European Journal of Operational Research xxx (xxxx) xxx

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing, Transportation and Logistics

# Government regulations to mitigate the shortage of life-saving goods in the face of a pandemic

Dong Li[a], Chuanwen Dong[b,*]

[a] School of Business, Sun Yat-sen University. 135 Xingang Xi Road, Guangzhou, China
[b] ESCP Business School, Heubnerweg 8-10, Berlin, Germany

ARTICLE INFO

*Article history:*
Received 1 June 2021
Accepted 19 November 2021
Available online xxx

*Keywords:*
Supply chain management
COVID-19 pandemic
Government regulation
Shortage mitigation
Panic buying

ABSTRACT

During a pandemic, it is essential to secure a broad allocation of life-saving goods, such as medical and protective products, to save lives. However, these goods are often in short supply, due to consumer hoarding, insufficient manufacturing capacity and price gouging. Herein, we develop a game-theoretic supply chain model to evaluate the impact of government regulations on the shortage of life-saving goods and profit within the supply chain. Our model considers three types of regulation: (i) price regulation in the form of a price cap, (ii) purchase regulation or demand rationing and (iii) a combination thereof. The most distinguishing feature of our model is that it captures consumer panic buying, insufficient capacity, price surges and controls on the supply and demand side of the supply chain that are widely observed during a pandemic. The results establish reasonably simple prescriptions for policymakers to design effective and easy-to-implement regulations to mitigate shortages of critical supplies in the face of a pandemic.



## 1. Introduction

Since winter 2019, an outbreak of pneumonia from a novel coronavirus has affected people worldwide. The World Health Organization (WHO) recognised the coronavirus disease 2019 (COVID-19) outbreak as a pandemic (WHO, 2020a). As of September 2021, more than 231 million cases have been confirmed, with over 4.73 million deaths attributed to COVID-19 (JHU, 2021), making it one of the deadliest pandemics in human history. The increasing number of cases and widening geographical spread have raised grave concerns regarding its socioeconomic impacts. The outbreak is regarded as "the greatest test that we have faced together since the formation of the United Nations" (UN2, 2020).

One crucial challenge during the pandemic has been a severe global shortage of *critical life-saving goods*, such as personal protective equipment (PPE), drugs, sanitisers, disinfectants, etc. Burki (2020); Ranney, Griffeth, & Jha (2020); WHO (2020b). This shortage has not been a short-term shock: months after the outbreak of the pandemic, medical supply issues in the U.S. have still not been solved, and if anything, they are getting even worse (Finkenstadt, Handfield, & Guinto, 2020), thereby putting lives at risk across the world (WHO, 2020b) and exerting pressure on firms to rethink their supply chain operations.

On the supply side, firms are struggling to fulfill their orders, as insufficient raw materials, inflexible production lines, suspended logistics flows, etc. are limiting the supply of critical life-saving goods to the market. However, even though supply is already below market demand, the limited amounts of critical goods are not equitably distributed to consumers, due to hoarding. At a tangible level, panic buyers stockpile goods as long as they are available and affordable. This irrational behaviour weakens the market and further exacerbates shortages (Campbell, Inman, Kirmani, & Price, 2020). Sellers, on the other hand, take the opportunity to raise prices in order to generate higher profits. (WHO, 2020b) have noted that since the start of the pandemic, the price of surgical masks has increased sixfold, the price of N95 respirators has trebled and the price of surgical gowns has doubled.

Such market distortion calls for government intervention. The design of regulations is a highly challenging task, since policymakers must consider supply chains disrupted by both the supply and the demand side during a global pandemic. To date, a significant amount of governmental effort has been expended on: pricing control on the supply side (e.g. capping the selling price of products – as observed in Italy Rotondi, 2020), purchase control on the de-

* Corresponding author.
*E-mail addresses:* lidong9@mail.sysu.edu.cn (D. Li), cdong@escp.eu (C. Dong).

https://doi.org/10.1016/j.ejor.2021.11.042

mand side (e.g. rationing consumer demand – as reported in the U.S. Emanuel et al., 2020) and a combination thereof (e.g. limiting purchase quantity and price in Korea Kim, 2020 and Taiwan Glazer, 2020). However, despite heated discussions in media reports (e.g. NYT, 2021), the impact of regulations still lacks comprehensive characterisation in academia (e.g. Chowdhury, Paul, Kaisar, & Moktadir, 2021; Sodhi, Tang, & Willenson, 2021).

In this paper, we develop a novel supply chain game-theoretic model to support governments in designing supply chain regulations to mitigate the shortage of critical life-saving goods during a pandemic. We propose an innovative approach to modelling *consumer panic buying* observed in the pandemic. This phenomenon should be distinguished from *consumer hoarding* studied in the *field of marketing* (e.g. Meyer & Assunç ao, 1990). The latter is interpreted as consumers' strategic responses to price promotion, i.e. when the price is low, consumers will plan ahead and stock up for future consumption; instead, consumer panic buying is a response to external threats in times of trouble and has only recently been conceptually framed in the *field of consumer research* (Campbell et al., 2020). Recent panic buying during the COVID-19 pandemic has also raised much interest in the *field of economics*, though it is claimed that current economic theory cannot provide a satisfactory explanation for this behaviour (Noda & Teramoto, 2020). In the *field of OR/OM*, a few studies have examined consumer panic buying behaviour (Zheng, Shou, & Yang, 2021). In the models provided by Yoon, Narasimhan, & Kim (2018) and Zheng et al. (2021), for instance, consumers are heterogeneous in their subjective beliefs in relation to product shortage. Both studies reveal the existence of a "belief-threshold," whereby consumers with a higher belief in shortage hoard two units of goods; otherwise, they only place a standard order of one unit. However, their model does not allow consumers to hoard an arbitrary amount of goods, including nothing. Their assumption also cannot explain the recent empirical findings by academia (Hansman, Hong, de Paula, & Singh, 2020) and the media[1] that hoarding has been concentrated in richer households during the COVID-19 pandemic. Our model, instead, suggests examining consumer panic buying on the basis of their willingness to pay (WTP) and therefore allows a consumer with a higher WTP to hoard more.

We argue for a distinct objective to evaluate the effectiveness of government regulations in the face of the pandemic, i.e. to minimise the shortage of critical life-saving goods, instead of any monetary-related terms. Traditionally, the natural assessment of a regulation is the net benefit obtained in monetary terms (e.g. Pacces, 2012). Since the Ford administration (referring to Executive Order No. 11821 issued in 1974), every U.S. president has established a formal system to review the benefits and costs of regulations. If the benefits of a policy do not exceed the costs, then clearly it should not be pursued. Such efforts are coined "cost-benefit analysis" (CBA). However, the U.S. Supreme Court has remained sceptical of using CBA in the assessment of regulations related to health, safety and environmental matters. In *American Textile Manufacturers Institute v. Donovan*, for example, the Supreme Court explicitly prohibited Occupational Safety and Health Administration (OSHA) from basing its regulation on CBA[2] (e.g. Viscus, Harrington, & Sappington, 2018). Considering the severe market distortion and devastating death toll caused by the COVID-19 pandemic, the objective of the corresponding regulations should be arguably unique. It has been observed across the world that governments are highly concerned about protecting their people with sufficient life-saving goods, and, in contrast, they have hardly focused on the profits of life-saving goods manufacturers or the surplus consumers with access to these goods (e.g. The European Council, 2021; TWH, 2021). To be consistent with these concerns, the objective of any government regulation is set to mitigate shortages of life-saving goods, rather than any other monetary-related terms. Nevertheless, the impact on firms' profit cannot be underestimated, so we include a discussion on this issue when analysing how well regulations perform.

We examine the performances of three interventions: price regulation (limitations on retail prices), purchase regulations (limitations on purchase quantities) and both options. These three regulations have been observed across the world during the COVID-19 pandemic (e.g. Emanuel et al., 2020; Kim, 2020; Rotondi, 2020). Interestingly, we find that consumer panic buying is *not* always detrimental to the supply shortage, and a purchase regulation that prevents consumer hoarding can reduce the shortage rate only when production capacity is rather small compared to demand. In contrast, when production capacity is ramped-up, the standard price regulation, which caps the product retail price with a price ceiling, can stimulate the supplier to produce more (we define this as the *production-boosting effect*) and mitigate the shortage rate; however, its impact must be evaluated in combination with the *hoarding-exacerbation effect*, under which a lower price stimulates consumers to stockpile more and therefore exacerbates the shortage. We then propose a new *relative* price regulation that caps the ratio of the wholesale price in relation to the retail price. We show that such a price regulation is immune to the hoarding-exacerbation effect and is more effective in mitigating the shortage rate. Mixed regulation combining both the (relative) price and purchase regulation always outperforms purchase regulation, but it performs better than relative price regulation only when production capacity is smaller than the demand. Besides evaluating the impact on the shortage rate, we also compare the impact of the regulations on supply chain profit. Interestingly, an appropriately designed relative price regulation can not only reduce the shortage rate, but it can also alleviate double marginalisation in the supply chain and increase profit.

Our analysis extends existing knowledge on supply chain management during a pandemic and provides easy-to-implement prescriptions for policymakers to mitigate the shortage of critical life-saving goods. Our study is a timely answer to the latest literature reviews on pandemic-related supply chain studies calling for research on guidance for policymakers (Chowdhury et al., 2021; Sodhi et al., 2021).

## 2. Related literature

Our cross-disciplinary research is related to the OR/OM perspective of (1) infectious disease management and (2) government regulation studies.

### *2.1. Infectious disease management*

This study contributes to the broad field of infectious disease management from an OR/OM perspective (e.g. Keskinocak & Savva, 2020). (Ekici, Keskinocak, & Swann, 2014) consider the problem of delivering food to households during an influenza pandemic and design a distribution network that is responsive and yet computationally efficient. Deo & Sohoni (2015) propose a simulation model to allocate HIV diagnostic devices to health facilities in an efficient manner. Long, Nohdurft, & Spinler (2018) develop a two-stage model for optimising a time and location to assign Ebola treatment units during the outbreaks early phases and compare

[1] For example, the *Washington Post* reports that the pandemic has worsened income inequality, and a growing number of Americans can simply not afford to stock up on groceries (Bhattarai, 2020).

[2] The Court wrote:"In effect, then, as the Court of Appeals held, Congress itself defined the basic relationship between costs and benefits by placing the 'benefit' of worker health above all other considerations save those making attainment of this 'benefit' unachievable."

the performance of several policies. Silal (2020) reviews a wide range of problem-solving techniques and computational methods and shows how operational research can strengthen health systems and support decision-making at all levels of disease control.

