown pathogens can be the result of both unintentional and intentional attacks. For instance, in 1984 followers of a Rajneesh movement attempted to poison a large amount of people in order to gain a competitive advantage in upcoming voting elections. During a trial run of their plan, salmonella was used to contaminate 10 salad bars in the Antelope area of Oregon. As a result 751 people became ill and 45 were hospitalized between August and October of that year (Mohtadi & Murshid, 2009). This is an example of an intentional attack. In contrast, an investigation by the Food and Drug Administration into a salmonella outbreak related to peanut butter, concluded in November 2012. In this case 42 individuals from 20 states were infected but the incidence was considered to be an unintentional attack. Manufacturing and testing practices of a supplier, Sunland Inc. led to contaminated peanut butter being distributed to Trader Joe's (FDA, 2013). There are millions of food and toxin combinations that can threaten the food supply. Research in food safety is typically focused on a small selection of product/toxin combinations (Liu & Wein, 2008).

It has been established that certain products are more at risk for intentional attacks on the food system than others: in particular, products in liquid form. Liquid products are produced in large batches, and the production process is relatively quick. Liquid egg products are more attractive than other liquids in general due to their versatility and perishability; they are used in various ways throughout the food system and must be consumed in a short time frame after opening. In addition, liquid eggs are distributed to customers from multiple distribution channels, increasing the number of people who could consume the product and be exposed to any type of contamination.

1.3 Research Scope

The objective of this research is to assess the vulnerability of the liquid egg supply chain. Vulnerability is quantified by the number of causalities that result from consumer purchases of contaminated products. It is assumed that the product is introduced through multiple distribution channels. A stochastic model is presented that incorporates consumer purchasing behavior, product shelf life, and a dose response relationship to assess consumer mortality.

The proposed model considers a number of variables including purchase demand, product shelf life, and a dose response relationship to assess consumer mortality. This study investigates several elements of food contamination: (1) product consumption and illness, (2) the effect of toxin concentration levels, (3) magnitude of an intentional contamination, and (4) vulnerabilities of the various distribution channels. Given the information gathered on liquid eggs and two contaminates ethylene glycol and potassium cyanide, this project seeks to address the following research questions:

RQ 1: What is the relationship between the quantity of product consumed and the risk of death?

RQ 2: How will the concentration of the toxin affect a consumer?

RQ 3: How many people are likely to develop symptoms given a certain amount of products are available from a food distribution channel?

RQ 4: What are the vulnerabilities associated with the different supply chain distribution channels in terms of the number of days it takes for all the products to be sold?

1.4 Thesis Overview

The remainder of this thesis is outlined as follows. The second chapter summarizes modeling approaches currently used to evaluate food contamination. Dose-response models used to evaluate the effect of a toxin on individuals is also discussed. Chapter three provides an

overview of the liquid egg supply chain and toxicology information about ethylene glycol and potassium cyanide. The fourth chapter gives an overview of the problem and describes the modeling approach and formulation. The fifth chapter discusses the experimental design developed in order to answer the research questions. The sixth chapter summarizes the results from a numerical study. The seventh chapter provides concluding remarks and outlines the future work.

CHAPTER 2

Literature Review

2.1 Introduction

This literature review chapter is divided into three sections. The first section explains quantitative risk assessment, an approach widely used to evaluate and manage risk. Several examples of risk assessments are provided for select food product and pathogen combinations. Dose-response is one element covered in risk assessment, which is highlighted in the second section. The third section describes the use of Markov chains in modeling an individual's progression from a disease free state to death. Each model is described in terms of their approach to identifying the number of people to become ill following a contamination or outbreak.

2.2 Quantitative Risk Assessment

2.2.1 Overview of quantitative risk assessment. Risk assessment is a scientific process to estimate the possibility and severity of risk. The Food and Agriculture Organization and World Health Organization (FAO/WHO) has outlined four key components of risk assessment: hazard identification, exposure assessment, hazard characterization, and risk characterization (World Health Organization; Food and Agriculture Organization of the United Nations, 2002). Hazard identification is a collection of information about the presence of a pathogen in a food product. Exposure assessment defines the paths through which a pathogen is introduced, distributed, and consumed. Hazard characterization converts the exposure of a pathogen into a health response in the consumer population. Risk characterization integrates the previous information to estimate risk to a population or type of consumer (Holcomb et al., 1999). Quantitative risk assessment is simplified from reality, but realistic assumptions are made in order to have a credible model. When there is a lack of quality data, Qualitative risk assessments

can be used. Both types can aid risk managers in policy decision-making or priority setting (Coleman & Marks, 1999).

Liu and Wein emphasize the abundance of agent-food combinations by which attackers can choose to infiltrate the food supply chain. It is noted that only a small number of the combinations are likely to cause a large number of casualties. Therefore, they suggest prioritizing all combinations and dedicating studies to the more eminently dangerous situations. Generalized models can be produced for the remaining possibilities (Liu & Wein, 2008).

2.2.2 Quantitative microbial risk assessment. Quantitative microbial risk assessment (QMRA) is a popular approach to managing food safety risks. QMRA models account for microbial growth and decline as well as capture the effect of the cooking process. Danyluk and Schaffner (2011) present a QMRA of E. Coli found on spinach from a 2006 outbreak. Four methods of contamination are reflected in the model: irrigation water, poultry manure, and two types of dairy manure. Thomas' approximation of most probable number (MPN) is used to estimate pathogen level per gram using data from the bags of tested spinach. The probability of illness of a particular dose is predicted by a beta Poisson model that specifies a mean population risk. A Monte Carlo simulation is performed in @RISK software to evaluate the growth of E.Coli under certain temperature conditions.

Liu and Wein (2008) develop a model to monitor a botulin toxin in milk as it moves through the various stages in a processing facility. It allows for growth of the botulin toxin throughout the supply chain through the use of either Gompertz or Baranyi-Roberts growth model. The mean number of casualties is calculated as a function of the mean amount of contaminated food. Consumption rate and mean and standard deviation for the distribution system are used as basic parameters in the model. These parameters are directly related to the

shelf life of the milk, however that measure is not explicitly quantified. The probability of infection is based on a dose-response log function which considers the ID_{50} dose of the toxin assuming that a person gets sick by consuming no less than his infectious dose. Each person has an incubation period prior to displaying symptoms, including the time it takes for such person to report illness and receive a medical diagnosis. Eventually a contamination is detected and actions are taken to prevent further consumption; it is assumed that all consumption is stopped after the detection occurs. Liu and Wien determine the number of casualties as a function of increasing amounts of contaminated food products using a Monte Carlo Simulation. This model attempts to estimate approximately how many people are at risk of exposure and the likelihood that the exposed person will become ill.

The number of potentially ill individuals is important to most risk assessments. People who become ill will eventually seek health care service and require medical attention. In this way, food contamination has a major effect on the public health system. Hartnett, Paoli and Schaffner (2009) create a simulation model of the public health system response to an intentional contamination. One major statement made within the model is that a certain number of cases of illness must be reported and confirmed before the public advisory can be released. In order for a case to be successfully confirmed several events must take place. First the food item must be contaminated and consumed over time. Afterwards, an individual can develop symptoms or remain asymptomatic for the duration of the model. Once a person develops symptoms they can choose to seek care from a healthcare professional or not. Healthcare professionals proceed with regular routine care for the patient and must initiate a formal investigation into what caused the illness. This entire process is captured in their simulation model.

Hartnett et al. (2009) models a dynamic discrete event simulation that captures all of the events that take place after contamination including the PHA response. The simulation is partitioned into three sections: exposure to contaminated food, geographic dispersion of individual exposures, and the response of the health care system. The first part of the model measures the rate of exposure of individuals to contaminated food over time using a modified Gompertz equation. The Gompertz curve reflects the consumption pattern over time. The exposure rates vary between products that are considered to have short shelf life, medium shelf life, frozen food, and stable shelf life. Geographical dispersion estimates a spatial pattern of expected exposure cases relative to the source of contamination. Probabilities are associated with each stage of the public health systems response which is then modeled as a discrete event simulation. The entire model was simulated in Arena software. The research showed that for certain short shelf life products, all the contaminated products were consumed before an advisory was released.

