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CONTAMINATION CONTROL IN FOOD SUPPLY CHAIN

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ABSTRACT

In this paper, we study a contamination control problem in food supply chain. We formulate the problem as a dynamic programming problem and then study the structure of the optimal control which turns out to be very similar to the hedging-point type of policy. Under the environment in which there is uncertainty associated with contamination control, we propose a stochastic dynamic programming formulation with chance constraints, to which simulation based methods could be applied.

1 INTRODUCTION

The number of incidents of food poisoning and foodborne diseases caused by pathogenic microorganisms and other poisonous, harmful elements is a direct index reflecting food safety conditions. In fact, one third population in developed countries suffer from foodborne diseases annually. According to WHO, the fail-to-report rate (FRR) is over 90% in developed countries and over 95% in developing countries. Based on the recent statistics, there are 20 000 to 40 000 reported food poisoning cases every year, which is estimated to be less than 1/10 of total actual cases. In China, according to the statistics from Chinese Ministry of Health, food safety problem in recent years has been worsening. In 2003, the Ministry received a total of 379 national reports of severe food poisoning incidents, with 12,876 people poisoned and 323 people dead. Compared with 2002, the number of severe food poisoning reported, people poisoned and dead increased by 196.1%, 80.7%, and 134.1%, respectively (J.Han 2007). The most notorious incident was the one involved Sanlu Dairy Group[1].

Most food safety problems can be traced back to some points of their supply chain where poisoning or harmful materials are introduced or quality problems are occurred. So, in order to ensure food safety, it may be ideal to have tight control and inspection of every segment of the entire supply chain. However, food supply chains are usually quite complex and there are many different players involved, it could be very costly, and may not even be practical and necessary in some cases to do so. Therefore, one problem of interest is to find cost effective means to monitor and control food supply chains and to intervene whenever is necessary to ensure food safety. van der Gaag et al. (2004) define cost-effectiveness as "the ratio between the achieved reduction in prevalence and the change in net costs to obtain this reduction", and explore the cost-effectiveness of control measures against Salmonella in several stages: finishing, transport, lairage and slaughtering. Goldbach and Alban (2006) compare the estimated annual effect (decrease in number of human infection cases) of various intervention strategies on human incidences. Fraser and Monteiro (2009) study the cost-effectiveness for on-farm and abattoir interventions. Of course, it may be difficult to define what is the real cost when human tragedy is involved, which food safety problems often result in.

In this paper, we study a problem of how to effectively control bacteria prevalence in a food supply chain. The goal is minimize the total cost subject to the constaint that bacteria prevalence cannot exceed certain limit at each stage of the supply chain. We follow a model similar to the one studied in van der Fels-Klerx et al. (2008). We first formulate the problem as a dynamic programming problem. We then show the optimal control has a simple structure in which prevention at each stage is needed only when bacteria prevalence exceeds certain threshold. We then study

[1]Sanlu Dairy Group was once the largest Chinese dairy products company based in Shijiazhuang, the capital city of Hebei Province. The company had one of the oldest and most popular brands of infant formula in China. In 2008, it was involved in an adulterated milk powder scandal, affecting some 294,000 Chinese infants and killing six. It went into bankruptcy on December 24, 2008, and four of its top executives were given long prison sentences in January 2009.

the stochastic version of the problem in which some key parameters of the supply chain may be random variables. We propose a stochastic dynamic programming formulation with chance constraints, and propose some simulation based method to solve the problem.

The remainder of this paper is organized as follows. In Section 2, the model for the deterministic case is presented, followed with a dynamic programming formulation. We then prove that the optimal control policy has a very simple structure. In Section 3, the stochastic case is considered, and several possible methods for solving the problem are proposed and discussed. Finally, Section 4 includes a conclusion.

2 Deterministic Model

In this section, we present our deterministic intervention model and provide some structural properties of the optimal control policy. We first introduce the following notation:

- N: number of stages in the food supply chain;
- x_n: bacteria prevalence of the flock at stage n of the chain $(n = 1,\cdots,N)$;
- p_n: upper limit on bacteria prevalence at stage n of the chain $(n = 1,\cdots,N)$;
- α_n: contamination parameter, representing the percentage of negative flock at stage n-1, being positive an stage n, and $0 \le \alpha_n \le 1$ $(n = 1,\cdots,N)$;
- β_n: reduction parameter, representing the percentage of positive flock at stage $n-1$, being negative at stage n, and $0 \le \beta_n \le 1$ $(n = 1,\cdots,N)$;
- u_n: prevention decision variable at stage n,

$$u_n = \begin{cases} 1 & \text{if prevention is taken at stage } n; \\ 0 & \text{otherwise,} \end{cases}$$

  $(n = 1,\cdots,N)$;
- c_n: cost associated with the prevention action at stage n $(n = 1,\cdots,N)$.