Within the aforementioned broad area, much interest has been raised in relation to developing new OR/OM methods to manage supply chain disruptions since the outbreak of the COVID-19 pandemic. Queiroz, Ivanov, Dolgui, & Fosso Wamba (2020) apply a systematic literature review approach to reveal a future research agenda for supply chain management amid the pandemic. Craighead, Ketchen, & Darby (2020) and Ivanov & Dolgui (2021) discuss the use of well-established and emerging theories, such as game theory, network theory, prospect theory, etc., to analyse the disruption to supply chains caused by the pandemic. Ivanov & Dolgui (2020) reveal a novel angle of viability, i.e. the system's ability to meet the demands of surviving in a changing environment, in order to analyse supply chain disruptions in the face of a pandemic. In a follow-up study, Ivanov (2021) proposes a conceptual and formal generalisation of four major adaptation strategies to align with supply chain viability. Nikolopoulos, Punia, Schäfers, Tsinopoulos, & Vasilakis (2021) forecast COVID-19 growth rates using machine learning methods, Taylor & Taylor (2021) forecast COVID-19 mortality in the U.S. using a novel weighted combining method and Benítez-Peña et al. (2021) apply sparse ensemble methods to predict the evolution of COVID-19. Sinha, Kumar, & Chandra (2021) develop several models to ensure required service levels for COVID-19 herd immunity in the Indian vaccine supply chain. Nagurney (2021) constructs a game theory supply chain network model, subject to labour constraints. She obtains a generalised Nash equilibrium and reveals the impact of labour shortages on production disruption and the profit of firms. Li, Chen, Collignon, & Ivanov (2021) develop an agent-based computational model to simulate supply chain disruption propagation and distinguish different approaches to mitigate forward and downward propagation. Gupta, Ivanov, & Choi (2021) study firms' pricing strategies during a supply disruption episode by using the Nash and the Stackelberg game theory models.

Our work is different from the above studies in the following regards. First, we examine how to regulate the supply chain to reduce the supply shortage rate. Second, these papers mainly discuss the supply side, i.e. the internal operation of the supply chain, and not the demand side, i.e. consumer purchasing behaviour that leads to supply shortages. In contrast, we model consumer panic buying and investigate its impact on supply chain decisions. Third, these papers do not consider the role of government interventions. The recent literature reviews by Chowdhury et al. (2021); Sodhi et al. (2021) call for further research on public policies in terms of mitigating supply chain disruptions, and so our study is a timely answer to these calls.

### 2.2. Government regulation

Government regulation is a central element in the culture of microeconomics. Traditionally, this field relates to *economic* regulations in industries where competition is problematic or, allegedly, undesirable (Pacces, 2012). For example, government regulates the prices of public utilities (electricity, water, etc.), whose suppliers hold natural monopolies in the market. Since the beginning of the twentieth century, an increasing amount of effort has been placed on *social* regulations in terms of health, safety and environmental issues (Viscusi et al., 2018); for example, governments devise enforcement mechanisms to avoid health hazards imposed by workspace conditions.

The OR/OM community has been actively studying the interactions between various industry organisations and government policies (Joglekar, Davies, & Anderson, 2016). A major finding of this review paper is the heterogeneity of the objectives/measures of government regulations across industrial practices. For example, a waste regulation aims to reduce electronic waste, an environmental regulation promotes the adoption of technology to reduce emissions, and a healthcare regulation measures medicare cost savings. Taylor & Xiao (2014) study subsidising the distribution channel to improve the availability of Malaria drugs. Chen & Rao (2020) evaluate the impact of tax and price regulations on consumers' smoking behaviour. Akkaya, Bimpikis, & Lee (2021) investigate the impact of government policies on the adoption of innovative agriculture technology, and Anand & Giraud-Carrier (2020) find that a well-chosen regulation on $CO_2$ pollution can reduce pollution and increase firms' profits at the same time.

A few studies in this stream of the literature also consider supply chain settings. Arifoğlu, Deo, & Iravani (2012) study the impact of yield uncertainty (supply side) and self-interested consumers (demand side) on inefficiency in the influenza vaccine supply chain and investigate the relative effectiveness of government interventions on the supply and demand sides under various demand and supply characteristics. Kazaz, Webster, & Yadav (2016) model the Artemisinin supply chain and find that interventions to improve average yield, to create a support price and to manage semi-synthetic Artemisinin supply have the greatest potential for reducing price volatility.

Our study contributes to this body of literature by investigating government regulations on mitigating the shortage of life-saving goods in the face of a global pandemic, which, to the best of our knowledge, has never been studied before. Compared to these papers, our model has distinct settings. First, the aforementioned papers consider the normal state, where the inefficiency of the healthcare resource supply chain is mainly caused by operational uncertainties (yield, market price, etc.). In contrast, we consider the emergency state, where supply chain inefficiency is caused by capacity lockdown, price gouging and consumer panic buying. Second, interventions in these papers have mainly been subsidy policies, whereas in this paper, we discuss regulations that can reduce shortages without the need for government expenditure. In this regard, this paper resembles (Chen, Yang, & Wang, 2019), who investigate how price cap regulation affects pharmaceutical firms' pricing decisions in the supply chain. Compared to their model, our investigation of the regulations is more comprehensive, since we not only consider price regulation, but we also consider purchase regulation and a combination of the two options. In addition, the aims of shortage reduction and consumer panic buying are not captured in their model.

## 3. Model setup

The aim of this study is to support policymakers in designing supply chain regulations to mitigate the shortage of life-saving goods. We consider a two-stage supply chain with a supplier that manufactures the product and a retailer that sells it to heterogeneous consumers with panic buying behaviour. Regulations can be applied to the supply chain firms, who decide on production quantity and the prices they charge consumers.

In this section, we first model consumer panic buying and formulate the demand function in Section 3.1. We then introduce the supply chain partners decision game in Section 3.2. We define the shortage rate used to measure the supply shortage in Section 3.3 and present the equilibrium outcome without any regulations, which is the benchmark for evaluating the performance of the regulations in Section 3.4.

### 3.1. Consumer panic buying and market demand

Consider a continuum of risk-neutral consumers with a heterogeneous willingness to pay (WTP), denoted as $v$, uniformly distributed in $[0, \bar{v}]$. The essential demand required from each consumer is normalised to 1 (e.g. one facial mask per day), in which case total *nominal demand* in the market is $\int_0^{\bar{v}} dv = \bar{v}$.

The question arises as to how to measure quantitatively the demand of panic hoarders. As a point of departure, recent empirical studies have found that hoarding is concentrated in rich households (Bhattarai, 2020; Hansman et al., 2020). To capture such consumer behaviour, we assume a consumer compares his WTP $v$ with the selling price $p$ and then decides how much to hoard. If $v$ is smaller than $p$, he/she will not (be able to afford to) purchase anything; if $v = p$, he/she will purchase the essential volume 1; and if $v > p$, the hoarding volume $y(v, p)$ is larger than the essential demand 1. The *real demand* of a consumer with WTP $v$ is then:

$$d(v, p) = \begin{cases} y(v, p) & \text{if} \quad v > p, \\ 1 & \text{if} \quad v = p, \\ 0 & \text{if} \quad v < p. \end{cases} \tag{1}$$

Furthermore, the paradigmatic approach in the OR/OM literature is to model the demand function $y(v, p)$ in either an additive fashion or a multiplicative fashion (e.g. Cohen, Lobel, & Perakis, 2016; Petruzzi & Dada, 1999). The former represents a linear demand curve and the latter an iso-elastic demand curve. From an economics perspective, the two demand functions demonstrate contrasting price elasticity of demand (PED), i.e. the percentage change in demand divided by the percentage change in price. In the additive demand model, the PED changes from perfect elastic (any increase in the price, no matter how small, will cause demand to drop to zero) to unitary elastic (a percentage change in demand is equal to that in price) and finally to perfect inelastic (changes in price do not affect demand at all) when the price falls, which is hardly realistic for life-saving goods during a pandemic. On the other hand, the PED remains constant (the percentage change in demand is a fixed proportion of price) in the multiplicative demand model. Empirical economic studies find that the PED of pharmaceuticals is generally stable (see, e.g. Yeung, Basu, Hansen, & Sullivan, 2018, & the references cited). As a result, we use the multiplicative demand model.[3]

The multiplicative demand function is $y(v, p) = vp^{-r}$, and $r$ is a parameter. Setting $y(v, p)$ to the normalised value of 1 when $v = p$, elasticity is unified with $r = 1$. Hence, as long as the consumer hoarding behaviour is incorporated in the model, price-setting details do not appear to be sensitive to government interventions. Given the demand function of our heterogeneous consumers, the total *real demand* in the market, denoted as $\bar{q}$, is:

$$\bar{q} = \int_0^{\bar{v}} d dv = \int_p^{\bar{v}} \frac{v}{p} dv = \frac{\bar{v}^2 - p^2}{2p}. \tag{2}$$

We assume $\bar{v} \geq p$ to exclude a situation whereby even the consumer with the highest WTP cannot afford the product.

### 3.2. The supply chain

Consider a supply chain with two risk-neutral firms – an upstream supplier and a downstream retailer. When making decisions, the supplier is the leader and the retailer is the follower. This assumption is consistent with observations made during the pandemic that life-saving goods suppliers have much more market power.

[3] Note, if an additive demand function $y(v, p) = v + 1 - p$ is used, the mathematical analysis is even simpler, but the results do not change structurally and the insights remain the same.

The retailer (denoted with the subscript $r$) makes two decisions: order quantity $q$ it purchases from the supplier, and selling price $p$ it offers to consumers. The retailer is aware of the panic buying behaviour of the consumers and pays a unit wholesale price $w$ to the supplier, thus maximising its profit:

$$\max_{p>0, q>0} \pi_r = (p - w)q. \tag{3}$$

Anticipating the retailer's decisions, and subject to a critical capacity constraint $K$, the supplier (denoted with the subscript $m$) incurs a unit production cost $c$ and decides the wholesale price $w$ (with $\bar{v} \geq p \geq w \geq c$) to maximise its profit:

$$\begin{aligned} &\max_{w>0} \pi_m = (w - c)q^*, \\ &s.t. \\ &q^* = \underset{p>0, q>0}{\operatorname{argmax}} \left\{ \pi_r = (p - w)q, \;\; s.t. \; q \leq \min\{K, \bar{q}\} \right\}, && \text{(IC)} \\ &\pi_r(q^*, w) \geq 0. && \text{(IR)} \end{aligned} \tag{4}$$

As with the follower, the retailer's problem is incorporated as the incentive compatibility (IC) constraint in the supplier's problem. This constraint also includes the fact that total sales quantity $q$ should be smaller or equal to the supplier's production capacity $K$ and the total market demand $\bar{q}$. The retailer accepts the supplier's offer, but only if it can obtain a profit larger or equal to a reservation pay-off (which is normalised to 0), as formulated by the individual rationality (IR) constraint.