Liquid eggs are a short shelf life product that can be used to make stable shelf life products. Whiting and Buchanan (1997) develop a microbial risk assessment model for Salmonella contamination of pasteurized liquid eggs in mayonnaise. The first stage of their model evaluates the prevalence of Salmonella in the raw liquid egg ingredient. TBased on information collected about infectious flocks of birds and the percent of contaminated eggs laid, the probability a container of mayonnaise has salmonella is determined. The next stage of their assessment involves monitoring changes in cfu/g during food processing operations. CFU or colony forming unit is the aggregate unit used to measure the number of viable bacteria cells in a sample. Changes in cfu/g are affected by temperature; therefore the storage temperature and home storage temperature are included as factors into their model. In the next stage information

on consumption patterns is gathered. The amount of food consumed directly correlates to the number of pathogens ingested. The serving size of mayonnaise is estimated as 10g. The final stage was their dose-response assessment.

2.3 Dose Response Models

Dose-response (D-R) models examine the relationship between the exposure to a contaminant and an individual's bodily response to a certain dose. The D-R relationship can be for a specific effect where the amount of exposure is compared to the frequency of an outcome occurring (Teunis et al., 1996). A threshold level can be inferred from a chart plotting the number of bacteria ingested against the percent of the population that becomes infected at that level (Buchanan et al., 2000).

Holcomb et al. (1999) compare the use of six dose response models for microbial hazards. Log-normal, Log-logistic, Simple exponential, Flexible exponential, Beta-Poisson, and Weibull-Gamma are considered in the evaluation. Their findings suggest that there is limited ability to successfully account for low doses within a data set.

In order to circumvent the limitation of low-dose inaccuracies, Teunis et al. (1996) use experimental data at high doses to calibrate their model. Their model describes the number of infected cells on tobacco leaves and features four sequential events represented stochastically: pathogen ingestion, infection, illness, and death. The probability of exposure is Poisson distributed. The probability of infection is expressed using two different models: exponential and Beta Poisson. These models are used when the probability of an organism surviving and causing infection is not a constant. The probabilities for illness and death are multiplicative.

Buchanan et al. (2000) address the hypothesis that a threshold level of bacteria cells that must be ingested in order to cause an illness response in a human can be inferred geographically.

A chart plotting the number of bacteria ingested against the percent of the population that becomes infected is constructed. They consider an alternative where the ingestion of a single pathogenic bacterial cell has a finite possibility of causing an infection. Furthermore this probability increases as the level of the pathogen increases. This study explains the differences in five dose response models: exponential, Beta-Poisson, Weibull-Gamma, Weibull, and Gompertz. The exponential model considers that the probability of a cell causing infection is independent of dose. In contrast, Beta-Poisson assumes the opposite. The exponential and beta-Poisson models are viewed as special cases of Weibull models which can take on more shapes depending on the parameters. The Gompertz model has been used widely in predictive microbiology.

Mataragas et al. (2010) employ an exponential dose response equation to evaluate the probability of illness from deli meat contaminated with listeria monocytogenes. The model predicts illness for high risk populations only. The probability of illness is dependent on the dose and the likelihood of illness after consuming just one cell of the bacteria. The dose is calculated as a function of the serving size and the concentration of the pathogen. The probability of illness is then used along with other variables to determine the number of listeriosis cases per year. This research study also includes a Gompertz equation to calculate changes in the population.

2.4 Markov Chain and Early Disease Detection

Non-insulin dependent diabetes mellitus (NIDDM) is a disease prevalent in Taiwan. NIDDM leads to other illnesses and eventually death. There is an extreme need to detect the disease in the early stages which is heavily dependent on tracking a patient's medical history. A discrete Markov chain model is developed to track the natural history from disease free to death using data from a community-based NIDDM screening project in Taiwan. Due to certain

exclusions, only 742 participants from the first set and 473 from the second set were actually used in the study. The Markov chain consists of five states. A person can transition from disease free (state 0) to asymptomatic (state 1); from asymptomatic to symptomatic (state 2); and from symptomatic to death from NIDDM (state 3). To account for deaths unrelated to NIDDM, the fourth state is introduced to represent other causes of death. The annual transition rate between states are obtained and used to find the 10 year survival rate for asymptomatic and symptomatic NIDDM. Parameters estimated in the Markov chain are subsequently used in a simulation model to investigate the efficacy of several screening policies (Kuo et al, 1999).

2.5 Research Contribution

Much of the literature surrounding food contamination focuses on bacteria as a toxin; Table 1 provides a summary of the literature. This research will contribute to the current literature by approaching this issue from an alternative view point using a chemical contaminant. Very little research has been done in the area of intentional chemical contamination, primarily due to the lack of data. The research attempts to fill this gap by introducing an examination of a chemical toxin based on the data available. Chemical contamination is a likely form of attack for a person looking to cause harm to a substantial amount of individuals. The current study also highlights the risk associated with distribution channels as a function of the amount of people each channel serves. Food suppliers, processors, and distributors need to understand the magnitude of such an attack.

Table 1

Summary of Research

Paper	Contaminant	Food Product	Dose Response	Model/Approach
Buchanan et al., (2000)	Salmonella E. coli Listeria		Exponential; Beta Poisson; Weibull; Gompertz	Sigmoidal mathematical equations
Coleman & Marks, (1999)	Salmonella E. coli		Gompertz; Logistic	Monte Carlo Simulation
Danyluk & Schaffner, (2011)	E. coli	Spinach	Beta-Binomial	Monte Carlo Simulation
Hartnett et al., (2009)	Salmonella E.Coli	Spinach; Hotdogs; peanut butter	Exponential	Discrete Event Simulation
Lammerding & Paoli, (1997)	E. coli	Ground beef		Monte Carlo Simulation
Liu & Wein, (2008)	Botulin	Milk	Probit Log function	Approximation of Mean & Monte Carlo Simulation
Mataragas et al., (2010)	Listeria	Deli meat	Exponential	Modular Process Risk Model
Teunis et al., (2010)	Salmonella	Numerous	Beta Poisson	Markov Chain Monte Carlo
Whiting & Buchanan, (1997)	Salmonella	Pasteurized liquid eggs	Exponential; Beta Poisson	Simulation
WHO/FAO, (2002)	Salmonella	Eggs and broiler chickens	Beta-Poisson	

CHAPTER 3

Supply Chain and Toxicology

3.1 Product Supply Chain

Liquid egg production is a rapid process with several stages and actors involved that make the supply chain complex. Table 2 provides a brief list of actors involved in the process and their specific roles. Figure 1 illustrates the flow of both shell and liquid eggs at a high level according to the actors involved at a particular stage

Table 2

Liquid Egg Actors

Actor	Role	
Producers	House layers of hens to produce eggs	
Processors	Receive shelled eggs to turn into liquid form.	
Distributors	Distribute shelled or liquid eggs to companies (distribution channels).	
Distribution Channels	Food Retailers	Sell liquid eggs to customers for personal use (Ex: grocery stores, markets)
	Food Service Industry	Serve eggs to customers in prepared meals (Ex: cafeterias, restaurants)
	Food Manufacturers	Use liquid eggs as an ingredient to make other products (Ex: bakeries, smoothie makers, factories)

Examples of food retailers include grocery stores or supermarkets. Food service locations are restaurants and cafeteria settings. Food manufacturers are considered to be bakeries, factories or smoothie makers.

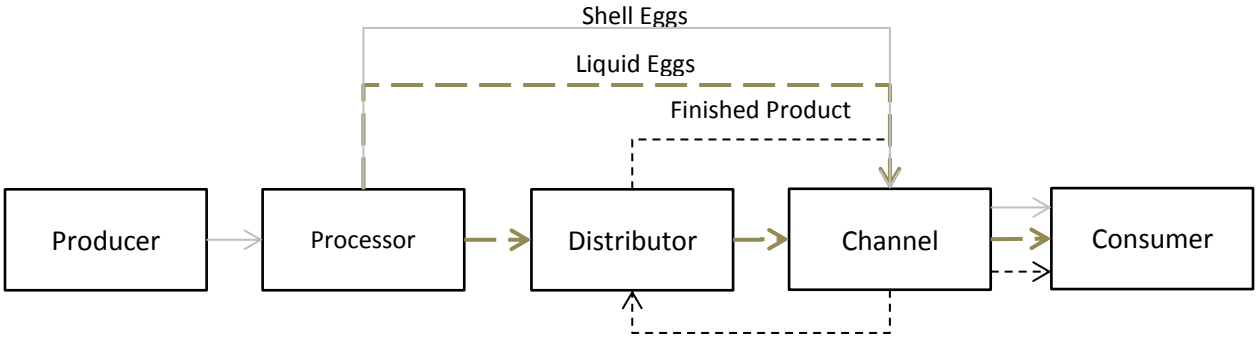


Figure 1. General supply chain design.

