

Sourcing Decisions for Goods with Potentially Imperfect Quality under the Presence of Supply Disruption

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1 STAGE OF THE RESEARCH

- Research questions set and expected outcome identified,
 - Methodology determined (stochastic Dynamic Programming with periodic control and numerical analysis),
 - Literature review mostly completed, positioning of the papers done,
 - Preliminary research on numerical analysis and determination of ranges for input parameters
- What is the optimal replenishment and allocation strategy when supply sources differ in their cost, quality protection and reliability?
 - Under which circumstances would a dispenser procure from sources where quality cannot be ascertained?
 - Is multi-sourcing a valuable strategy against recurrent shortages at the expense of potentially receiving inferior product quality?
 - What is the impact of (post-sales) detection ability and timing of inferior quality goods on the optimal allocation policy?
 - What is the value of implementing a track-and-trace system for the dispenser?

2 OUTLINE OF OBJECTIVES

In 2012, counterfeited versions of Avastin– an injectable medicine used to treat cancer– had been (unintentionally) administered to patients in at least 19 clinics, hospitals and pharmacies in the US, potentially harming patients due to a lack of the active ingredient, bevacizumab. Although the Food and Drug Administration (FDA) indicated that the supply of that particular drug was adequate to meet demand, there is an ongoing shortage of some cancer drugs that could increase the incentive of counterfeiters to infiltrate falsified products in legal supply chains (Hellerman, 2012). These types of incidences are quite recurrent. According to a survey conducted by the Pharmaceutical Security institute (PSI) close to 2000 counterfeit incidents were reported in 2012 alone, involving some 100 countries with 523 different pharmaceutical products in a wide array of therapeutic and organic system categories (PSI, 2012).

The aim of this paper is to provide further insights into the optimal periodic review replenishment and allocation policy of a dispenser having access to a pool of alternative wholesalers who differ in their quality protection efforts, delivery reliability and costs. In particular, we are interested in the following research questions:

The analysis aims firstly to inform the policy makers under which conditions medicines are sourced from doubtful providers, and secondly, it will also provide a decision support tool to dispensers on their willingness to invest in a track-and-trace system.

3 RESEARCH PROBLEM

Complex pharmaceutical supply chains enable counterfeiters to push fake products through the distribution channels. Although the prevalence of counterfeits is not exactly known, FDA estimates that approximately 1% of all medicines consumed in developed countries and up to 30% in developing / under-developed countries are fake medicines, causing grave social and financial damages to the societies (WHO, 2010).

Counterfeit goods mimic genuine manufacturers' original products in looks and packaging, however, they possess inferior product attributes potentially leading to resistance and/or adverse effects when (unintentionally) consumed. Recent examples of counterfeited goods that garnered significant media attention is the case of Heparin a blood-thinner provided by Baxter International that caused unexpected

allergic reaction in dialysis patients in 2007 as reported by FDA. Another example is that of cough medicine containing toxic syrup which was unknowingly bought and dispatched by the Panamanian public health sector, resulting in more than 78 deaths. Manufactured in China, this medicine passed through brokers and wholesalers in Asia and Europe and finally reached end-consumers in Latin-America (Pew-Health-Group, 2011).

Even though the distribution channels are dominated by few large wholesalers handling most of the drugs, thousands of smaller distributors exist who buy excess products, repackage and sell them amongst each other. In times of shortages (unavailability of the genuine manufacturer), these distributors are the prime source for downstream buyers, providing the essential drugs at inflated prices. The scattered landscape, combined with high margins and the lack of transparency invite fake producers to mingle their falsified products with the original ones, subsequently harming end-consumers if these counterfeits are not detected beforehand. As technology advances to detect these illegal products, fake producers respond quickly by using sophisticated methods to pass inspections, thus rendering new detection methods ineffective.

In addition to random quality checks performed by local health authorities such as FDA (Food and Drug Administration) in the US, the health care society has allocated significant resources for consumer awareness programs to train medical personnel and end-consumers about the perils associated with fake medicines, including identification of falsified products.