### 3.3. Shortage rates

When a pandemic hits, it is most likely that the entire market will experience a shortage of life-saving goods, due to various disruptions throughout the supply chain. Define $\mathcal{S}^0$ the *nominal shortage rate* as:

$$\mathcal{S}^0 = \frac{\text{total nominal demand in the market} - \text{total supply in the market}}{\text{total nominal demand in the market}}.$$

Since the nominal demand of each consumer is normalised to 1 and the total nominal demand in the market is $\bar{v}$, $\mathcal{S}^0 = \frac{\bar{v} - q}{\bar{v}}$. The nominal shortage rate is the theoretical shortage, deduced by comparing total supply and essential demand in the market. This shortage is often the result of disruptions in the supply chain in the face of a pandemic (e.g. a lack of supplier capacity) and can hardly be mitigated by government interventions at short notice. In other words, from a government's perspective, this is the lowest shortage rate obtainable when the market is centrally controlled. In reality, however, self-interested market participants may exacerbate the nominal shortage when narrowly maximising their own utilities (e.g. consumer panic buying). We define the *real shortage rate* in the market $S$ as follows:

$$S = \frac{\text{the nominal demand of the uncovered consumers}}{\text{total nominal demand in the market}}.$$

Uncovered consumers are those (i) who cannot afford the price $p$ or (ii) whose WTP is above $p$ but cannot obtain the products because of panic buying by other consumers. If the price $p$ is market-clearing, then $S = p/\bar{v}$. If the price $p$ is not market-clearing (for example, under absolute price regulation), then $S$ is not a constant but depends on the sequence of the arriving consumers (for more discussion on this point, refer to Section 4.1).

The real shortage rate reflects how the goods are actually distributed among the consumers when market distortions such as panic buying and price surges happen. It can be conjectured that $S \geq \mathcal{S}^0$ and the objective of a government is to reduce the real shortage rate.

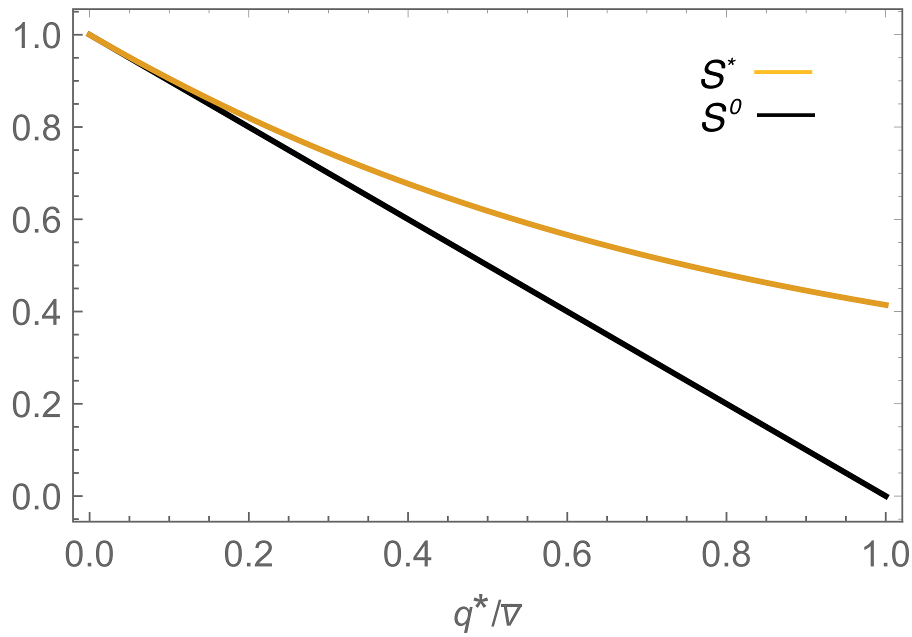



**Fig. 1.** Shortage rates in the free market.

### 3.4. Equilibrium in the free market

If there is no government intervention, equilibrium can be achieved by solving the supplier's problem formulated in Eq. (4) by backward induction: first, obtain the retailer's optimal decision on selling price $p^*$ and the order quantity $q^*$ given wholesale price $w$, and then obtain the optimal wholesale price $w^*$, thereby maximising the supplier's profit.

**Proposition 1.** *In a free market without any intervention, supply chain members can obtain a unique Sub-game-Perfect Nash Equilibrium (SPNE) in the following manner:*

(i) *The retailer's optimal order quantity $q^* = \min\{\hat{q}, K\}$, where $\hat{q}$ satisfies:*

$$-4\hat{q} + \frac{4\hat{q}^4 + 6\hat{q}^2\bar{v}^2 + \bar{v}^4}{\left(\hat{q}^2 + \bar{v}^2\right)^{3/2}} - c = 0. \tag{5}$$

*The retailer's optimal selling price*

$$p^* = -q^* + \sqrt{q^{*2} + \bar{v}^2}. \tag{6}$$

(ii) *The supplier's optimal wholesale price*

$$w^* = \frac{q^{*2}}{\sqrt{q^{*2} + \bar{v}^2}} + \sqrt{q^{*2} + \bar{v}^2} - 2q^*. \tag{7}$$

(iii) *The real shortage rate $S^* = p^*/\bar{v}$ and is always larger than the nominal shortage rate $\mathcal{S}^0$. The more life-saving goods sold in the market, the larger the gap between them.*

We refer readers to the Appendix for proof of all propositions. In market equilibrium, goods sold in market $q^*$ are determined by the unit production cost $c$, the total nominal demand in the market $\bar{v}$, as well as capacity $K$ of the supplier. If consumer demand surges but supplier capacity still lags behind, which is often observed in the early stages of a pandemic, $K$ is the bottleneck in the supply chain. When capacity is ramped-up, the volume of the goods sold in the market is characterised by Eq. (5).

Naturally, both shortage rates decrease when $q^*$ increases. However, gap $S^* - \mathcal{S}^0$ increases in $q^*$, and the goods are even less fairly distributed (see Fig. 1). Richer consumers stockpile more goods. The supplier and the retailer, now aware of this consumer panic buying behaviour, use the price mechanism to exploit the surplus of the richer buyers (with higher WTP) and maximise their own profits, without considering whether or not the product is affordable for the poor (with lower WTP).

## 4. Government regulations

Firms seek to obtain the highest profit, and panicked consumers irrationally stockpile goods. These two phenomena cause market distortion and severe shortages. Policymakers can intervene in the market from the supply and/or the demand side(s) of the supply chain (see Fig. 2).

On the demand side, because supply shortages can be caused by panic buying, the government can regulate consumer purchasing by limiting the quantity of a product that can be bought to the essential value. We call this *purchase regulation*. On the supply side, the regulator can impose a cap on the product's selling price to prevent vendors from inflating prices. We call this *price regulation*. Moreover, these measures can be taken simultaneously, which we term *mixed regulation*.

### 4.1. Price regulation

In industrial organisation theory, price can be regulated in the form of (i) a pure cap and (ii) a flexible term linked to the realised cost (see, e.g. Armstrong & Sappington, 2007). In this section, we define absolute price regulation and relative price regulation and analyse them separately.

#### 4.1.1. Absolute price regulation

Traditional price regulation, which we call *absolute* price regulation, means that the retail price $p$ must not exceed an absolute price ceiling $x$. In such a case, the supply chain decision-making problem can be formulated by adding a constraint $p \le x$ to the (IC) constraint in Eq. (4). We summarise the equilibrium outcome under this type of regulation (with superscript $AP$) in the following proposition.

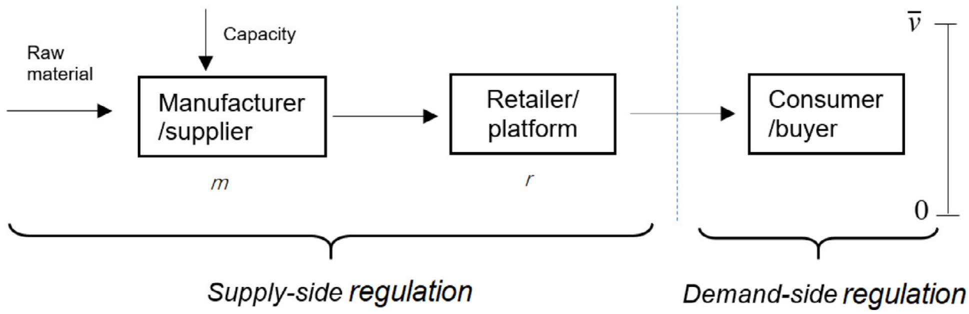



**Fig. 2.** Supply chain with regulations.

**Proposition 2.** *If the government imposes an absolute price cap x on the retailer, supply chain members can obtain the following equilibrium:*

(i) *If $p^* \le x$, the result is the same as that in Proposition 1.*
(ii) *If $c \le x < p^*$, then*
   a) *if $K \ge \frac{\bar{v}^2 - x^2}{2x}$, $q^{AP} = \frac{\bar{v}^2 - x^2}{2x} > q^*$ and $S^{AP} = \frac{x}{\bar{v}} < S^*$,*
   b) *if $K < \frac{\bar{v}^2 - x^2}{2x}$, $q^{AP} = K$ and $S^{AP} \in [(x + \bar{v} - \sqrt{2Kx + x^2})/\bar{v}, \sqrt{\bar{v}^2 - 2Kx/\bar{v}}]$.*
(iii) *If $x < c < p^*$, $q^{AP} = 0$ and $S^{AP} = 1$.*
(iv) *A sufficient condition for $S^{AP} < S^*$ is*

$$\max\left\{c, \frac{\bar{v}^2 - p^{*2}}{2K}\right\} < x < p^*, \tag{8}$$

*under which $S^{AP}$ is minimised when $x = \max\left\{\sqrt{K^2 + \bar{v}^2} - K, c\right\}$.*

Absolute price regulation changes equilibrium in the free market, but only when $x$ is smaller than $p^*$. However, if $x$ is too small with $x < c$, as stated in part (iii) of Proposition 2, the supplier does not make a profit and leaves the market. Price regulation leads to a 100% shortage rate.