At the egg production facility, hens lay eggs that are sent to be washed and graded. A producer can distribute shell eggs directly to a distribution channel or send them to another facility for processing. At the egg processing facility shell eggs are broken and mixed together to generate liquid egg products. Additional ingredients can be added for the end product depending on the requirements of the customer. Liquid products are sold as whole egg, egg whites, or egg yolks. The egg processor can then send the liquid egg to one of the three channels to eventually be purchased by the consumer. Figure 2 displays all of the optional channels the processor can distribute to as well as the flow of product between channels. Notice that products can only be purchased by the consumer from two of the three channels.

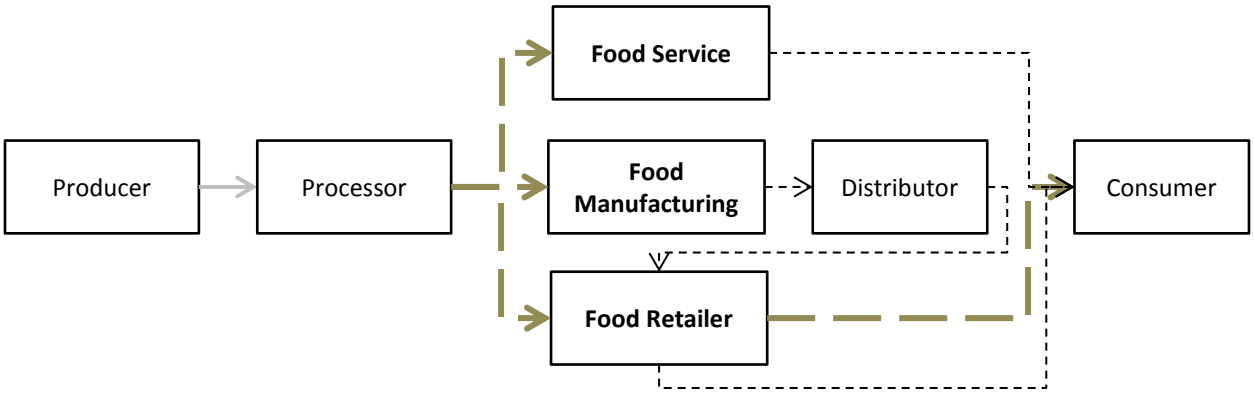


Figure 2. Supply chain distribution channels.

Also note that the customer only consumes liquid eggs directly from a food retail location. If the eggs are channeled through either food manufacturing or food service the egg is cooked before being purchased by the customer. In the food service industry the egg is cooked to order on site and served in a meal (e.g. scrambled eggs, omelets, or fried eggs). Food Service can also use the egg as an ingredient in other dishes such as casseroles, fried chicken, and baked goods. Food manufacturing uses the liquid egg as an ingredient for a finished product which is then repackaged and distributed through the food retail channel. Process diagrams for egg production, processing, and distribution can be found in the appendix. This research considers a case where an attack has taken place at a single egg processing facility which distributes liquid eggs to all three channels. The toxins chosen for the attack are Ethylene Glycol and Potassium Cyanide.

3.2 Toxin Information

3.2.1 Ethylene Glycol.

Ethylene Glycol (EG) is a synthetic liquid substance that absorbs water. There are several characteristics of this toxin that make it appealing to attackers for use as a contaminant. It is odorless, colorless, and sweet tasting. It is mostly used in antifreeze, de-icing solutions for automobiles, solvents, paints and coolants. Individuals can be exposed to EG through ingestion, inhalation or contact with the skin. Once EG enters the body, it can cause damage to the nervous system, kidneys, and the heart (Agency for Toxic Substances and Disease Registry, 2010). The body begins to formulate calcium oxalate crystals and causes metabolic acidosis; an acid-base imbalance in the body.

Human reactions to ethylene glycol vary depending on the amount ingested and the individual. A sufficient amount of ethylene glycol can cause death but there are other effects that occur prior to death which are shown in Table 3. Studies have shown that humans have a lower

tolerance for ethylene glycol and tend to metabolize the chemical much slower than animals. Research in animals also demonstrates that there are different levels of effects caused by EG ingestion: acute, long term, and reproductive effects.

Table 3

Adverse Effects of Ethylene Glycol

Effect	**Reaction**		
Short Term	Numbness Visual Impairment Light-headedness Headache	Lethargy Drowsiness Slurred speech Delirium	Convulsive seizures Renal failure Loss of Reflexes Coma
Long Term	Reduced red blood cells and hemoglobin (in rats)		
Reproductive	Reduced number of offspring (in rats)		

3.2.2 Potassium Cyanide. Potassium Cyanide (KCN) is a substance that is white, granular or crystalline solid in appearance. Industrial uses of the substance include fumigation, extracting gold and silver from ores and adding a metal coat to a conductor through electricity (i.e. electroplating). Attackers might be drawn to use this substance because exposure can rapidly turn into a fatality. The routes of exposure are ingestion through food or water, inhalation, skin contact, and eye contact which can occur through droplets released in the air or a liquid aerosol spray. It is a highly toxic substance that can lead to asphyxiation as a result of the body's inability to use oxygen. Exposure to potassium cyanide has a systemic effect. It affects the whole body, specifically organ systems that are significantly impacted by a lack of oxygen such as the brain, heart and blood vessels, and the lungs (CDC, 2011). Table 4 summarizes the adverse effects of KCN.

Table 4

Adverse Effects of Potassium Cyanide

Effect	**Reaction**		
Short Term	Abdominal pain Nausea & Vomiting Headache	Hypotension Pancreatitis Visual Impairment Seizures	Renal failure Respiratory failure Cardiac failure Coma
Long Term	Blindness	Tremors	

CHAPTER 4

Methodology

4.1 Problem Overview

This research considers a liquid egg supply chain that has been intentionally contaminated with a toxic substance. The contaminated product is dispersed to multiple distribution channels where customers will purchase the tainted liquid eggs. The consumer demand for liquid eggs in terms of how frequently people purchase the item will determine how many people are exposed to the toxin. Subsequently, other factors such as the amount of toxin in the liquid egg and the amount of product consumed affect whether the consumer develops symptoms and gets sick. Several assumptions are made in order to model an individuals' progression from a healthy state to potentially getting ill.

4.2 Problem Description & Assumptions

The following assumptions are considered for this research:

Channels for Liquid Eggs Distribution

1. There are three channels which can receive liquid eggs from an egg processing plant (food service, food manufacturer, and food retail).
2. Each of these channels can receive a fraction of the contaminated packages from the egg processing plant.
3. Each channel is modeled independently.

Liquid Eggs

1. Liquid eggs are contaminated by a known level of toxin at an egg processing plant.
2. The number of contaminated packages produced by the egg processing plant and sent to each distribution channel is known.

3. The shelf life of each liquid egg product is known.

Consumer Demand

1. The maximum number of people that can purchase eggs is based on the number of products available at the time of purchase.
2. Each consumer is modeled independently of each other and buys a maximum of one product a day.
3. The probability $p(e)$ that a person purchases an egg product is characterized by a binomial probability distribution.
4. After purchase, the consumer has the potential to become symptomatic.
5. The probability a person gets sick is based on a log probit dose response equation.
6. If a consumer purchases an egg product they cannot become symptomatic within the same time period.