The end-consumer efforts to detect and protect themselves from inferior products, however, rely heavily on subjective measures such as perceived changes in smell, taste or packaging, hence these methods are at best noisy signals for inferior quality. Likewise, medical personnel trained to observe lack of drug effectiveness (LODE) in patients might suspect counterfeit products as a cause, when informed about this potential harm.

To combat against counterfeiting the pharmaceutical industry recently discussed the implementation of track-and-trace systems to increase end-to-end supply chain visibility. This method, once it is prevalent world-wide, will allow the purchaser to gain information about each drug's source and history.

4 STATE OF THE ART

Our work is closely related to the procurement models with dual/multiple sourcing under supply

disruption, random yield models, models with product returns where the quality of the product is questionable, and also models analyzing the impact of counterfeit goods on supply chains.

Inferior quality products, if detected *at the source*, may lead to low yields, high lead times for making the product available to end-consumer, and/or procurement disruption. Mitigation strategies against these supply uncertainties have gained increasing attention from practitioners and researchers alike.

One of the first papers analyzing the advantages of dual sourcing in the context of supply disruption are provided by (Parlar and Perry, 1996) and (Gürler and Parlar, 1997). Both authors consider a firm that can allocate its replenishment among two suppliers with identical costs and with infinite capacity to serve deterministic demand. (Tomlin, 2006), extends this research stream by analyzing a setting where a firm can procure from one unreliable low cost supplier and/or one costly back-up supplier to serve a random amount of end-consumers. In a setting where the back-up supplier may offer volume flexibility, the author characterizes the conditions under which single sourcing, dual sourcing or volume flexibility is optimal.

Similarly, multi-sourcing has been shown beneficial in supply uncertainties such as production yield and lead-time. Examples of authors analyzing the benefit of such mitigation strategies are (Veeraraghavan and Scheller-Wolf, 2008) and (Federgruen and Yang, 2011).

However, in case the detection process is insufficient or *imperfect*, defective products might reach end-consumers. Depending on the physical/financial harm these products cause, such situations may not only lead to losing customers forever, but also to significant penalties on the immediate sellers and/or on other upstream providers. Firms that offer warranties for such products share the risk of these post-consumption failures with the end-consumers. As warranty models constitute an extensive body of literature, we reviewed only the most relevant ones. (Dai et al., 2012) explores the trade-off between an extended warranty protection period to boost sales and the associated warranty costs in case of poor product quality in a single period decentralized supply chain. The authors determine under which conditions quality improvement and warranty extensions should be provided. (Huang et al., 2008) explore periodic inventory systems with replacement warranties. The authors consider stochasticity from two sources, namely from demand and product returns. Under these conditions the authors characterized the system as a warranty

length-dependent threshold policy. An overview of this literature stream is provided by (Murthy and Djameludin, 2002).

This paper concentrates around a particular quality issue and its mitigation strategies, namely the increasing presence of counterfeit products in complex supply chains, with imperfect post-consumption detection.

Recently, some articles have emerged that analyze the potential harm of counterfeit trading. The research stream can be broadly classified into two categories, namely deceptive and non-deceptive counterfeiting. While the latter is concerned with the existence of gray markets in which consumers deliberately buy goods from illegal sources, the former category is composed of goods where the inferior quality counterparts cannot be distinguished by consumers a-priori. Dating back to 1988, (Grossman and Shapiro, 1988) showed that non-deceptive counterfeits can contribute positively to consumer welfare assuming that the illicit market offers inferior products at a lower price. This however is unlikely the case for deceptive goods, such as for pharmaceutical counterfeiting, as consumers do not deliberately buy inferior quality goods as is the case for non-deceptive goods. Since consumers can not distinguish the genuine product from the fake ones price discounts are usually not transferred.

(Soo-Haeng et al., 2011) addressed these distinct supply distribution systems in a game-theoretic setting and discussed the sensitivity of each counterfeit system with respect to various anti-counterfeit actions. Similar analyses have been provided by (Zhang et al., 2012), (Lybecker, 2007) and (Zhang, 2011). A literature review composed of empirical and modeling approaches discussing counterfeiting is provided by (Staake et al., 2009). While the aforementioned papers all propose a game-theoretic model in which the decision maker is deliberately choosing its quality product mix, they neglect the operational decisions (e.g. inventory decisions). (Liu et al., 2004) take this operational view point by studying a one-period newsvendor model. The authors assume that the buyer deliberately chooses the quality based on cost margins, while random checks hinder the decision-maker from acquiring inferior quality products.