If $c \le x < p^*$, the price deduction stimulates consumption. If capacity is sufficient with $K \ge \frac{\bar{v}^2 - x^2}{2x}$, price regulation fosters production ($q^{AP} > q^*$) and can reduce the shortage rate ($S^{AP} < S^*$). We call this the *production-boosting effect*. On the other hand, if $K < \frac{\bar{v}^2 - x^2}{2x}$, capacity constraint is binding. This might happen when $x$ is too small, since $\frac{\bar{v}^2 - x^2}{2x}$ decreases in $x$. In this case, only $K$ units of products are available in the market, but the real demand from all the consumers, since the selling price $x$ is enforced by the regulation to a low level, is larger than $K$. In other words, the enforced price $x$ no longer clears the market, and consumers thus need to compete to buy products. The real shortage rate $S^{AP}$ is no longer a fixed term but rather depends on which type of consumer (characterised by the WTP) arrives at the retailer first, which is practically rather random and beyond the control of the retailer/government. We specify the range of $S^{AP}$. If rich consumers visit the shop first, $S^{AP}$ takes the maximum possible value $S^{AP}_{\max} = \sqrt{\bar{v}^2 - 2Kx/\bar{v}}$. Since consumers need to compete for access to products that are already in short supply, panic buying is aggravated, which we call the *hoarding-exacerbation effect*. Both the production-boosting effect and the hoarding-exacerbation effect affect the real shortage rate $S^{AP}$, and Eq. (8) characterises a sufficient condition for $S^{AP} < S^*$.

Fig. 3 illustrates the results in Proposition 2. To be more specific, curve A(C)D represents $x = p^*$, curve BC represents $x = \frac{\bar{v}^2 - p^{*2}}{2K}$ and curve AE represents $x = c$. The area above curve AD shows the situation in which the price cap is too high to make an impact (part (i) of Proposition 2), while the area below AE describes part (iii) of Proposition 2, where the supplier leaves the market and the shortage rate is 1. In Fig. 3(a), curves AD and BC intercept at point C, and the vertical line CG represents the condition $\hat{q} = K$ in the free market described in Proposition 1. In the left area of CG, $\hat{q} > K$, and total market sales $q^*$ are bounded by capacity constraint $K$. In this case, the absolute price cap $x$ can never mitigate the shortage rate, since the production-boosting effect is inactivated by the hard constraint of insufficient capacity. Such a situation does not happen when capacity is ramped-up, and point C can only be obtained when $c < 0$, as described in Fig. 3(b).

The region bounded by curves AD, AE and BC (also curve $c = 0$ in Fig. 3(b)) highlights the "effective area" characterised by Eq. (8), in which absolute price regulation successfully mitigates the shortage rate. Interestingly, the effective area should be divided into two sub-areas, each formulated by different effects. Taking ABC in Fig. 3(a) as an example, it is divided by the dashed line FC, representing $K = \frac{\bar{v}^2 - x^2}{2x}$. In the upper region ACF, the supplier has sufficient capacity ($q^{AP} = \frac{\bar{v}^2 - x^2}{2x} < K$) and $x$ clears the market. Only the production-boosting effect takes place in this area, while the shortage rate is mitigated ($S^{AP} < S^*$). When $x$ falls below line FC, the hoarding-exacerbation effect starts to take place. In the BCF region, the production-boosting effect dominates the hoarding-exacerbation effect, and the maximum possible shortage rate $S^{AP}_{\max}$ is still less than $S^*$. Curve BC represents the condition $x = \frac{\bar{v}^2 - p^{*2}}{2K}$ mentioned in Eq. (8), under which the two effects countervail and $S^{AP}_{\max} = S^*$. In area BCDE, the hoarding-exacerbation effect is stronger, and $S^{AP}_{\max}$ is larger than $S^*$.

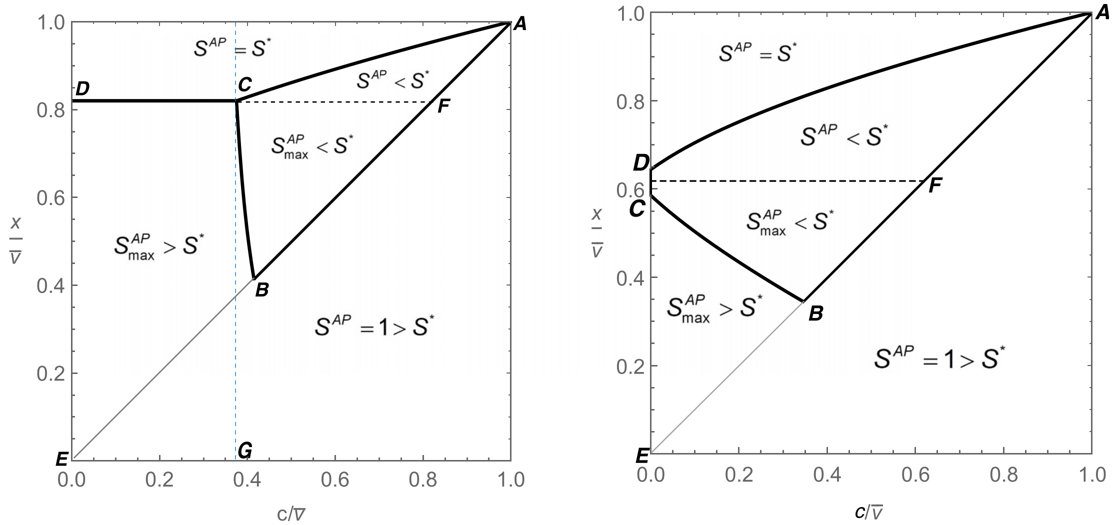
Fig. 4 provides a direct comparison between $S^{AP}$ and $S^*$. The relative size of $S^{AP}$ and $S^*$ depends on not only the price cap $x$, but also on other supply chain parameters such as $c$ and $\bar{v}$. The lowest shortage rage is achieved when $K = \frac{\bar{v}^2 - x^2}{2x}$ (the dashed line in Fig. 3). $S^{AP}$ could be larger than $S^*$ if the supply chain parameters are not fully calibrated (e.g. region BCDE and the area below AE in Fig. 3(a)).

### 4.1.2. Relative price regulation

During a pandemic, it is difficult for suppliers to purchase raw materials, labour, logistics services, etc. and manage production. The unit production cost $c$ may fluctuate dramatically, so it is therefore inconvenient for policymakers to keep tracking the changing market and adopt absolute price regulation accordingly. Once the absolute price cap $x$ falls below $c$, the intervention can even drive the supplier out of the market.

We therefore propose a better solution: *relative* price regulation, whereby the government sets a relative ratio $\delta$ so that the retail price $p$ will not exceed $(1+\delta)$ times the wholesale price $w$, i.e. $p \le (1+\delta)w$. We add this term to the (IC) constraint in Eq. (4) and obtain the equilibrium outcome (with superscript RP) summarised below:

**Proposition 3.** *If the government imposes a relative price cap $(1+\delta)w$ on the retail price $p$, supply chain members can obtain the following equilibrium:*




(a) If $K = 0.2\bar{v}$, capacity of the supplier is insufficient ($K < \hat{q}$) when $c$ is small.

(b) If $K = 0.5\bar{v}$, the supplier always has sufficient capacity in the free market, i.e. $K \geq \hat{q}$.

**Fig. 3.** A comparison between the real shortage rate $S^{AP}$ under absolute price regulation and the real shortage rate $S^*$ in the free market.

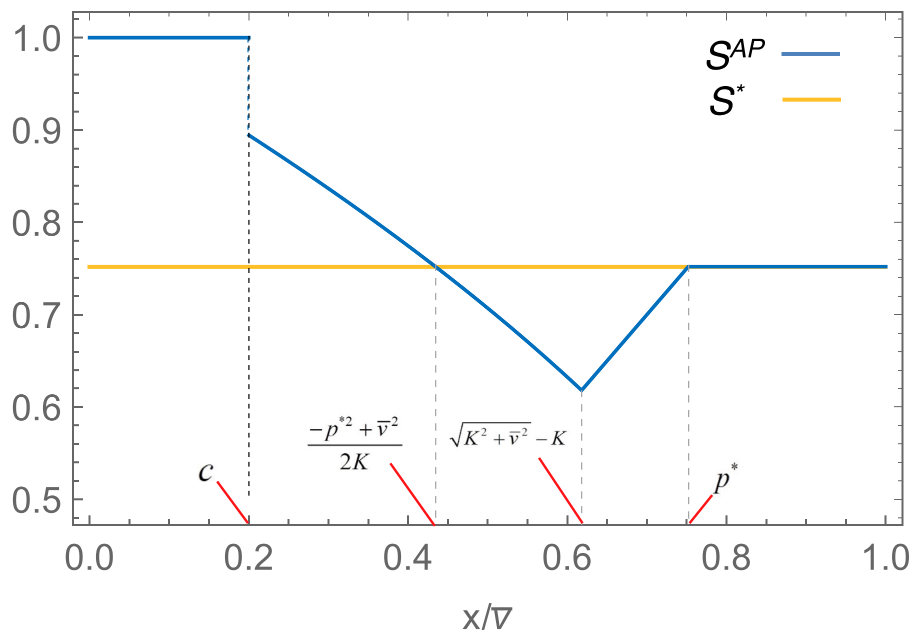



**Fig. 4.** Shortage rate under absolute price regulation. $c = 0.2\bar{v}$, $K = 0.5\bar{v}$.

(i) *If $\delta > (p^* - w^*)/w^*$, the equilibrium solution is the same as that in Proposition 1.*

(ii) *If $\delta \leq (p^* - w^*)/w^*$, the retailer's optimal order quantity $q^{RP} = \min\{\tilde{q}, K\}$, where $\tilde{q}$ satisfies*

$$\frac{\frac{2\tilde{q}^2+\bar{v}^2}{\sqrt{\tilde{q}^2+\bar{v}^2}} - 2\tilde{q}}{1+\delta} - c = 0. \qquad (9)$$

*The retailer's optimal selling price $p^{RP} = -q^{RP} + \sqrt{{q^{RP}}^2 + \bar{v}^2}$.*

*The supplier's optimal wholesale price $w^{RP} = \frac{-q^{RP}+\sqrt{{q^{RP}}^2+\bar{v}^2}}{1+\delta}$.*

*The shortage rate $S^{RP} = (-q^{RP} + \sqrt{{q^{RP}}^2 + \bar{v}^2})/\bar{v}$.*