4.3 Model Formulation

A Markov Chain (MC) is a discrete time, discrete space, stochastic process. There are four components to the basic structure of a MC which consist of the following: time horizon, state space, transition function, and transition probabilities. State space is a collection of values that represent the condition (state) of the system. The time horizon is the length of time the state of the system will be observed. The transition function is a mathematical equation that defines the progression between states based on stochastic events. Transition probabilities characterize the uncertainty in the system associated with moving from one state to the next at a specific time.

A discrete time, discrete space, stationary Markov Chain with rewards is developed to address the problem in this study. In this case, the "reward" for an attacker is considered to be a person becoming ill, which is a successful attack. The MC determines the total expected number

of purchasers that become ill after purchasing a contaminated egg product at the end of the time horizon. The time horizon is segmented by days; during each time period there is an opportunity to observe the number of people who purchase egg products and those who become sick after purchase or remain healthy.

Time Epochs: The opportunity to purchase ends when the shelf life of the product ends because it will no longer be sold. To capture this, the time horizon extends over the shelf life of a product represented by $T = \{0,1 \ldots . L\}$ where L is the shelf life of the product in days.

State Space: A three dimensional state space is considered for this model, represented as $S = (s_1, s_2, s_3)$. s_1 represents the number of people that purchased eggs (packages) in the last time period but are not symptomatic; s_2 represents the number of people who are symptomatic given they purchased eggs; and s_3 represents the number of people that remain healthy after purchasing a product. The number of people who purchase the egg product cannot exceed the maximum number of contaminated packages of product at the distribution channel (N). The number of people who can become sick or remain healthy cannot exceed the maximum number of people who purchased a contaminated product.

$$S = \{s_1, s_2, s_3 | s_i = 0,1, \ldots N\} \qquad \textbf{(Eq. 1)}$$

The number of products at the distribution channel at a specific point in time is represented by $N - (s_1 + s_2 + s_3) = N_0$.

Events: There are two events that make the state of the system transition from the current state to future states within the Markov Chain. The first event is a consumer purchasing an egg product. The second event corresponds to a purchaser who develops symptoms and dies. The random variables associated with the purchase event and development of symptoms are denoted as E and Krespectively.

Transition Function: A function is created in order to model transitions to the future state $s'(s_1', s_2', s_3')$ given the current state (s_1, s_2, s_3) .

$$s = (s_1, s_2, s_3) \rightarrow (s_1', s_2', s_3') = s' \quad \textbf{(Eq. 2)}$$

$$\begin{aligned} s_1' &= e \\ s_2' &= s_2 + k \\ s_3' &= s_3 + s_1 - k \end{aligned} \quad \textbf{(Eq. 3)}$$

The probabilities associated with transition are the likelihood of *e* people purchasing an item, denoted as $p(e)$ and the likelihood of *k* purchasers becoming symptomatic, denoted as $p(k)$. Both probabilities are binomially distributed and defined as follows:

$$P(E = e) = \binom{N_0}{e} p_{cp}^{e}(1 - p_{cp})^{N_0 - e} \qquad 0 \le e \le N - (s_2 + s_3) \quad \textbf{(Eq. 4)}$$

$$P(K = k) = \binom{s_1}{k} p_d^{k}(1 - p_d)^{s_1 - k} \qquad 0 \le k \le s_1 \quad \textbf{(Eq. 5)}$$

$$p(s'|s) = p(e) \times p(k) \quad \textbf{(Eq. 6)}$$

where $p_{cp}$is the probability of consumer purchase (Eq. 4) and $p_d$is the probability of death (Eq. 5). The probability of illness comes from a probit dose-response equation, which will be discussed in detail in a subsequent section.

Reward: There is a sequence of rewards associated with transitioning from the current state, *s* to the next state, *s'* where the reward is, *r(s,s')*. This determines the number of new deaths given the current state *s* and future state, *s'*. In the reward function, s_2 is the number of deaths in the current state, s_2' is the number of deaths in the future state which cannot exceed the maximum number of people who purchased, N. The function $r(s)$, s is formally defined in (Eq. 7).

$$r(s, s') = \begin{cases} \max(s_2' - s_2, 0) & if\ s_2' \le N \\ 0 & otherwise \end{cases} \quad \textbf{(Eq. 7)}$$

The expected number sick (q_s) given the current state s reflects the probability of transitioning from s to all future states s'.

$$q_s = \sum_{s\prime} p(s'|s)r(s\,,s') \qquad \textbf{(Eq. 8)}$$

Total Expected Reward: The total expected reward at time n in state *s*, is denoted as $v_s(n)$ and represents the number of illnesses at a specific point in time.

$$v_s(n) = q_{s,n} + \sum_{j=1}^{N} p(s'|s)v_s(n-1) \qquad \forall s = 0 \ldots N, n = 0 \ldots L \qquad \textbf{(Eq. 9)}$$

4.4 Dose Response

In order to determine the likelihood that a person will develop symptoms, a Log_{10} Probit D-R is used. This model is most suitable for a chemical toxin. The Chemical Terrorism Risk Assessment team associated with the Department of Homeland Security uses this model as a standard in all consequence assessments in order to represent the likelihood of illness given an exposure. The $\log_{10}$ probit model is used to linearize dose-response data which generally takes on the shape of a sigmoidal curve. In this model, response data is binary in that the response to illness is either yes or no. Dose response data is represented as probits and plotted against the $\log_{10}$ of the dose or concentration. A regression analysis is then performed on the resulting graph. The linear relationship between the probits and the dose is described by (Eq. **10)**.

$$y = mx + b \qquad \textbf{(Eq. 10)}$$

m is the probit slope, x is the $\log_{10}$ (Dose), and b is the intercept.

This study is concerned with consumer mortality therefore our binary responses are: yes the consumer died after ingestion of a contaminated product or no the consumer did not die. In terms of the log probit analysis, from (Eq. 10) the probability of death can be expressed as

$$p_{death} = Y^{-1}(\beta log_{10}(d) + a) \quad \textbf{(Eq. 11)}$$

Y^{-1} is the cumulative distribution function of the standard normal distribution. β represents the probit slope, d is the dose of toxin ingested by the consumer, and a is the y-intercept. The dose is calculated as a function of the concentration of the contaminant, (c) and the serving size ingested by the consumer (s). This amount is divided by the weight of an average adult male (70 kg) to determine the dose per kg of body weight.

$$D = \frac{(c)(s)}{70} \quad \textbf{(Eq. 12)}$$

Concentration is expressed in parts per million which is used to represent a diluted concentration usually in mg/L or mg/kg. All the parameters necessary to execute the Dose-Response and Markov chain model are represented in Figure 3.

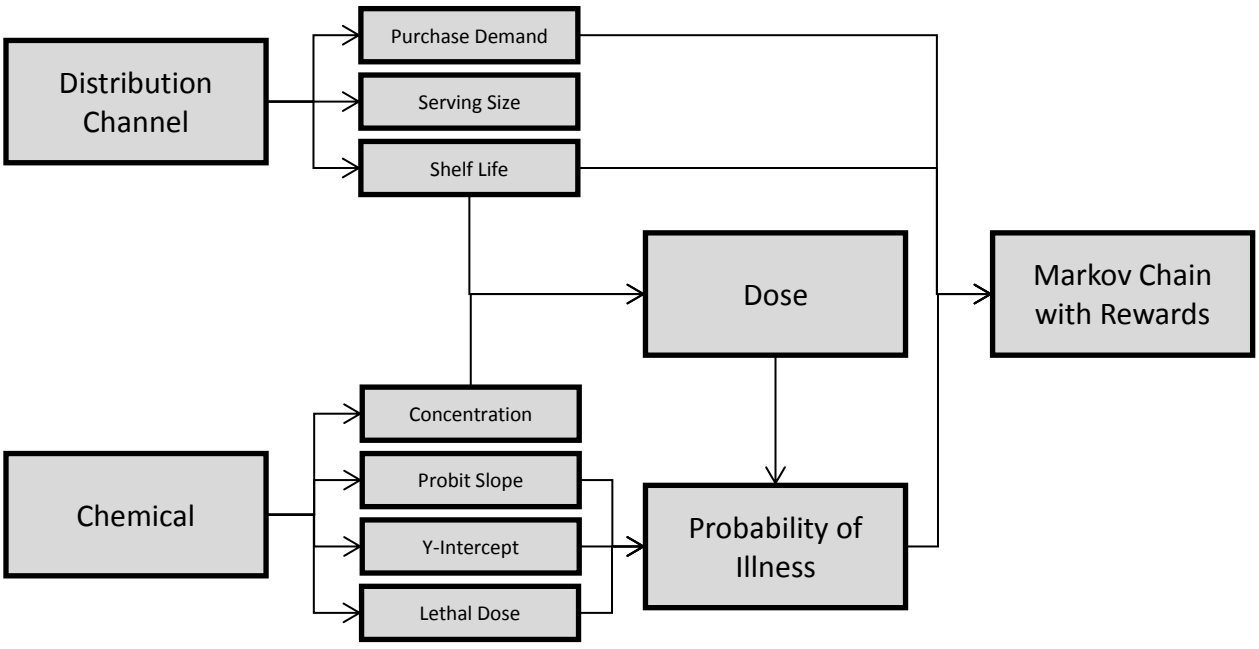


Figure 3. Diagram of Model Parameters.