5 METHODOLOGY

In an environment where numerous entities are involved in distributing and handling medicines and

medical shortages are recurrent, security breaches exists. This section analyses the optimal periodic review replenishment and sourcing policy from the perspective of a dispenser having access to multiple sources that differ in their cost, disruption and quality reliability. In particular, we discuss conditions under which dispensers might be compelled to procure the needed drug from potential inferior sources as a mitigation strategy against supply uncertainties. In a setting where quality can be at best revealed after end-consumers' consumption—potentially leading to medication errors—fake drugs not only result in social tolls for individuals but also in financial costs including higher operational expenses and/or law suits against dispensers. We proceed by quantifying the information gain obtained by the dispenser when track-and-trace systems are implemented. The later analysis aims to inform the health care society to set appropriate incentives in order to fasten the adaptation of such systems that can protect patients from the pervasive risk of counterfeit products.

We use the following mathematical notation in this paper: $[x]^+ = \max\{x, 0\}$, $[x]^- = -\min\{x, 0\}$. Further, we let $\mathbf{x} = (x_0, x_1, \dots, x_n)$ denote a vector and $x = \sum_{i=0}^n x_i$ refers to the sum of its components, unless otherwise indicated. $\mathbf{x}_{-i} = (x_0, x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_n)$ is used to indicate the vector of components other than i .

5.1 Model

We concentrate our study on the optimal periodic replenishment policy of a single product from the perspective of a cost minimizing dispenser (e.g. hospitals/pharmacies) serving a random number of homogeneous end-consumers over a finite horizon with length denoted by T . We assume that the potential number of end-consumer to be treated is large and the requests are independent across different periods, which essentially allows us to represent the end-consumers' request by a random variable D with probability distribution $f_D(\xi)$. The dispenser has access to N sources, namely a genuine manufacturer and various wholesalers. We represent the vector of all suppliers by $\mathbf{W} = (0, 1, 2, \dots, N-1)$, where $j \in \mathbf{W}$ denotes the j 'th wholesaler and $j = 0$ is associated with the genuine manufacturer.

Although the genuine manufacturer certainly sells only high quality products, it also randomly announces shortages. When this happens, the genuine manufacturer is unavailable, leaving the dispenser with the option to operationally insure supply through the remaining $N-1$ wholesalers. We will refer to such a situation as a “down” period with procurement

option $\mathbf{W}_{-0} = (1, 2, \dots, N-1)$ and indicate the availability of the genuine manufacturer by an “up” period (with sourcing option \mathbf{W}). We model the genuine manufacturer’s availability as being in one of the two states, which we denote by $\delta \in \{0, 1\}$: either he is available (in an “up” state $\delta = 0$) with some probability π or not (i.e. in a “down” state $\delta = 1$) with probability $(1 - \pi)$, where π is the parameter of a Bernoulli distribution known before a sourcing decision is made.

These wholesalers, although available at all times with ample capacity, differ in their safety efforts, hence potentially carry inferior quality products. That is, wholesalers might have procured a sufficient amount of goods from genuine manufacturers prior to a shortage announcement to profit from the increased margin that can be obtained when supply is scarce and/or use non-secure channels risking fake products to enter.