(iii) *$S^{RP} < S^*$ if*

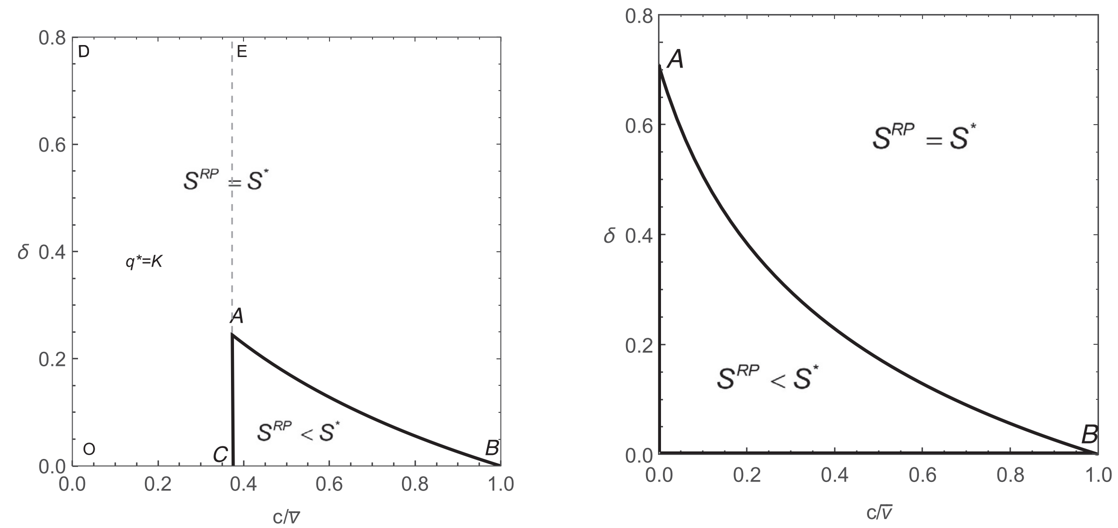
$$\delta < \bar{\delta}^{RP} \text{ and } c > \max\{0, \underline{c}^{RP}\}, \qquad (10)$$

*where $\bar{\delta}^{RP}$ satisfies*

$$\frac{\bar{v}\sqrt{\frac{1}{1+2\bar{\delta}^{RP}}}\left(1+2\bar{\delta}^{RP}\left(2+\bar{\delta}^{RP}\right)\left(1+2\bar{\delta}^{RP}\left(1+\bar{\delta}^{RP}\right)\right)\right)}{\left(1+\bar{\delta}^{RP}\right)^3} - \frac{4\bar{v}\bar{\delta}^{RP}}{\sqrt{1+2\bar{\delta}^{RP}}} = c \qquad (11)$$

*and $\underline{c}^{RP} = \frac{4K^4+6K^2\bar{v}^2+\bar{v}^4}{(K^2+\bar{v}^2)^{3/2}} - 4K$; otherwise, $S^{RP} = S^*$.*

Similar to the situation for absolute price regulation, the supplier's capacity is also decisive. In area OCED in Fig. 5(a), capacity constraint is binding (in curve AC, $\hat{q} = K$ and $c = \underline{c}^{RP}$) and the supply chain decisions remain the same as those in the free market. When the supplier has sufficient capacity, absolute price regulation effectively mitigates the shortage rate when $p^{RP}$ is smaller than $p^*$,




(a) If $K = 0.2\bar{v}$, capacity of the supplier is insufficient ($K < \hat{q}$) when $c$ is small.

(b) If $K = 0.5\bar{v}$, the supplier always has sufficient capacity in the free market, i.e. $K \geq \hat{q}$.

**Fig. 5.** Comparison of the shortage rate under *relative* price regulation.

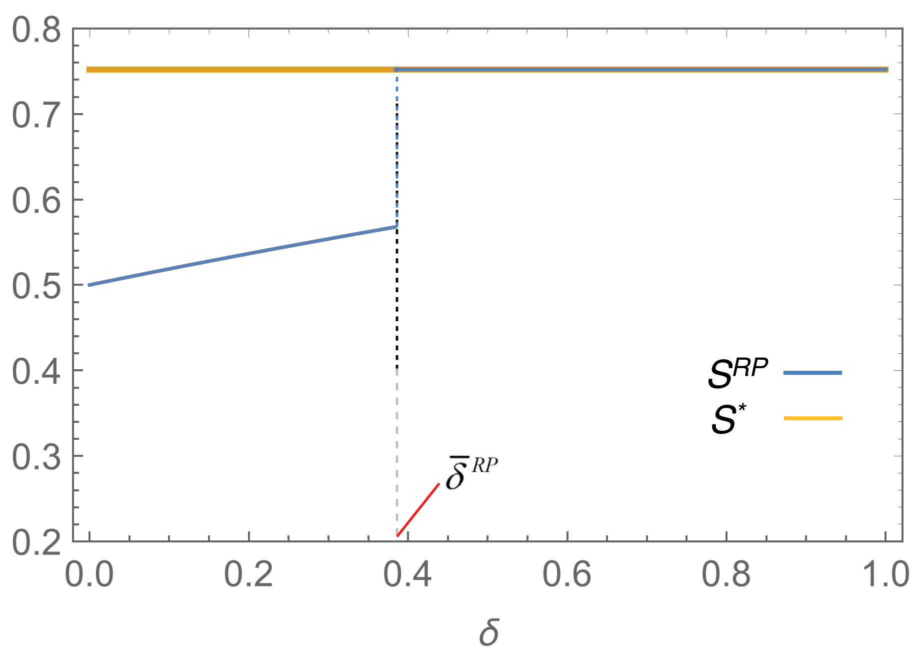



**Fig. 6.** Shortage rate under relative price regulation. $c = 0.2\bar{v}$, $K = 0.8\bar{v}$.

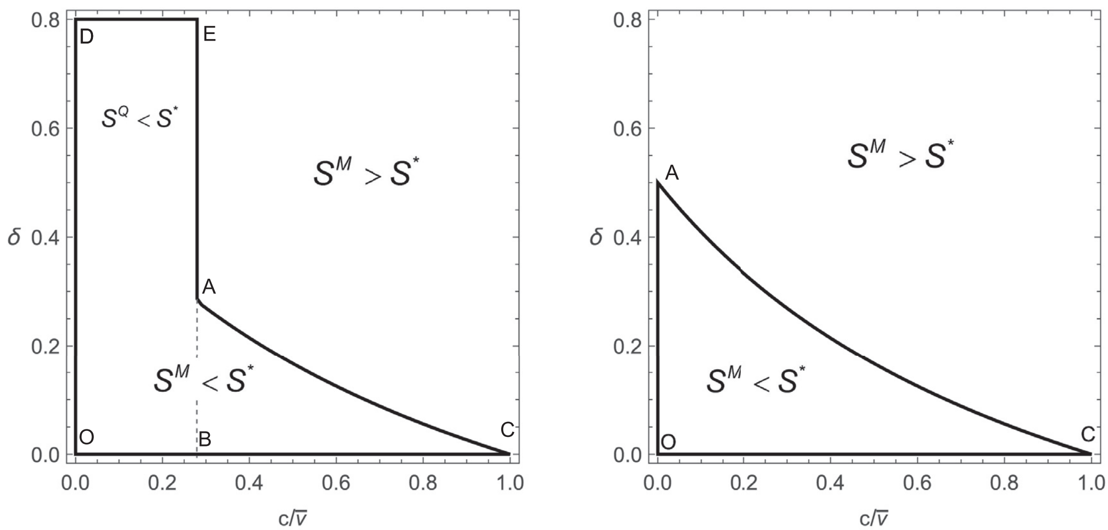
i.e. when $\delta < (p^* - w^*)/w^*$, which is the area below curve AB in Fig. 5. Fig. 6 provides a direct comparison between $S^{RP}$ and $S^*$.

*4.1.3. Comparison between absolute and relative price regulation*

Different from absolute price regulation, relative price regulation never exacerbates the shortage rate, i.e. $S^{RP}$ never exceeds $S^*$. Under absolute price regulation, the price ceiling $x$ is exogenous. If $x$ is too low to clear the market, the hoarding-exacerbation effect takes place and $S^{AP} > S^*$. In the case of relative price regulation, however, the retail price is linked to $w$. The supplier can therefore leverage the price cap to optimise its profit and indirectly control the retail price to clear the market. As a result, the hoarding-exacerbation effect does not take place. Meanwhile, the constrained retail price drives the production-boosting effect – more products are manufactured and the shortage rate is mitigated. Even if greater production cannot be incentivised (either because the price limit is too high or production is constrained by capacity limit), the shortage rate does not become worse.

The effectiveness of relative price regulation is robust against production cost variations. And especially when capacity is reasonably large (see Fig. 5(b) with $K = 0.5\bar{v}$), there always exist effective price ratio limits that can reduce the shortage rate, regardless of how the production cost changes, because limiting the ratio of $p$ to $w$ encompasses the production cost into the policy.

Relative price regulation shares the same weakness with absolute price regulation, in that it is ineffective when the supplier's capacity is too low (e.g. area OCED in Fig. 5(a)). However, the merits discussed above can greatly enhance the implementability of the regulation in practice, and so the policymaker does not need to worry that regulations "make things worse". Unlike absolute price




(a) If $K = 0.2\bar{v}$, the supplier's capacity is insufficient ($K < \hat{q}$) when $c$ is small.

(b) If $K = 0.5\bar{v}$, the supplier always has sufficient capacity in the free market, i.e. $K \geq \hat{q}$.

**Fig. 7.** Comparison of the shortage rate under mixed regulation.

regulation, even if relative price regulation is ineffective, it does not increase the shortage rate. Furthermore, the policymaker does not need to track many operational parameters (such as production cost) when designing the regulation. A sufficiently low ratio (say $\delta = 10\%$) will enable regulation to resist most cost variances.[4] Hence, it is fair to conclude that relative price regulation is superior to absolute price regulation.

Hereafter, we only discuss relative price regulation when comparing the different intervention policies.

### 4.2. Purchase regulation

Since consumer panic buying is widely observed during the pandemic, it is reasonable to posit that demand rationing could enable a fairer distribution of goods and therefore mitigate the shortage rate. In this section, we discuss purchase regulation on the demand side, whereby each consumer is only allowed to purchase the essential demand, normalised to one. Supply chain members' decision problem can be written in the following manner:

$$\begin{aligned} &\max_{w>0} \ \pi_m = (w-c)q^Q, \\ &s.t. \\ &q^Q = \operatorname*{argmax}_{p>0,q>0}\left\{\pi_r = (p-w)q, \ s.t. \ q \leq \min\{K, \int_p^{\bar{v}} dv\}\right\}, \quad \text{(IC)} \\ &\pi_r(q^Q, w) \geq 0. \quad \text{(IR)} \end{aligned} \tag{12}$$

The equilibrium solution (with superscript Q) is summarised in the following proposition.