CHAPTER 5

Experimental Design

5.1 Parameter Estimation

Parameter values used within the model were extracted from a variety of sources during the data collection process. Interviews were conducted at several distribution channel locations to represent Food Retail (FR), Food Service (FS) and Food Manufacturing (FM) such as grocery stores, university cafeterias, and bakeries. Table 5 summarizes how the data was collected.

Table 5

Model Parameters and Sources

	Parameter	Source
	Product Information	
N	Max Number of Purchasers	—
L	Shelf Life of product (days)	Interviews & Product Expiration
s	Serving size (mg)	Interviews & Product Package
p_{cp}	Probability of Consumer Purchase	Interviews
	Toxin Information	
c	Concentration (ppm)	—
LD_{50}	Lethal Dose to 50% of population (mg/kg)	Literature
β	Probit Slope	Literature
a	Y-intercept	Probit Analysis
p_d	Probability of Death	Probit Analysis

5.2 Product Parameters

5.2.1 Serving size. The product information varied for each distribution channel because the type of product sold is different. At the retail location liquid eggs are sold in 16 or 32 ounce cartons. The serving sizes listed on the carton range from 53-56 grams for both cartons, which is equivalent to roughly one whole egg. Most individuals consume 2 eggs or 112 grams of liquid egg in one sitting. Similarly, in the Food Service sector, two eggs are typically given to customers in an order. Food Service personnel use four ounce ladles to prepare an order of liquid

egg. Four ounces equals 113.4 grams. Shell eggs vary in size and weight; therefore conversions from liquid to whole eggs are approximations.

The serving size for Food Manufacturing was determined by choosing a specific product with egg as an ingredient. The most common use for eggs other than a breakfast dish is baking. Chocolate chip cookies are a popular baked item that uses eggs. Based on their recipe, a bakery owner in the Greensboro community determined that each customer received 0.11 eggs in each cookie sold in their shop. Assuming one egg is equal to 53 grams of liquid eggs, each customer consumes 5.83 grams of liquid egg per cookie.

5.2.2 Shelf life. The shelf life for Food Retail products are determined by expiration dates printed on the package. Liquid eggs in a carton can last for one month or 30 days. Food Service locations must use their liquid egg products within seven days after opening. Manufactured cookies can last for about three weeks or 21 days in an air tight container or plastic wrapper.

5.2.3 Probability of consumer purchase. The demand for liquid eggs from Food Retail, Food Service, and Food Manufacturing is low, medium, and high, respectively. Interviews with Food Retail locations revealed that demand was extremely low for in-store purchases of liquid eggs. For model simplicity this low demand is captured as a 10% probability of purchase. Food Service locations receive higher demand for egg products due to the variety of breakfast menu items such as scrambled eggs, omelets, and fried eggs. However breakfast service at most restaurants only account for a portion of the daily business considering lunch and dinner service as well. Only a percentage of their customer base will be exposed to contaminated eggs, given they are only sold at breakfast. Their purchase probability is 50%. Food

Manufacturing has the highest demand and therefore will be characterized by a 90% purchase probability. All of the parameters for the product information are summarized in Table 6.

Table 6

Summary of Liquid Egg Product Related Variables

Product Information	**Food Retail**	**Food Service**	**Food Manufacturing**
Product Type	Liquid Egg	Breakfast Dish	Cookie
Serving size (mg)	112000	113400	5830
Max Number of Purchasers	15	15	15
Shelf Life of the Product (days)	30	7	21
Probability of Purchase	0.10	0.50	0.90

5.3 Toxin Parameters

Information was gathered to determine the amount of toxin needed to cause death. The Agency for Toxic Substances and Disease Registry (ATSDR) released a Toxicological Profile for Ethylene Glycol in November of 2010. The profile indicates the lethal dose of ethylene glycol to be in the range of 1,400-1,600 mg/kg per body weight (Agency for Toxic Substances and Disease Registry, 2010). The lower bound is used as the lethal dose (LD_{50}), the amount required to cause death in 50% of a population. The LD_{50} for potassium cyanide is 0.84 mg/kg (Noblis, 2009). The doses are based on the weight of an average man of 70 kg.

Due to a lack of data on human consumption of ethylene glycol, assumptions are made to determine the probit slope. Ethylene glycol shares similar properties of other alcohols such as methanol which has also been used as a main ingredient in antifreeze. Methanol like ethylene glycol is a solvent in that it can dissolve other substances without any change in chemical composition. Although ethylene glycol and methanol produce different symptoms, both poisonings can result in metabolic acidosis which usually occurs with a serum concentration of greater than 20 mg/dl for ethylene glycol and 25 mg/dl in methanol. Patients with metabolic

acidosis should be treated with an alcohol dehydrogenase (ADH) inhibitor; therefore victims with either poisoning are likely to receive the same treatment. ADH inhibitors such as ethanol are used to breakdown toxic alcohols in the human body. It is similar to a process that occurs naturally where enzymes are present in the liver and lining of the stomach to catalyze the oxidation of ethanol to allow for consumption of alcoholic beverages. Methanol from the intestinal tract goes to the liver through the blood system, where methanol is converted into formaldehyde by the liver enzyme alcohol dehydrogenase. When the body accumulates a surplus of formaldehyde, the body converts it to formic acid. The issue occurs with the build-up of formic acid in the blood. The breakdown of formic acid is slower than the breakdown of formaldehyde, consequently a large dose of methanol entering into the body leads to a build-up of formic acid which causes the adverse effects seen in methanol poisoning. For this reason, the probit slope (8.1) of formaldehyde provided by the CTRA is used to represent the probit slope of ethylene glycol (Noblis, 2009). Table 7 summarizes the parameters for each toxin used in the probit model.

Table 7

Summary of Toxin Related Variables

Toxin Information		**Ethylene Glycol (EG)**	**Potassium Cyanide (KCN)**
LD_{50}	Effective Dose to 50% (mg/kg)	1400	0.84
β	Probit Slope	8.10	6.90
a	Y-intercept	-25.48	0.52

5.4 Experimental Design Summary

Several experiments are needed to address the research questions. Three experiments are defined in Table 8 to identify which parameters will vary. The values for the serving size and the

concentration of contaminant are changed based on the investigative interest of a particular experiment. Experiments 1-3 correspond to research questions 1-3 respectively. Research question 4 utilizes the parameters outlined in experiment 3.

Table 8

Experiment List

Experiment Number:			1	2	3
Factor:			Serving Size	Concentration	Deaths/Time
Product Information					
N	Max Number of Purchasers		15	15	15
L	Shelf Life of product (days)	FR	30	30	30
s	Serving size (mg)	FR	—	112000	—
p_{cp}	Probability of purchase	FR	—	—	0.10
L	Shelf Life of product (days)	FS	7	7	7
s	Serving size (mg)	FS	—	113400	—
p_{cp}	Probability of purchase	FS	—	—	0.50
L	Shelf Life of product (days)	FM	21	21	21
s	Serving size (mg)	FM	—	5830	—
p_{cp}	Probability of purchase	FM	—	—	0.90
s	Serving size (mg)	General	20,000 - 200,000	—	—
Toxin Information					
c	Concentration (ppm)	EG	0.80	0.40 - 1.40	0.017 & 0.010
LD_{50}	Lethal Dose (mg/kg)	EG	1400	1400	1400
β	Probit Slope	EG	8.10	8.10	8.10
a	Y-intercept	EG	-25.4836	-25.4836	-25.4836
c	Concentration (ppm)	KCN	0.0005	.0002 - .005	0.0007 & .0004
LD_{50}	Lethal Dose (mg/kg)	KCN	0.84	0.84	0.84
β	Probit Slope	KCN	6.90	6.90	6.90
a	Y-intercept	KCN	0.5225	0.5225	0.5225

CHAPTER 6

Results

6.1 Dose-Response Model

Figure 4 shows the relationship between serving size and the probability of death. In the numerical study it is assumed that each individual only consumes one serving of whichever product was purchased. Increasing the serving size directly impacts the probability of illness.