In any case, when procuring from wholesaler j a random proportion $\Theta_j \in [0, 1]$ of the procurement quantity will be of inferior quality with mean β_j for all $j \in \mathbf{W}$. The probability distribution $g_j(\theta)$ is assumed to be time invariant and independent of the order quantity. This assumption is consistent with proportional random yield models. For notational reasons, we indicate $j = 1$ as the wholesaler with the lowest mean of delivering inferior products and ranking the remaining ones accordingly from lowest to highest. That is $\beta = (\beta_0, \beta_1, \dots, \beta_j, \dots, \beta_{N-1})$ represents an ordered vector of inferior quality procurement assumed to be time invariant with the genuine manufacturers’ expected quality unreliability normalized to zero ($\beta_0 = 0$) such that $\beta_0 < \beta_1 < \beta_2 < \dots < \beta_{N-1}$. The procurement cost of each source is denoted by c_j for all $j \in \mathbf{W}$. Although it is possible that some sources might offer the desired product for a lower price than the genuine manufacturer itself, we assume that the cost of procuring from the genuine manufacturer $j = 0$ is at most the cost of any other source ($c_0 \leq c_j \quad \forall j \in \mathbf{W}_{-0}$). This allows us to approximately capture the steep price increase offered by wholesalers when shortages persist and ensures that the genuine manufacturer, when available, will be selected as one of the primary sources.

It is questionable whether prices offered by wholesalers can signal inferior product quality in times of shortages. For instance a survey conducted by (Bate et al., 2012) suggests that less protected sources offer almost no price-discount relative to the original genuine manufacturer. According to the authors, non-price signals such as chain affiliation of the wholesalers or pharmacies may lead to more accurate results when assessing drug quality, although do not en-

sure either high quality procurement with certainty. This findings suggests that the procurement prices c_j in times of shortages may be arbitrary with respect to the perceived amount of counterfeits a wholesaler may carry, while the perceived amount of acquiring falsified versions from wholesaler j , may be formed by the particular dispenser based on other factors.

Assumption 1a: In times of genuine manufacturers’ shortage announcement metrics other than costs form the the dispenser’s belief about the sources protection capability: c_j for each $j \in \mathbf{W}_{-0}$ is arbitrary relative to other sources’ procurement costs.

This assumption states, that a price discount from a source is not necessarily a signal for potential lower quality goods.

However, due to the complexity of the pharmaceutical supply chain, it might be difficult or almost impossible for a dispenser to perform a thorough quality assessment of the source, especially in times when medications are needed instantaneously. In this case, costs might still be used to assess the quality of the source.

Assumption 1b: In times of genuine manufacturers’ shortage announcement, the dispensers’ belief about the wholesalers’ protection effort is based on the procurement costs: $c_1 > c_2 > \dots > c_{N-1}$ This assumption on the other hand states, that when for instance an offer is below the market value, the dispenser might suspect a higher percentage of inferior goods.

Therefore, we will separately analyze both, a cost and a non cost metric to assess the perceived protection efforts of wholesalers:

The dispenser, in any period $t \in (0, \dots, T)$, first observes the state of the genuine manufacturer δ used to decide from whom to procure the desired quantity, to be able to serve the random number of end-consumers. We assume that the lead-time is zero, that is, goods ordered in period t arrive in the same period and can be used to meet end-consumers demand within that period while unmet demand is lost. Further, let the on-hand inventory in period t be indicated by $\mathbf{x}_t = (x_{0,t}, x_{1,t}, \dots, x_{N-1,t})$ with $x_{j,t}$ representing the amount of products in stock from supplier j . We further denote with x_t the total on-hand inventory in period t before the receipt of current orders. Likewise, let $\mathbf{y}_t = (y_{0,t}, y_{1,t}, \dots, y_{N-1,t})$ represent the vector of orderings in period t and let $\mathbf{z}_t = (z_{0,t}, z_{1,t}, \dots, z_{N-1,t})$ account for the amount of inventory after ordering before demand realizes.

The total on-hand inventory after ordering, z_t , in period t is given by:

$$z_t = x_t + y_t = \sum_{j=0}^{N-1} x_{j,t} + \sum_{j=0}^{N-1} y_{j,t} \quad (1)$$

In addition, we assume that the dispenser will deplete the drugs with decreasing order of perceived quality reliability. For instance, the dispenser will first use the stock from the wholesaler, perceived to be the most quality-protected one and in case of insufficient stock he will proceed with depleting inventory from wholesalers' $j = 1, 2, \dots, N - 1$ procurements. The inventory dynamics \mathbf{x}_{t+1} can be described as follows:

$$\begin{aligned} x_{0,t+1} &= (z_{0,t} - D)^+ \\ x_{j,t+1} &= (z_{j,t} - (D - \sum_{i=0}^{j-1} z_{i,t})^+)^+ \quad \forall j = 1, \dots, N - 1 \end{aligned} \quad (2)$$

That is, all demand not filled by stock from presumably higher quality protected sources will be filled by lower ones given its instock availability.