**Proposition 4.** *If the government imposes a purchase limit on buyers, supply chain members can obtain the following equilibrium:*

(i) *The retailer's optimal selling price $p^Q = \bar{v} - q^Q$.*
*The retailer's optimal selling quantity $q^Q = \min\{K, (\bar{v} - c)/4\}$.*
*The supplier's optimal wholesale price $w^Q = \bar{v} - 2q^Q$.*
*The shortage rate $S^Q = (\bar{v} - q^Q)/\bar{v}$.*

(ii) *The shortage rate under purchase regulation $S^Q$ can only be smaller than $S^*$ in the free market when $K < 7\bar{v}/24$ and $c < \bar{c}^Q = 4\sqrt{K^2 + \bar{v}^2} - 4K - 3\bar{v}$; otherwise, $S^Q \geq S^*$. Total production and sales quantity $q^Q$ are always no larger than $q^*$ in the free market.*

The tendency is to believe that purchase regulation enforces a fairer distribution of goods and therefore leads to a lower shortage rate, but our result shows it is often not the case. The main reason is that rationing demand suppresses consumption, and so total demand in the market is significantly reduced. The supplier therefore lowers their production output to save costs. As stated in part (iii) of Proposition 4, production quantity $q^Q$ is always less than $q^*$ in the free market, unless the production output is bound by capacity $K$ and $q^Q = q^* = K$.

Nevertheless, purchase regulation can reduce the shortage rate ($S^Q < S^*$) when capacity is seriously insufficient ($K < 7\bar{v}/24$) and the production cost is low ($c < \bar{c}^Q$), which might happen at the beginning of a pandemic. However, it is worth mentioning that because the total production quantity is small, any improvement in the shortage rate should be insignificant.

### 4.3. Mixed (price and purchase) regulation

So far, we have shown that the effectiveness of supply-side (price regulation) and demand-side (purchase regulation) intervention is dependent on the supplier's production capacity. When capacity is insufficient, purchase regulation encourages a fairer distribution of scarce goods; when capacity is ramped-up, a cap on the selling price stimulates production. A natural follow-up idea is to combine them together – intervention on both the supply side and the demand side of the supply chain, which we call "mixed regulation." To be more specific, the retail price $p$ should not exceed $(q + \delta)w$, and each consumer can only purchase one unit of the good. The problem under mixed regulation scenario can be formulated by adding $p \leq (1 + \delta)w$ to the (IC) constraint in Eq. (12). We summarise the equilibrium outcome (with superscript M) in the following proposition.

**Proposition 5.** *If both (relative) purchase regulation and relative price regulation are imposed, the supply chain obtains the following equilibrium outcome:*

[4] Theoretically, the shortage rate is minimised when $\delta = 0$ (see Fig. 6). However, a low price ratio limit may harm firms' profits, which we discuss in Section 5.2.

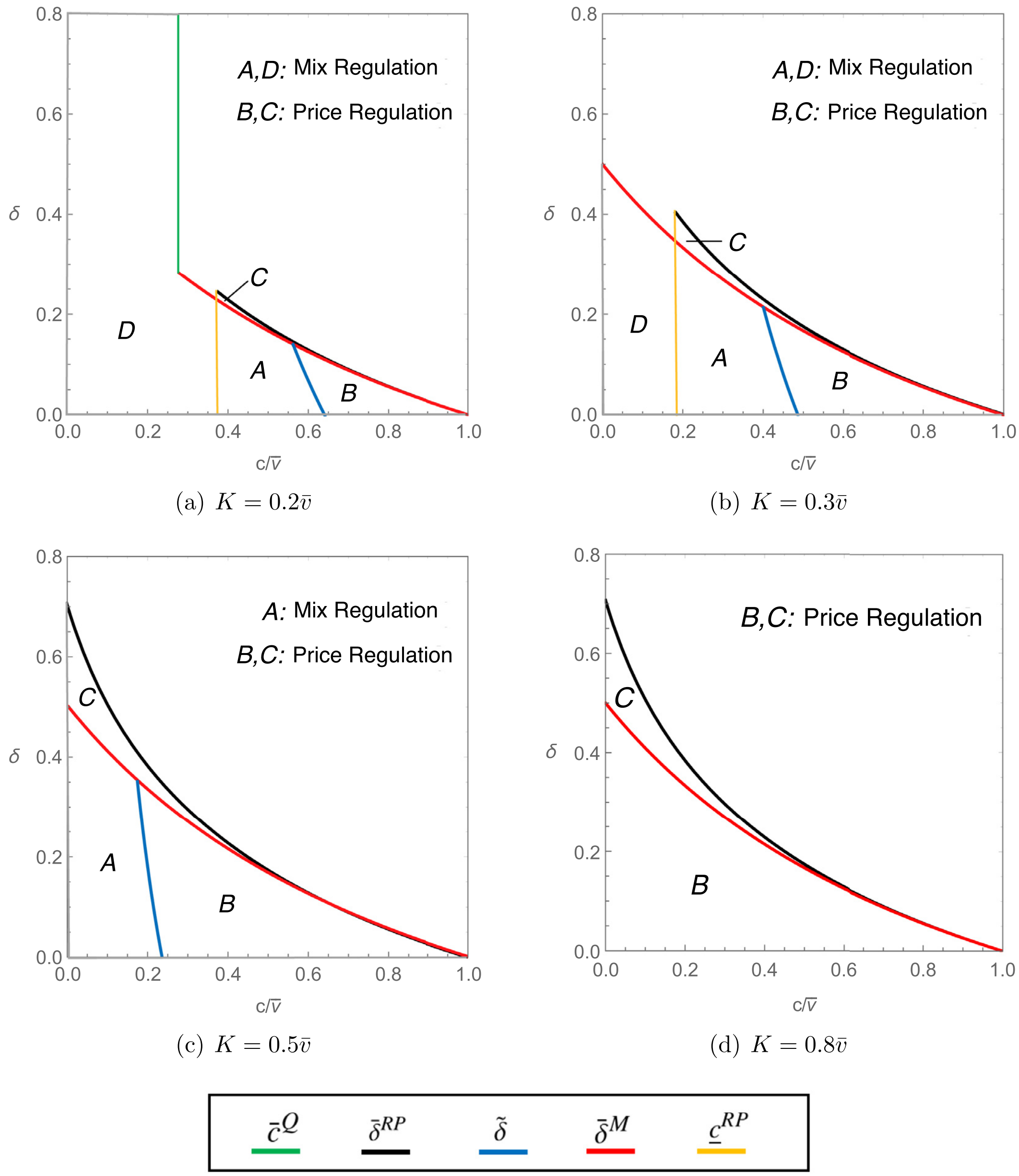



**Fig. 8.** The regulation leading to the lowest shortage rate in different regions.

(i) *If* $\delta > (p^Q - w^Q)/w^Q$, *the result is the same as that in Proposition 4.*

(ii) *If* $\delta \le (p^Q - w^Q)/w^Q$, $q^M = \min\{[\bar{v} - c(1+\delta)]/2, K\}$, $p^M = \bar{v} - q^M$, $w^M = p^M/(1+\delta)$. *The shortage rate* $S^M = 1 - q^M/\bar{v}$.

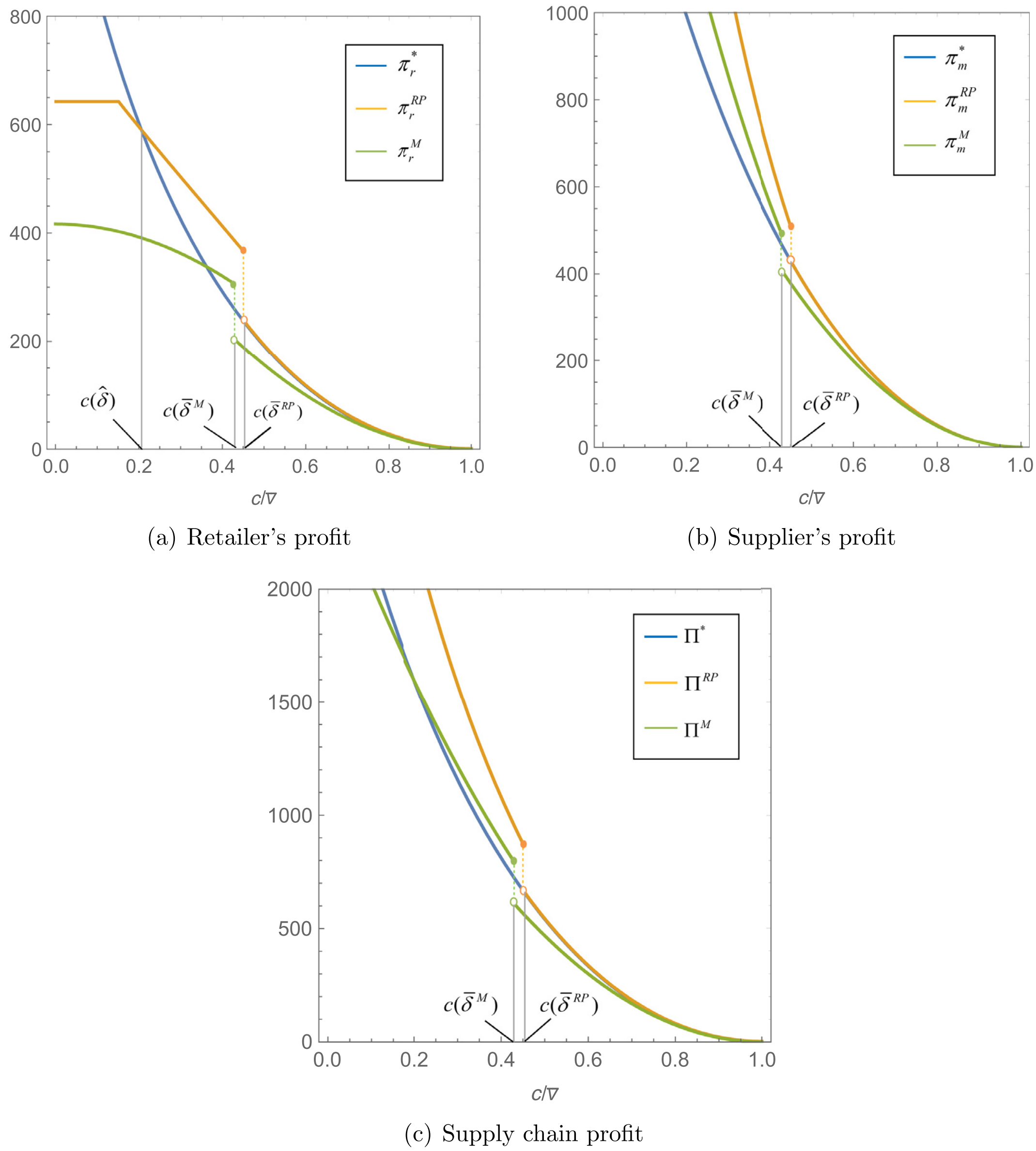
(iii) *Compared to the free market,* $S^M < S^*$ *when:*
 (a) $K < 7\bar{v}/24$, $c < \bar{c}^Q$;
 (b) $K < 7\bar{v}/24$, $c > \bar{c}^Q$, $\delta < \bar{\delta}^M = (\bar{v} - c)/(2(c + \bar{v}))$;
 (c) $K > 7\bar{v}/24$, $\delta < \bar{\delta}^M$.
 *Otherwise,* $S^M > S^*$.