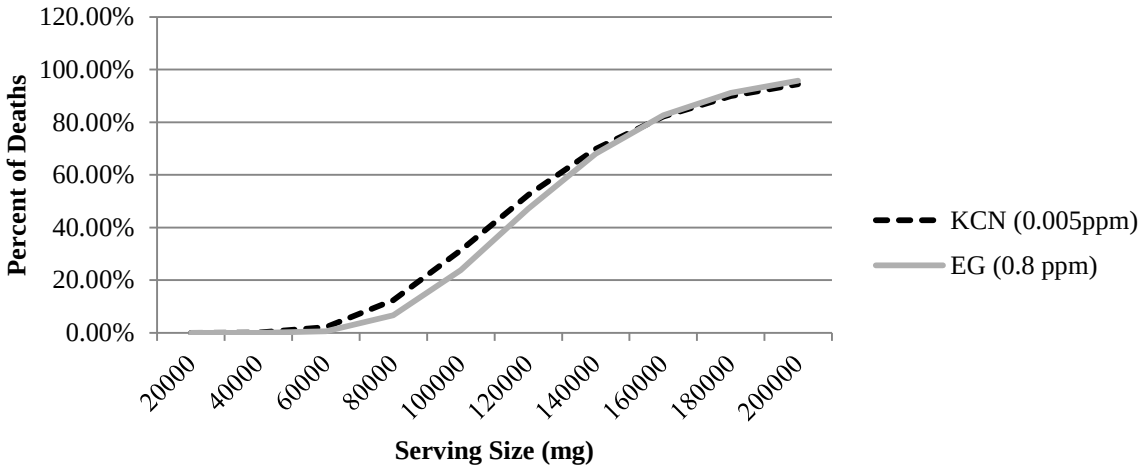
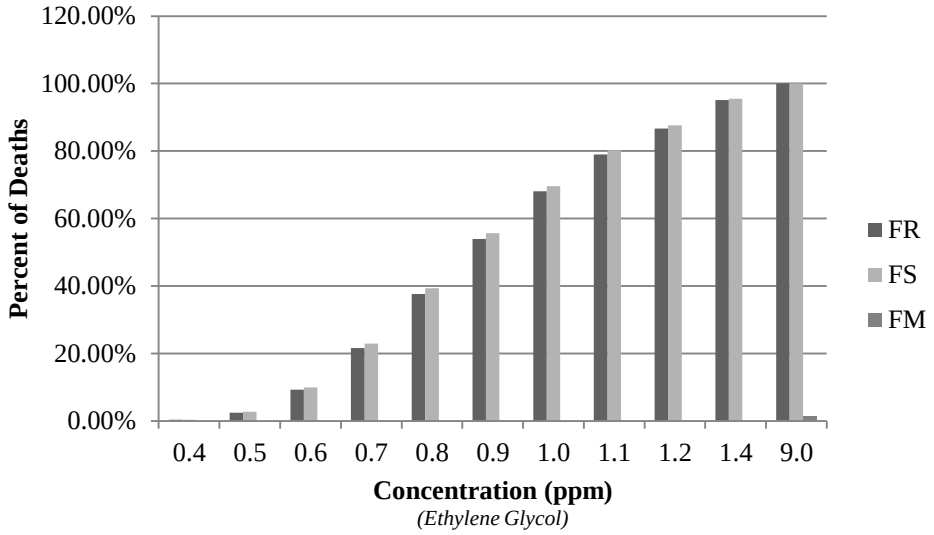


Figure 4. Effects of serving size (RQ1).

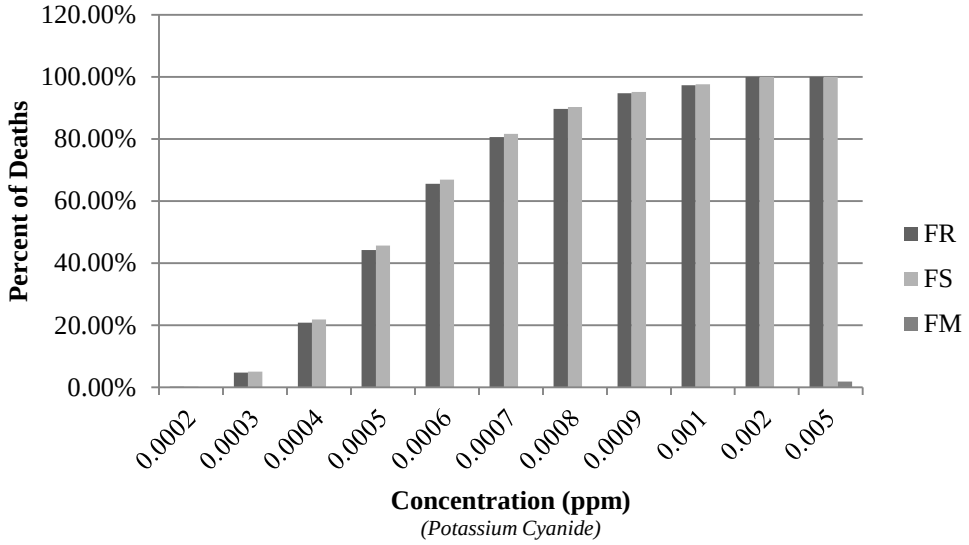
The cases shown are given ethylene glycol concentration levels of 0.800 ppm and potassium cyanide of .005 ppm. One key point in this figure is that as the serving size exceeds 60,000 mg the risk of death begins to significantly increase. There is little to no risk at serving sizes less than 50,000 mg. Food Retail and Service channels have serving sizes over 100,000 where there is about 40% probability of death from consumption of contaminated liquid egg products.

An evaluation of the concentration of both toxins in the egg product and the probability of death is shown in Figure 5 for each distribution channel. The increasing probability of illness corresponds to increases in concentration levels of the toxin as shown on the *x*-axis. Food

Service and Food Retail have similar results most likely because the serving sizes are close. Therefore the dose amount is nearly the same. Food Manufacturing shows zero percent chance of death until the concentration rises above 9 ppm for EG and 0.005 ppm for KCN.



(a)



(b)

Figure 5. Effects of toxin concentration level: (a) EG (b) KCN (RQ2).

Results show that even when the serving size is the same, the probability of death can vary widely when the concentration is larger. The largest incremental increase occurs between

0.003 and 0.007 ppm for potassium cyanide. Ethylene glycol shows a more linear trend in the escalation of the probability of death.

6.2 Markov Chain Model

Figure 6 represents the ratio between the number of people who die after purchasing a contaminated product relative to the number of products that were available at the beginning of the time horizon. For example,N the maximum number of products available for Food Retail is set to 15. At the end of the product shelf life, a total of 13 people are expected become ill which indicates that almost 87% of the contaminated products that were available contributed to consumer mortality.