We denote the per period per unit inventory holding cost incurred through purchases from wholesaler j by h_j and assume that unmet demand is lost, resulting in a lost sales cost of p . In the situation of essential drugs this per person lost sales cost can be substantial, especially when the interruption of medical treatments may result in long lasting consequences such as is the case of antivirals used for HIV patients. Unless strategically interrupted treatments are prescribed by medical professionals, the non-adherence to daily dosages of antivirals may lead to patients developing resistance against the drug in use, and in turn may result in high switching costs from first to second line treatments (Chesney MA, 1999).

Model without Track-and-Trace System

In this section we analyze the dispenser's optimal procurement and allocation strategy under the circumstances of not having a track-and-trace system implemented as is the case of today's pharmaceutical distribution chains. The dispenser in this situation is unable to discover counterfeits before administering fake drugs to patients, hence relies on the feedback from patients and medical personnel.

Administering inferior quality goods to patients potentially render treatments ineffective and may cause medication errors. In a recent study conducted by McKinsey, (Ebel et al., 2013), medication errors induced by dispensers can have several roots, including unintentional fake drug prescription. It is estimated that these errors occur in 10 – 20% of all inpatient hospital admissions, one third of which result in adverse drug events (ADE). Each of these ADE's not only result in high social tolls but also in direct financial costs estimated to amount to USD 4000 to 8000 per person in the US.

For our study we consider only the measurable costs

associated directly to the procurement of counterfeits by the dispenser. Though we are aware that the true social and financial harm induced by fake products is far higher, estimating these global economic and social costs of drug-counterfeiting is a challenge to the health community. These costs include but are not only limited to tax related costs, reputation damage, lost sales, operational expenses, quality assurance and social harm.

In addition to these estimation difficulties, counterfeit drugs, even when consumed, can go undetected by individuals due to the subjective measures of counterfeits like changes in smell, taste or packages, lack of drug effectiveness (LODE) and/or adverse effects. These medication errors are assumed to occur with one period time-lag after prescription of the drug. Due to these noisy detection principles associated with counterfeits patients and medical personal might not always be aware of the causes associated with medication errors. We will model this situation by assuming that with some known probability γ , end-consumers having received a fake product will suffer from a medication error caused by counterfeit prescription. Each harmed end-consumer that returns due to fake drug consumption will incur a per patient cost denoted by R . This cost can represent an increase in operational health cost associated with medication errors such as switching to an alternative drug, further examinations and/or costs associated to law-sues. Since this counterfeit related cost only accounts for the proportion which is internalized by the dispenser, it is an underestimate of the true social cost. For mathematical clarity we additionally assume that individuals having received a high quality drug will not suffer medication errors or, in other words, medication errors arising from non-procurement related causes are normalized to zero.

The potential number of end-consumers returning due to medication errors resulting from wholesaler j in period t is denoted by $s_{j,t}$ and the dynamics are defined as follows:

$$s_{j,t+1} = \Theta_j \left[\min \left\{ \left(\xi - \sum_{i=0}^{j-1} z_{i,t} \right)^+, z_{j,t} \right\} \right] \quad \forall j \in W_{-0} \quad (3)$$

Where $s_{j,t+1}$ represents the potential medication errors induced by supplier j 'th procurement. It is composed of demand served from wholesaler j 's procurement when the inventory from more quality reliable suppliers was insufficient, adjusted by the probability of administering fake products. In other words, the potential number of patients' suspecting counterfeit in the next period is determined by the sales of goods from supplier j 'th inventory in period t

and the random fraction of carrying inferior products. Further, s_t represents the total potential medical errors arising from inferior product procurement ($s_t = \sum_{j=1}^{N-1} s_{j,t}$).

In addition we assume throughout this study that fixed costs are negligible, a situation that might be relaxed in the extension.