Mixed regulation leads to a new equilibrium outcome – as opposed to purchase regulation. When capacity is insufficient ($K < 7\bar{v}/24$) and production costs are low ($c < \bar{c}^Q$), mixed regulation mitigates the shortage rate ($S^M < S^*$), which is consistent with purchase regulation. However, even if capacity is ramped-up ($K > 7\bar{v}/24$), mixed regulation can still mitigate the shortage rate, as long as the price ratio $\delta$ is lower than the threshold $\bar{\delta}^M$. Hence, mixed regulation will always be effective in shortage rate reduction, regardless of the supplier's capacity level.

Fig. 7 illustrates the results. Curve AC represents the condition $\delta = \bar{\delta}^M$, and the vertical line across point A represents the condition $c = \bar{c}^Q$. Compared to the one-side only intervention, mixed regulation shows an advantage in terms of its immunity to production capacity. As illustrated in Fig. 7(a), when production capacity is low, mixed regulation can always reduce the shortage rate, regardless of the value of the price ratio limit (region DOBE), while price regulation cannot reduce the shortage rate given the same condition. On the other hand, when production costs are high, or capacity is significant, the capacity constraint becomes non-binding. In such a case, mixed regulation also can reduce the shortage rate when $\delta$ is below a threshold.

## 5. Comparison of regulations

In this section, we provide a detailed comparison of the impact of regulations on the shortage rate as well as firms' profit.




(a) Retailer's profit

(b) Supplier's profit

(c) Supply chain profit

**Fig. 9.** Firms' profit in equilibrium under different regulations. $\delta = 20\%$, $\bar{v} = \$100$, $K = 0.8\bar{v}$.

### *5.1. Impact on the shortage rate*

Life-saving is the primary goal of government interventions. Corollary 1 summarises what regulation is (more) effective in mitigating the shortage rate, and under what conditions.

**Corollary 1.** *In terms of the shortage rate under different regulations:*

(i) *Mixed regulation is not worse than purchase regulation – that is, $S^M \leq S^Q$.*

(ii) *The comparison of mixed regulation and price regulation depends.*

(a) *$S^M < S^*$ and $S^M < S^P$ (1) if*

- *$K < 7\bar{v}/24$, $c < \bar{c}^Q$; or $\bar{c}^Q < c < \underline{c}^{RP}$ and $\delta < \bar{\delta}^M$;*
- *$K > 7\bar{v}/24$, $\bar{c}^Q < c < \max\{\underline{c}^{RP}, 0\}$ and $\delta < \bar{\delta}^M$,*

*when only mixed regulation is effective.*

*(2) if $K > 7\bar{v}/24$, $c > \max\{\underline{c}^{RP}, 0\}$, $\delta < \min\{\bar{\delta}^M, \tilde{\delta}\}$, where $\tilde{\delta} = \frac{2\sqrt{K^2+\bar{v}^2}-c-2K-\bar{v}}{c}$.*

(b) *$S^P < S^*$ and $S^P < S^M$ if $c > \max\{\underline{c}^{RP}, 0\}$, $\min\{\bar{\delta}^M, \tilde{\delta}\} < \delta < \bar{\delta}^{RP}$.*

Mixed regulation dominates purchase regulation in terms of shortage rate mitigation. The comparison between (relative) price regulation and mixed regulation depends. Some cases exist whereby only one regulation is effective: (i) when the capacity constraint is binding in the free market (region D in Fig. 8(a) and (b)), only mixed regulation can reduce the shortage rate; (ii) when $\bar{\delta}^M < \delta < \bar{\delta}^{RP}$ (region C in Fig. 8) and only price regulation can reduce the shortage rate. When both price and mixed regulations are effective, mixed regulation has a stronger effect when $\delta < \tilde{\delta}$ (Region A in Fig. 8). This happens when the capacity constraint is binding under price regulation but is non-binding under mixed regulation. When $\delta > \tilde{\delta}$ (region B in Fig. 8), price regulation can reduce the shortage rate to a greater extent. In particular, when production capacity is significant, price regulation will always dominate (see Fig. 8(d)) as a result of its production-boosting effect.

Under (relative) price regulation, the retail price is constrained, more consumers can afford the product and total demand in the market increases. This in turn generates a strong production-boosting effect. In the meantime, the upstream supplier can optimise the wholesale price to make the final retail price clear the market, which does not lead to the hoarding-exacerbation effect. Hence, compared to the free market, an increase in total production quantity can lead to a reduction in the shortage rate. By contrast, under mixed regulation, price regulation stimulates a similar production-boosting effect, and purchase regulation ensures a fairer distribution among consumers. However, this fair distribution leads to a demand reduction compared to the free market case and price regulation. As a result, the production-boosting effect is weaker than that under price regulation. The interaction of these effects leads to a non-monotonic result of performance comparison between price regulation and mixed regulation.

### 5.2. Impact on firms' profits

Even though it is critical for a regulation to mitigate the shortage of critical life-saving goods during a pandemic, the corresponding impact on firms' profits should not be underestimated. Government interventions might move firms away from their optimal decisions in the free market and cause profit losses. In what follows, we compare the impact of different regulations on supply chain members' profits.

**Corollary 2.** *Compared to the free market, relative price regulation leads to a higher profit for the supplier ($\pi_m^P \geq \pi_m^*$) and a higher profit for the total supply chain ($\Pi^P \geq \Pi^*$). The profit of the retailer $\pi_r^P$ is larger than $\pi_r^*$ if $\delta > \hat{\delta}$ and vice versa, where $\hat{\delta}$ satisfies*

$$q^{*2} - \frac{q^{*3}}{\sqrt{q^{*2} + \overline{v}^2}} = \frac{q^P\left(-q^P + \sqrt{q^{P2} + \overline{v}^2}\right)\hat{\delta}}{1 + \hat{\delta}}. \tag{13}$$

Surprisingly, the profit of the supplier and the supply chain duo under relative price regulation can be larger than that obtained in the free market. The retailer can also make a higher profit if the price ratio limit is not too low ($\delta > \hat{\delta}$). In other words, price regulation can reduce the shortage rate and increase firms' profits *simultaneously*, which is a win-win situation for firms and consumers. The main reason for this is that limiting the ratio of the retail price to the wholesale price alleviates double marginalisation in the supply chain. In the free market, both the self-interested supplier and the retailer aim to maximise their respective share of supply chain profit, which leads to a double mark-up in their prices. Such behaviour is detrimental to production quantity and increases the shortage rate. When a relative ratio limit is imposed on prices, room for the retailer to increase the retail price is reduced. Consequently, the degree of double marginalisation becomes lower, which can increase total production quantity and benefit the supply chain.

For mixed regulation, an analytical comparison of profits is not tractable. Therefore, we conduct a numerical analysis and present the results in Fig. 9, from which we note that when the policy is effective in reducing the shortage rate, depending on the price ratio, there are cases when firms' profits can be higher or lower than in the free market. Compared to price regulation, firms' profits are generally lower, because, on the one hand, limiting the price ratio can reduce channel efficiency loss and increase order quantity, whilst on the other hand, demand-rationing significantly reduces total demand in the market, which subsequently weakens the production-boosting effect of the price ratio limit.

## 6. Conclusion

The COVID-19 pandemic has been an urgent wake-up call for the current healthcare system, political vacillation and scientific denialism. Furthermore, the pandemic is not a new occurrence in our history – and it will most likely happen again.

Our model is sufficiently rich to cover a number of facts widely observed during the COVID-19 pandemic. For example, panicked consumers hoard goods, retailers increase prices for higher profit and manufacturers struggle to ramp up their capacity. These phenomena play a critical role in causing shortages of critical life-saving goods. It is known, in general, that government regulations may mitigate shortages. However, there is a lack of comprehensive quantitative analysis in the current literature. This study, to the best of our knowledge, is the first attempt to design and analyse three types of regulation to mitigate the shortages of life-saving goods in the face of a pandemic. Our study could provide guidance for policymakers in the face of the COVID-19 pandemic, as well as offer support for other infectious disease and public emergency management strategies in the future.

From a government perspective, it is important to alleviate the shortages of critical life-saving goods in such a situation. This can be fulfilled by capping retail prices (price regulation) or rationing consumer demand (purchase regulation). We propose relative price regulation, i.e. the retail price should not exceed a fixed ratio of the wholesale price, as it is more effective than conventional absolute price regulation, i.e. the retail price should not exceed a fixed cap, because a relative price cap provides a strong production-boosting effect for the supply chain to increase production and does not stimulate consumers to hoard more goods. On the other hand, purchase regulation seems to eliminate consumer hoarding and enforces a fairer allocation of scarce goods, albeit, in the majority of cases, it may cause even higher shortages: since demand is rationed, firms significantly reduce order quantity and production, which then exacerbates the overall supply shortage. In contrast, mixed regulation (a combination of price and purchase regulation) rations demand and caps prices simultaneously, thereby combining the merits of both regulations. It is especially effective in mitigating the shortage rate when production capacity is low, which is often the case at the beginning of a pandemic.

From a company perspective, external interventions are likely to result in a loss of profit. Compared to the free market, firms may make lower profits when regulated. Interestingly, properly-designed relative price regulation can not only mitigate shortages, but also increase profits within the supply chain, this resulting in a win-win situation. This occurs because the relative price cap constrains any price mark-up along the supply chain and therefore alleviates the double marginalisation effect of the supply chain. Firms are encouraged to be transparent with governments in terms of their price/costs changes, which are rather volatile during a pandemic, and in this way, the relative price can be smoothly tracked.

Although our insights are derived from a two-player supply chain model, it also can be applied to more complex (multi-stage) supply chain settings. In such a case, purchase regulation follows. For relative price regulation, the limit should be imposed on the B2B prices at each stage. Namely, the price charged by the firm to its downstream partners should be capped by a ratio based on the price charged by its upstream partners. In such a manner, the double marginalisation of each stage of the supply chain can be alleviated, which encourages larger production quantities.

The uniform distribution of the consumer willingness to pay (WTP) guarantees the tractability of the model and facilitates the analytical investigation of the property of the equilibrium outcomes. Using other distributions (e.g. normal) only shifts the place and the number of the rich (high WTP) and the poor (low WTP) located across the entire consumer base, but consumer panic buying still exists – buyers with high WTP stockpile more goods than those with low WTP. Hence, the main insights of our model still apply.