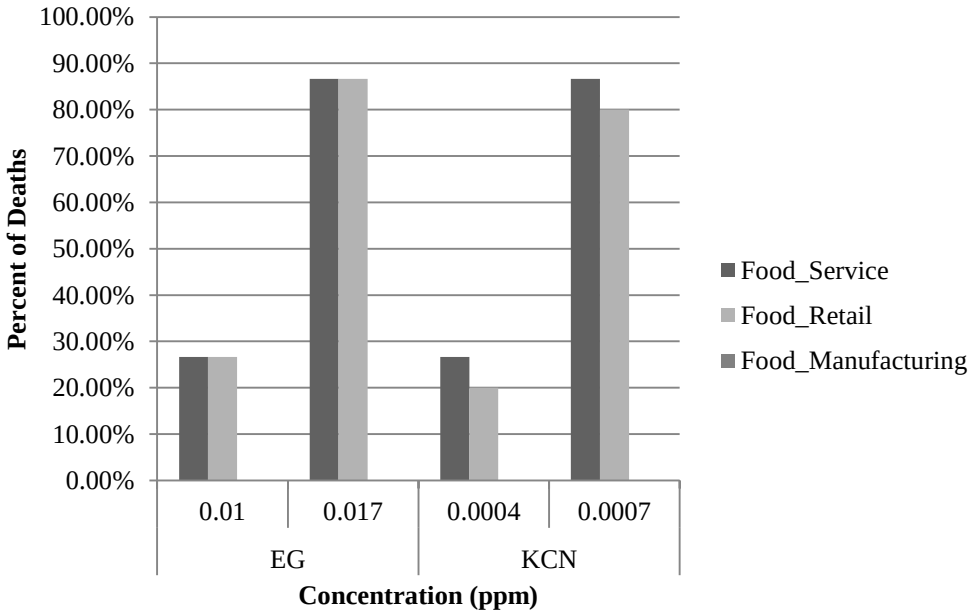


Figure 6. Individuals that become ill after consumption (RQ3).

Ethylene Glycol shows no difference in the probability of illness between Food Service and Food Retail however with potassium cyanide there is a 7% decrease among the two distribution channels. EG also shows that an increase of 0.007 leads to a 60% increase in the probability of death.

The time to absorption for each distribution channel specific Markov chain is determined. This represents the time in days it takes for the system to reach a state that it cannot transition out of (absorbing state). Absorbing states include those in which all products have been purchased, all the people who purchased have died, or all the people who purchased remained healthy. The absorption time is calculated at the beginning of a time period with N number of products on the shelf ($s_1 = 0$), no deaths from consuming a contaminated product ($s_2 = 0$), and no one considered to be healthy after purchase ($s_3 = 0$). Time to absorption for Food Retail, Food Service, and Food Manufacturing are shown in Figure 7. This figure also shows the decline in products that are available at the distribution channel as consumers continue to purchase over each time period. It takes 33 days for Food Retail to reach an absorbing state. Food Retail takes the longest time to reach an absorbing state mainly due to the lowest probability of purchase (10%). Food Service consumer demand does not all. Food Manufacturing has the highest probability of demand (90%) and the shortest time to absorption (3 days).

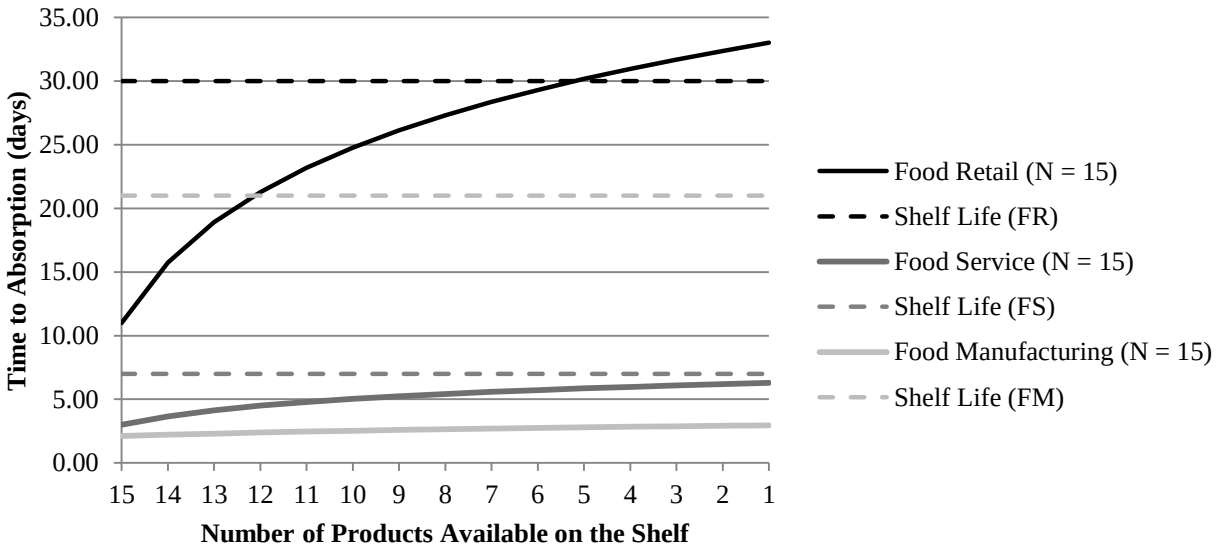


Figure 7. Time to absorption for Food Retail, Food Service, and Food Manufacturing (RQ4).

Understanding the risk is one step towards protecting the food supply chain and consumers. The discussion section will further explain these results and give insight into what can be learned from this study.

CHAPTER 7

Discussion and Future Work

7.1 Implications

Companies in the food industry must protect their business and the health of their customers by understanding the risk for each distribution channel. This research presented a model to quantify this risk based on consumer mortality. This research presented a model to quantify the risk of consumer mortality resulting from consumption of potentially contaminated products. Two chemical toxins are presented in this study

Potassium cyanide is shown to be more lethal than ethylene glycol. This is evident by comparing the lethal dose expected to cause death. However ethylene glycol is more widely available because it can be found in a common household product. Ethylene glycol or similar products with lower toxicity could be used to contaminate a small or targeted group of people. Whereas the potassium cyanide and other highly toxic chemicals could be used in a wide spread contamination. Recall the lethal dose of KCN is 0.84 mg/kg of body weight and the average weight of a man is 70 kg. Thus the average man requires 58.8 mg of KCN to have a deadly effect. That amount is less than one percent of the recommended serving of liquid eggs (112,000 mg).

Serving sizes on a typical package are merely suggestions to purchasers on how much to consume and serve as a notification of the dietary benefits from one serving. Customers can consume more or less depending on their personal preferences. The amount of product consumed changes the risk of illness. When the concentration level is extremely low, customers may experience treatable symptoms. In general, fewer people result in a fatality from the Food

Manufacturing channel since the serving size is smaller, but does not mean they will not become ill or require medical treatment.

In general, fewer people result in a fatality from the Food Manufacturing channel since the serving size is smaller, but it does not mean they will not become ill or require medical treatment.

In order to avoid the expected morbidities, it is essential to examine the time frame in which all the products would be sold in relation to their shelf life. Products that have not been purchased after 30 days are likely to be discarded and no longer pose a risk for customers in the Food Retail channel. On the other hand, the product shelf life for food manufacturing is 21 days which implies that 18 days after all of the products have been purchased there is still a chance a customer has not thrown away their product. All of those people are still potentially at risk. This presents a small window of opportunity to react to a contamination outbreak and begin intervention measures for the Food Manufacturing distribution channel. When the time to absorptions extends past the product shelf life this implies there is more time to pull the product from that distribution channel. Longer shelf life products also present a better opportunity for consumers to report illnesses. If shorter shelf life products or high demand products sell out in the distribution channels, there is less time for individuals to develop symptoms, have a reaction and seek medical attention. Public health officials need time to pose an intervention when there after there are a certain number of confirmed cases, and the link has been made to determine the product source.

7.2 Future Work

There are several limitations to the current model. One limitation is the availability of data on chemical contaminations and its effects on humans. There has been no official study

conducted to determine the minimum toxic dose of ethylene glycol ingested by humans. Most of the literature gives estimations based on scientific studies performed on rodents and other animals. Their studies also show that humans metabolize certain chemicals slower than a rodent which implies the tolerance is lower. In addition, the ATSDR has developed minimum risk levels (MRLs) for over 180 substances while the CTRA established profiles for fourteen other chemicals not presented here. There are thousands of chemicals that are potentially harmful if consumed in excess or with malicious intent. Another limitation of the model is the lack of specific information on the demand for liquid egg products. Distribution channels are cautious about revealing sensitive sales data to non-industry personnel.