Similar to van der Fels-Klerx et al. (2008), we assume the dynamic of $\{x_n\}$ can be modeled as following[2]:

$$\begin{aligned} x_n &= \alpha_n(1-u_n)(1-x_{n-1}) + (1-\beta_n u_n)x_{n-1} \\ &= \begin{cases} \alpha_n(1-x_{n-1}) + x_{n-1} & \text{if } u_n = 0, \\ (1-\beta_n)x_{n-1} & \text{if } u_n = 1. \end{cases} \end{aligned}$$

Then the problem of bacteria prevalence control can be formulated as the following optimization problem:

$$\begin{aligned} (CDP) \qquad & \min \sum_{n=1}^{N} c_n u_n \\ & \text{s.t.} \quad x_n = \alpha_n(1-u_n)(1-x_{n-1}) + (1-\beta_n u_n)x_{n-1}, \qquad n = 1,2,...,N \\ & \qquad\quad x_n \le p_n, \qquad n = 1,2,...,N \\ & \qquad\quad u_n \text{ binary variable}, \qquad n = 1,2,...,N. \end{aligned}$$

Then we can prove the following properties associated with the optimal cost:

Proposition 1. *(i) The optimal cost increases with respect to the initial state x_0;*
(ii) The optimal cost decrease with respect to p_n;
(iii) The optimal cost increases with respect to α_n;
(iv) The optimal cost decreases with respect to β_n.

We now consider a special case in which $\alpha_n = \alpha$, $\beta_n = \beta$, $c_n = 1$, and $p_n = p$ for $n = 1,...N$. Let us consider two prevention control policies: $U = (u_1,\cdots,u_N)$ and $\bar{U} = (\bar{u}_1,\cdots,\bar{u}_N)$, where $u_n = \bar{u}_n$ for $1 \le n < k-1$, $u_{k-1} = \bar{u}_k = 0$, $u_k = \bar{u}_{k-1} = 1$ (where $1 < k \le N-1$). Let $X = (u_1,\cdots,u_N)$ and $\bar{X} = (\bar{x}_1,\cdots,\bar{x}_N)$ be associated with U and $\bar{U}$, respectively. We can then show:

Lemma 1. $x_k \le \bar{x}_k$.

[2] In fact, the dynamic of our model is slightly different from the one used in van der Fels-Klerx et al. (2008); however all the results obtained in this paper still hold for their model as well

Based on (ii) of Property 1 and Lemma 1, and also using the dynamic programming formulation, we can show that the optimal control policy is of the following threshold type policy:

$$u_n = \begin{cases} 1 & \text{if } x_n > S; \\ 0 & \text{if } x_n \le S. \end{cases}$$

In fact, we can further prove that for the optimal value of S is equal to $(p-\alpha)/(1-\alpha)$. The details of the results presented in this section can be found in Hu et al. (2010).

3 Stochastic Model

In the previous section, we assumed that both α and β are deterministic. In many applications, they could be random variables, or x_n be affected by some other random factors. Therefore, in this section, we present a stochastic model based on the one in the previous section. It is clear that if x_n is a random variable, then the constraint $x_n \le p_n$ has to be modified. Here, we replace it with a chance constraint $P(x_n \le p_n) > 1-\varepsilon_n$, where $0 < \varepsilon_n < 1$ is some constant. The the deterministic model in Section 2 can be replaced by the following stochastic model:

$$\begin{aligned} (SCDP) \qquad & \min \sum_{n=1}^{N} c_n u_n \\ & \text{s.t.} \;\; x_n = \alpha_n(1-u_n)(1-x_{n-1}) + (1-\beta_n u_n)x_{n-1}, \quad n = 1,2,\ldots,N \\ & \qquad P(x_n \le p_n) > 1-\varepsilon_n, \quad n = 1,2,\ldots,N \\ & \qquad u_n \in \{0,1\}, \quad n = 1,2,\ldots,N. \end{aligned}$$

The above optimization problem can be also thought as a stochastic dynamic programming problem with stochastic constraints, which in general is a very difficult problem to deal with. However, we note that our decision variables are binary variables, so efficient algorithms could be potentially developed, especially if we limit ourselves to the threshold type of policy which we have already prove is optimal for the deterministic case. Furthermore, some of the simulation based techniques may be applied to solve this problem, e.g., see (Chang et al. 2005). We should also point out that the chance constraint in (SCDP) may be replaced by other stochastic constraints and it may also be put into the objective function as a penalty term. Some preliminary simulation based results will be reported.

4 CONCLUSION

In this paper, we studied a bacteria prevalence control problem for food supply chain. We first discussed the deterministic version of the problem and presented its formulation, based on which we proved that the optimal prevention policy is of threshold type of policy. We then considered the stochastic version of the problem and formulated it as a stochastic (dyanmic) optimization problem with chance constraints. One further research direction is to develop efficient simulation based methods to solve this problem.

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