In our model, information for supply chain partners can be found in the public domain. If information on consumers' WTP becomes asymmetric, the game between supply chain partners will be affected. However, as analysed by our model, the optimal retail price specified by the retailer is dependent on the WTP of the consumer and its distribution. Hence, the supplier can infer such information from the retail price, which is relatively easy to see (e.g. via online platforms or in stores), and so perfect information is not a strict assumption in our setting.

Our research has several limitations that can be addressed in future studies. It focuses on anti-price gouging and demand rationing, but it would be interesting to consider other policies, such as subsidies. Governments can subsidise the supply chain to increase production capacity and/or to compensate production costs. The effect of subsidy policies can even be jointly considered with the regulations studied in this paper. Another limitation of our research is that it only considers a two-stage supply chain with a manufacturer and a retailer. Future research could therefore consider more complicated supply chain scenarios with multiple players and periods.

## Funding

The first author is supported by The National Natural Science Foundation of China (NSFC) [Grant number 71801228].

## Acknowledgements

The authors would like to thank the editor and the anonymous reviewers for their helpful comments and feedback during the review process.

## Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.ejor.2021.11.042

## References

Akkaya, D., Bimpikis, K., & Lee, H. (2021). Government interventions to promote agricultural innovation. *Manufacturing and Service Operations Management, 23*(2), 437–452.

Anand, K. S., & Giraud-Carrier, F. C. (2020). Pollution regulation of competitive markets. *Management Science, 66*(9), 4193–4206.

Arifoğlu, K., Deo, S., & Iravani, S. M. R. (2012). Consumption externality and yield uncertainty in the influenza vaccine supply chain: Interventions in demand and supply sides. *Management Science, 58*(6), 1072–1091.

Armstrong, M., & Sappington, D. E. (2007). Recent developments in the theory of regulation. In *Handbook of industrial organization: vol. 3* (pp. 1557–1700). Elsevier.

Benítez-Peña, S., Carrizosa, E., Guerrero, V., Jiménez-Gamero, M. D., Martín-Barragán, B., Molero-Río, C., et al. (2021). On sparse ensemble methods: An application to short-term predictions of the evolution of COVID-19. *European Journal of Operational Research, 295*(2), 648–663.

Bhattarai, A. (2020). *'If coronavirus doesn't get us, starvation will': A growing number of Americans say they can't afford to stock up on groceries*. The Washington Post.

Burki, T. (2020). Global shortage of personal protective equipment. *The Lancet Infectious Diseases, 20*(7), 785–786.

Campbell, M. C., Inman, J. J., Kirmani, A., & Price, L. L. (2020). In times of trouble: A framework for understanding consumers' responses to threats. *Journal of Consumer Research, 47*(3), 311–326.

Chen, J., & Rao, V. R. (2020). A dynamic model of rational addiction with stockpiling and learning: An empirical examination of e-cigarettes. *Management Science, 66*(12), 5886–5905. Forthcoming:mnsc.2019.3490.

Chen, X., Yang, H., & Wang, X. (2019). Effects of price cap regulation on the pharmaceutical supply chain. *Journal of Business Research, 97*, 281–290.

Chowdhury, P., Paul, S. K., Kaisar, S., & Moktadir, M. A. (2021). COVID-19 pandemic related supply chain studies: A systematic review. *Transportation Research Part E: Logistics and Transportation Review, 148*, 102271.

Cohen, M. C., Lobel, R., & Perakis, G. (2016). The impact of demand uncertainty on consumer subsidies for green technology adoption. *Management Science, 62*(5), 1235–1258.

Craighead, C. W., Ketchen, D. J., & Darby, J. L. (2020). Pandemics and supply chain management research: Toward a theoretical toolbox *. *Decision Sciences, 51*(4), 838–866.

Deo, S., & Sohoni, M. (2015). Optimal decentralization of early infant diagnosis of HIV in resource-limited settings. *Manufacturing and Service Operations Management, 17*(2), 191–207.

Ekici, A., Keskinocak, P., & Swann, J. L. (2014). Modeling influenza pandemic and planning food distribution. *Manufacturing and Service Operations Management, 16*(1), 11–27.

Emanuel, E. J., Persad, G., Upshur, R., Thome, B., Parker, M., Glickman, A., et al. (2020). Fair allocation of scarce medical resources in the time of COVID-19. *New England Journal of Medicine, 382*(21), 2049–2055.

Finkenstadt, D. J., Handfield, R., & Guinto, P. (2020). Why the U.S. still has a severe shortage of medical supplies. *Harvard Business Review* https://hbr.org/2020/09/why-the-u-s-still-has-a-severe-shortage-of-medical-supplies.

Glazer, A. (2020). Price controls don't work – but mask rationing is the exception that proves the rule. *The Conversation*.

Gupta, V., Ivanov, D., & Choi, T.-M. (2021). Competitive pricing of substitute products under supply disruption. *Omega, 101*, 102279.

Hansman, C., Hong, H., de Paula, A., & Singh, V. (2020). A sticky-price view of hoarding. *Working paper*. National Bureau of Economic Research, Cambridge, MA.

Ivanov, D. (2021). Supply chain viability and the COVID-19 pandemic: A conceptual and formal generalisation of four major adaptation strategies. *International Journal of Production Research, 59*(12), 3535–3552.

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research, 58*(10), 2904–2915.

Ivanov, D., & Dolgui, A. (2021). OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: Managerial insights and research implications. *International Journal of Production Economics, 232*, 107921.

Joglekar, N. R., Davies, J., & Anderson, E. G. (2016). The role of industry studies and public policies in production and operations management. *Production and Operations Management, 25*(12), 1977–2001.

Johns Hopkins University (2021). COVID-19 dashboard by the center for systems science and engineering.

Kazaz, B., Webster, S., & Yadav, P. (2016). Interventions for an artemisinin-based malaria medicine supply chain. *Production and Operations Management, 25*(9), 1576–1600.

Keskinocak, P., & Savva, N. (2020). A review of the healthcare-management (modeling) literature published at M&SOM. *Manufacturing and Service Operations Management, 22*(1), 59–72.

Kim, T. (2020). *How South Korea solved its face mask shortage*. The New York Times.

Li, Y., Chen, K., Collignon, S., & Ivanov, D. (2021). Ripple effect in the supply chain network: Forward and backward disruption propagation, network health and firm vulnerability. *European Journal of Operational Research, 291*(3), 1117–1131.

Long, E. F., Nohdurft, E., & Spinler, S. (2018). Spatial resource allocation for emerging epidemics: A comparison of greedy, myopic, and dynamic policies. *Manufacturing and Service Operations Management, 20*(2), 181–198.

Meyer, R. J., & Assunç ao, J. (1990). The optimality of consumer stockpiling strategies. *Marketing Science, 9*(1), 18–41.

Nagurney, A. (2021). Optimization of supply chain networks with inclusion of labor: Applications to COVID-19 pandemic disruptions. *International Journal of Production Economics, 235*, 108080.

Nikolopoulos, K., Punia, S., Schäfers, A., Tsinopoulos, C., & Vasilakis, C. (2021). Forecasting and planning during a pandemic: COVID-19 growth rates, supply chain disruptions, and governmental decisions. *European Journal of Operational Research, 290*(1), 99–115.

Noda, S., & Teramoto, K. (2020). A dynamic model of rational 'panic buying'. *Working paper*. University of British Columbia, Vancouver.

Petruzzi, N., & Dada, M. (1999). Pricing and the newsvendor problem: A review with extensions. *Operations Research, 47*(2), 183–194.

Queiroz, M. M., Ivanov, D., Dolgui, A., & Fosso Wamba, S. (2020). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the COVID-19 pandemic through a structured literature review. *Annals of Operations Research*. https://doi.org/10.1007/s10479-020-03685-7.

Ranney, M. L., Griffeth, V., & Jha, A. K. (2020). Critical supply shortages—The need for ventilators and personal protective equipment during the covid-19 pandemic. *New England Journal of Medicine, 382*(18), e41.

Rotondi, F. (2020). *Italy's plan to cap price of face masks at 50 cents has flopped*. Bloomberg.

Silal, S. P. (2020). Operational research: A multidisciplinary approach for the management of infectious disease in a global context. *European Journal of Operational Research*. S0377221720306482.

Sinha, P., Kumar, S., & Chandra, C. (2021). Strategies for ensuring required service level for COVID-19 herd immunity in Indian vaccine supply chain. *European Journal of Operational Research*. Forthcoming.

Sodhi, M. S., Tang, C. S., & Willenson, E. T. (2021). Research opportunities in preparing supply chains of essential goods for future pandemics. *International Journal of Production Research*, 1–16. https://doi.org/10.1080/00207543.2021.1884310.

Taylor, J. W., & Taylor, K. S. (2021). Combining probabilistic forecasts of COVID-19 mortality in the United States. *European Journal of Operational Research*. Forthcoming.

Taylor, T. A., & Xiao, W. (2014). Subsidizing the distribution channel: Donor funding to improve the availability of malaria drugs. *Management Science, 60*(10), 2461–2477.

The European Council (2021). COVID-19 coronavirus pandemic: The EU's response.

The New York Times (2021). The COVID-19 Pandemic. https://www.nytimes.com/news-event/coronavirus.

The White House (2021). The Biden–Harris plan to beat COVID-19.

United Nations (2020). UN launches COVID-19 plan that could “defeat the virus and build a better world”.

Van den bergh, R. J., & Pacces, A. M. (2012). Regulation and economics. In G. D. Geest (Ed.), *Encyclopedia of law and economics*. Cheltenham, UK: Edward Elgar Publishing.

Viscusi, W. K., Harrington, J. E., Jr., & Sappington, D. E. M. (2018). *Economics of regulation and antitrust* (5th ed.). The MIT Press.

WHO (2020a). Coronavirus disease (COVID-2019) situation reports. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports.,

WHO (2020b). Shortage of personal protective equipment endangering health workers worldwide. *Technical report*.

Yeung, K., Basu, A., Hansen, R. N., & Sullivan, S. D. (2018). Price elasticities of pharmaceuticals in a value based-formulary setting. *Health Economics, 27*(11), 1788–1804.

Yoon, J., Narasimhan, R., & Kim, M. K. (2018). Retailer's sourcing strategy under consumer stockpiling in anticipation of supply disruptions. *International Journal of Production Research, 56*(10), 3615–3635.

Zheng, R., Shou, B., & Yang, J. (2021). Supply disruption management under consumer panic buying and social learning effects. *Omega, 101*, 102238.