Future work on this research will address these limitations by obtaining more accurate data about the toxicology of chemical substances and consumer purchasing demand. More layers can be added to evaluate the probability of illness by including information about age and/or weight. Both factors influence an individual's susceptibility to illness.

With limited information, there is a distinct need in food safety to develop generic models that can evaluate the risk of illness/death given all of the uncertainty surrounding the food supply chain and potential contaminants. Supplementary data on purchase demand and historical data on chemical poisonings applied to the model presented can reduce that uncertainty.

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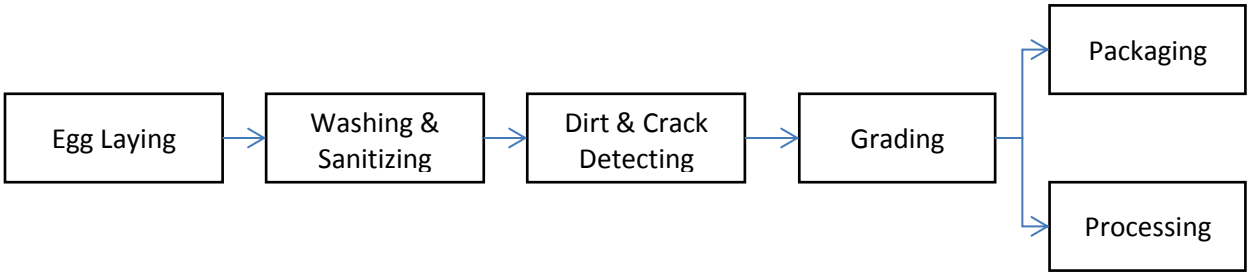
Appendix A

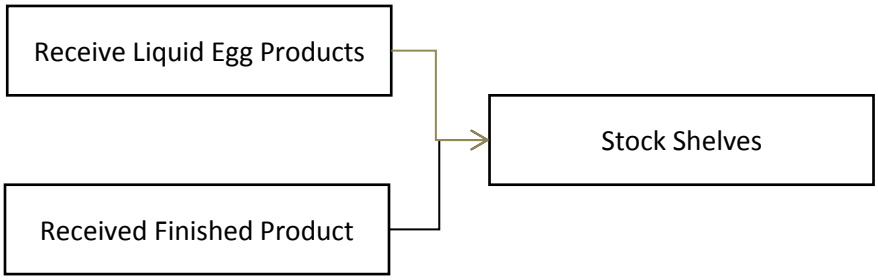
Process Diagram: Egg Producer



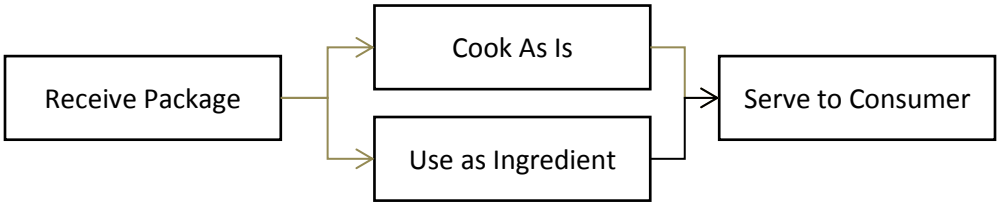
Process Diagram: Egg Processor

Process Diagram: By Distribution Channel

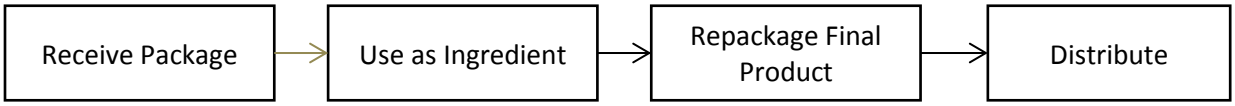
Food Retail



Food Service



Food Manufacturing



Appendix B

Egg Companies Evaluated

Supply Chain Design Description		
Phase	*Actor*	*Description*
1	Egg Producers	Farm location where hen houses are kept for egg laying
2	Egg Processors	Company that received shell eggs for the purpose of making liquid eggs and/or other products
3	Channels	Company that received liquid eggs in order to serve (S), sell (R.), or combine with other ingredients to make a final product (M)

Additional Descriptions		
Notation		*Description*
D	Distribution	The company also participates in the distribution process
S	Food Service	The company also participates in the food service industry
M	Food Manufacturing	The company also participates in the food manufacturing industry
R	Food Retailer	The company also participates in the food retail industry

Company	Location	Supply Chain Design	Additional Descriptions
American Dehydrated Foods Inc.	Springfield, MO	3	M
Ballas Egg Products Corporation	Zanesville, OH	2	D
Braswell Egg Company/Braswell Foods	Nashville, NC	1, 2	D
Cal-Maine Foods Inc.	Jackson, MS	1	D
Cooper Farms	Henry, OH	1	D
Country Charm Eggs	Gainesville, GA	1	D
Country Creek Farms	Rogers, AR	1, 2, 3	M, D
Crystal Farms	Chestnut Mtn., GA	2, 3	M, D
Country Creek Farms	Rogers, AR	1	D
Dakota Layers LLC.	Flandreau, SD	1	D
Dixie Egg Company	Jacksonville, FL	1	D
England Farms Inc.	Rison, AR	1	D
Golden Oval Eggs	Abbeville, AL	1, 2, 3	M, D
Hickman's Egg Ranch, Inc.	Buckeye, AZ	1, 2	D
Hidden Villa Ranch	Fullerton, CA	1, 2, 3	M, D
Hillandale Farms of Florida, Inc.	North Lake City, FL	1	D
Krieder Farms	Manheim, PA	1	D
L&R Farms, Inc.	Pendergrass, GA	1	D
Midwest Poultry Services	Mentone, IN	1	D
Moark LLC.	Chesterfield, MO	1	D
Norco Ranch	Norco, CA	1, 2, 3	M, D
NuCal Foods, Inc.	Ripon, CA	1	D
Pilgrim's Pride Corporation	Pittsburg, TX	1	D
R. W. Sauders Inc.	Lititz, PA	1	D
Radlo Foods	Gainesville, GA	1, 2	D
Rose Acre Farms, Inc.	Seymour, IN	1, 2	D
Simpson's Eggs, Inc.	East Monroe, NC	1	D
Sparboe Farms	Litchfield, MN	1, 2	D
Tampa Farm Service, Inc.	Dover, FL	1	D
Williamette Egg Farms	Canby, OR	1, 2, 3	M, D

Appendix C

Food Retail: Egg packaging

Food Manufacturing: Chocolate Chip Cookie Recipe

Ingredients

- 2 1/4 cups all-purpose flour
- 1 1/4 teaspoons salt
- 3/4 teaspoon baking soda
- 2 sticks unsalted butter, softened
- 3/4 cup packed light brown sugar
- 3/4 cup granulated sugar
- 2 large eggs, at room temperature
- 2 teaspoons vanilla extract
- 2 cups semisweet chocolate chips

Yield: 3 dozen cookies

Pasted from <http://www.foodnetwork.com/recipes/food-network-kitchens/crispy-cakey-chocolate-chip-cookies-recipe/index.html>

Appendix D

Ethylene Glycol Minimum Threshold

	ACGIH	ATSDR	N.H. DES	EPA	AAPCC
Route of Exposure	Inhalation	Ingestion	Ingestion	Ingestion	
Standard	Threshold Limit Value- Short Term Exposure Limit (TLV- STEL)	Minimal Risk Level (MRL)		Lifetime Health Advisory	Minimum Toxic Dose
Value	100 mg/m^3 Ceiling	0.8 mg/kg/day	7000 μg/L	14000 ppb	20 mg/dL
Additional Notes	- Air Concentration - Employee exposure	- Daily human exposure over time	- State drinking water	- State drinking water	- Serum Concentration
Time Frame	15 minutes	14 days	Lifetime	Lifetime	

[1] ACGIH American Conference of Governmental Industrial Hygienists

[2] ATSDR Agency for Toxic Substances and Disease Registry (US Department of Health and Human Services)

[3] N.H. DES New Hampshire Department of Environmental Services

[4] EPA Environmental Protection Agency

[5] AAPCC American Association of Poison Control Centers