Then, the immediate expected costs can be expressed as:

$$\begin{aligned} & \sum_{j=0}^{N-1} c_j(z_{j,t} - x_{j,t}) + R\gamma s_t \\ & + \sum_{j=0}^{N-1} h_j E[(z_{j,t} - (D - \sum_{i=0}^{j-1} z_{i,t})^+)^+] \\ & + pE[(D - z_t)^+] \end{aligned} \quad (4)$$

Where the holding cost component is derived from applying the previously explained depletion rule used by the dispenser (provide the drugs in decreasing order of perceived quality reliability).

The cost minimizing dispenser incurs the total purchasing cost from all available suppliers, cost associated with suspected medication errors associated with end-consumers return, holding costs and lost sales costs.

For mathematical purposes we define $g_t(\mathbf{z}_t, s_t)$ as the immediate expected costs plus the current on hand inventory before ordering:

$$\begin{aligned} & g_t(\mathbf{z}_t, s_t) \\ & = \sum_{j=0}^{N-1} c_j(z_{j,t}) + R\gamma s_t \\ & + \sum_{j=0}^{N-1} h_j E[(z_{j,t} - (D - \sum_{i=0}^{j-1} z_{i,t})^+)^+] \\ & + pE[(D - z_t)^+] \end{aligned} \quad (5)$$

The dispenser's objective is to minimize the expected cost over T periods. Hence, the Bellman equations for "up" ($\delta = 0$) and "down" ($\delta = 1$) periods are given

by:

$$\begin{aligned} V_t(\mathbf{x}, s, 0) = \min_{z_{j,t} \forall j \in \mathbf{W}} & \left\{ g_t(\mathbf{z}_t, s_t) \right. \\ & \left. + E[V_{t+1}(\mathbf{x}_{t+1}, s_{t+1}, \delta)] \right\} - \sum_{j=0}^{N-1} c_j x_{j,t} \end{aligned} \quad (6)$$

$$\begin{aligned} V_t(\mathbf{x}, s, 1) = \min_{z_{j,t} \forall j \in \mathbf{W}_{-0}} & \left\{ g_t(\mathbf{z}_t, s_t) \right. \\ & \left. + E[V_{t+1}(\mathbf{x}_{t+1}, s_{t+1}, \delta)] \right\} - \sum_{j=0}^{N-1} c_j x_{j,t} \end{aligned} \quad (7)$$

$$\text{s.t. } z_{0,t} \geq x_{0,t}$$

...

$$z_{j,t} \geq x_{j,t}$$

...

$$z_{N-1,t} \geq x_{N-1,t}$$

For convenience, we assume that in period 0 the genuine manufacturer is available $V_0(\mathbf{x}, s, 0)$ with initial inventory and potential future medication errors given by $\mathbf{x}_0 = 0$ and $s_0 = 0$. Further, the terminal value function is represented by

$$\begin{aligned} & V_{T+1}(\mathbf{x}, s, \delta) \\ & = R\gamma E[s_{T+1}] = R\gamma \sum_{j=0}^{N-1} E[\Theta_j \min\{(D - \sum_{i=0}^{j-1} z_{i,t})^+, z_{j,t}\}] \end{aligned} \quad (8)$$

That is, we extend the terminal value function to account for medication errors resulting from consumption of fake products in period T .

5.1.1 Model with Track-and-Trace System in Place

Opposed to the before-hand mentioned *post-consumption* counterfeit revealing method we now focus on the optimal periodic replenishment and allocation strategy when a track-and-trace system is in place. That is, instead of suspecting counterfeit post-consumption, the dispenser now is capable of filtering out quantities from doubtful origins prior to circulating the products to end-consumer. Since the pharmaceutical supply chain is scattered, with most suppliers and wholesalers trading medications worldwide, product liabilities is rarely enforceable in today's inconsistent legal systems. Even if supply chain members and/or government authorities are able to locate the counterfeit source it is unlikely that

members involved reimburse downstream members. We will hence assume that track-and-trace systems will be implemented without wholesalers being held liable for selling inferior products. We define Ξ_j as the random fraction of goods procured from supplier j which were genuine with probability distribution $h_j(\cdot)$: Further we approximate the effect of this new technology implementation by assuming that the dispenser will perform full-inspections of incoming goods and in case a suspicious good is found it will be subsequently discarded. The immediate cost function for such a system can be written as:

$$\begin{aligned} \tilde{g}_t(\mathbf{y}_t, \mathbf{x}_t) &= \sum_{j=0}^{N-1} c_j(y_{j,t}) \\ &+ \sum_{j=0}^{N-1} h_j E_{D, \Xi_j} [(x_{j,t} + \Xi_j y_{j,t} \\ &- (D - \sum_{i=0}^{j-1} x_{i,t} + \Xi_i y_{i,t})^+)^+] \\ &+ p E_{D, \Xi_j} [(D - \sum_{i=0}^{N-1} x_{i,t} + \Xi_i y_{i,t})^+] \end{aligned} \quad (9)$$

The dispenser will pay the procurement cost to each wholesaler j , perform a check of the source and incur holding cost for the random fraction Ξ of those units which are not detected as (and, therefore, are not) inferior. Then the dispensers' cost minimization problem is given by:

$$\tilde{V}_t(\mathbf{x}, 0) = \min_{y_{j,t} \geq 0 \forall j \in \mathbf{W}} \left\{ \tilde{g}_t(\mathbf{y}_t, \mathbf{x}_t) + E[\tilde{V}_{t+1}(\mathbf{x}_{t+1}, \delta)] \right\} \quad (10)$$

$$\tilde{V}_t(\mathbf{x}, 1) = \min_{y_{j,t} \geq 0 \forall j \in \mathbf{W}_{-0}} \left\{ \tilde{g}_t(\mathbf{z}_t, \mathbf{x}_t) + E[\tilde{V}_{t+1}(\mathbf{x}_{t+1}, \delta)] \right\} \quad (11)$$

With terminal cost function

$$\tilde{V}_{T+1}(\mathbf{x}, \delta) = 0 \quad (12)$$

6 EXPECTED OUTCOME

Recurrent shortages of essential drugs by themselves undermine the effective delivery of medicines due to steep price increases that persist when demand exceeds supply. Counterfeiters using such supply-constrained environments to infiltrate their drugs aggravate this situation even more.

This Ph.D. project aims to capture the intricate issues affecting the decision of medicine dispensers when facing observable and perceived uncertainties originated from supply disruptions, demand variability and

product quality. The problem is mathematically rich and, at the same time, can provide important insights on how to approach the implementation of quality detection mechanisms such as track-and-trace systems, which in turn can have substantial impact on the effective delivery of public health.

Upon completion of this project, we expect to have achieved the following:

- Develop a dynamic programming model for the dispenser's problem considering the existence of uncertainties from three different sources, extending the literature stream on stochastic multi-sourcing/multi-period models.
- Implement the model within a decision support tool that can be of use to pharmaceutical supply chain stakeholders in assessing their optimal risk mitigation strategies.
- Generate insights for public health officials and pharmaceutical manufacturers about the incentives of supply chain partners for adopting new technologies to increase visibility and combat against counterfeits, as well as the role of supplier unavailability in inducing the procurement of potentially inferior-quality drugs.

At the current stage of this work, and using the models described in the previous sections, we are starting to gain some insights and develop some conjectures on how these trade-offs develop for pharmaceutical dispensers. Specifically, regarding the procurement of inferior quality products, we believe that at least when costs form the perception of inferior quality procurement (e.g. $c_1 > c_2 > \dots > c_{N-1}$) a global optimal sourcing and allocation strategy can be found. This allocation may depend on the marginal differences of procurement costs, holding costs, perceived inferior quality and the return costs.

Second, our results seem to indicate that the less likely patients and medical personnel raise suspicion ($\gamma \rightarrow 0$), the more these inferior products will go unnoticed and become used as perfect substitutes, reducing the impact of improving visibility. Also, the value of the track-and-trace system is given by the difference of random yield and circulation; however, if γ is small then such a track-and-trace system would make the pharmacy worse off than before, in addition to the implementation and administration costs. If this holds true, it becomes critical for public authorities and manufacturers to develop proper incentive schemes and legal frameworks to reduce the financial burden for dispensers in participating in the ever-growing fight against counterfeiting.

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