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Supply chain resilience in the face of uncertainty: a study of wheat trade and supply chain optimization

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Abstract: This research paper explores the impact of disruptions such as the COVID-19 pandemic, Russia's invasion of Ukraine, and extreme weather events on global supply chains, with a focus on the grain trade. The paper reviews recent studies on supply chain resilience and risk management, highlighting the need for a comprehensive approach to managing supply chain risks. In an attempt to combine global wheat trade with supply chain resilience, this study proposes an optimization model to help supply chain professionals to pick from a variety of robust and resilient approaches. This proves the investigation of whether such a process ensures the best choice challenging, which might be a combination of both resilient and robust approaches. The author concentrates on the extreme weather and ban on exports disruptions, in order to acquire sufficient depth in the inquiry. A numerical case study of a real-world wheat supply chain is used to apply the model. The outcomes suggest that the best method for reducing the risks of supply-side disruption is a mixed combination of robust and resilient approaches.

1 Introduction to supply chain resilience

With the COVID-19 pandemic, the follow-up shipping and air freight troubles, and Russia's invasion of Ukraine, measuring supply chain efficiency and understanding its factors seem more crucial than it was. Demand for several products, such as electronics and household appliances, increased during the pandemic, but supply and transportation capacity decreased. For instance, the request for microprocessors, a key element in integrated circuit technology and the majority of manufacturing industries, increased, but their supply was constrained by the pandemic's effects as well as droughts and accidents at several important production locations. The pandemic hindered the availability of port and warehouse workers, truck drivers, train engineers, and other personnel in several nations, and it confounded crew adjustments on ships. Additionally, some nations implemented strong zero-COVID regulations that included thorough local lockdowns [1].

Furthermore, due to the suspension of exports from Belarus, Russia, and Ukraine following Russia's invasion of Ukraine, prices for food and energy had risen. This led to cascading repercussions including overshooting demand and export limits. When the majority of services to and from Russia were halted, container shipping was impacted. Flights across Russian airspace and container rail facilities concerning Europe and Asia via Russia were among the many commerce and transportation links that Belarus and Russia had with Europe.

As far as global seaborne grain trade is concerned, it experienced significant pressure in Q2 2022 from the Russia-Ukraine conflict and a slower start to the year for North American grains exports. During October 2022, however, a range of factors including the Black Sea Grain Initiative and a strong Brazilian corn harvest have helped to shape a more positive second half of the year for grain trade trends. After a strong period of growth in seaborne grain trade, 2022 presented significant challenges for the sector. Ukrainian grain accounted for 10% of global seaborne grain trade in 2021 but were effectively suspended by Russia’s invasion. Simultaneously, poor growing conditions undermined North American output; US wheat yields were down over 10% in the 2021-22 season and exports in 1H 2022 fell by 26% [2].

In November 2022, there had been some positive changes. Grain exports from the Ukrainian ports of Chornomorsk, Odessa, and Yuzhny started to ramp up from the beginning of August following the ratification of an UN-backed initiative between Ukraine, Turkey, and Russia. The initiative established a maritime corridor to facilitate the movement of foodstuffs. Elsewhere, other factors had also offered support. Brazil had been on track for a record corn harvest in 2022, with exports hitting a record in August, up 14%, while improved US and EU grain exports had also lent support at times. However, the geopolitical situation in Ukraine remained fluid and there is uncertainty around the renewal of the Black Sea Grain Initiative on 19th November 2022 in the midst of the peak Q4 harvest and export seasons for wheat and corn in the Black Sea region. Nonetheless, positive developments in Ukraine and beyond in end 2020 had set up a more positive second half of the year for seaborne grain trade, lending welcome support for smaller bulk carriers in particular [2].

In an attempt to combine global wheat trade with supply chain resilience, the author responds to the following research inquiries: which robust/resilient approaches are successful at reducing the risks associated with extreme weather and ban on export disruptions? How would the aforementioned disruptions affect the efficacy of robust/resilient approaches? How may businesses leverage global wheat trade to build a more resilient supply chain that can better withstand the challenges of an uncertain and fast-changing global marketplace?

This study proposes an optimization model to help supply chain professionals to pick from a variety of robust and resilient approaches. This proves the investigation of whether such a process ensures the best choice challenging, which might be a combination of both resilient and robust approaches. The author concentrates on the extreme weather and ban on exports disruptions, in order to acquire sufficient depth in the inquiry. To begin with, worldwide, ports, roadways, and factories are being hit harder and harder by extreme weather, from floods to wildfires. For example, late in August 2022, factories in China were closed; this had been common in a nation that had enacted sporadic lockdowns to combat the pandemic. However, the pandemic was not to blame that time; instead, a record-breaking drought damaged the economy in southwest China, stopping global supply chains for goods like electronics, cars, and other items that had been regularly interrupted during the previous three years [3]. Secondly, the ban on exports leads in a substantially longer than typical supply delay. For example, during summer 2022, major nickel producer Indonesia imposed a complete export prohibition, while the Philippines imposed non-automatic licensing. Australia put a stop to the shipment to Russia of alumina, a key component in the manufacturing of aluminum, on March 19, 2022 [4].

This paper makes an effort to close the empirical gap in prior research on the subject and throw some light on potential policy ramifications for supply chain professionals. It suggests a comprehensive and clearly stated practical context to choose risk management approaches from a group of reliable/durable ones. The framework meets supply, demand, and shipping capacity restrictions while maximizing anticipated net income. The remainder of the study is structured as follows: section 2 briefly reviews the relevant literature and emphasizes the research gap. Section 3 develops and explains the innovative methodological framework with an application to wheat production in India. Results are presented in Section 4 once a quantitative case study using the model is completed. Section 5 critically discusses major empirical findings.

2 Supply chain risk management and resilience: a review of the literature

By creating treatments that let a supply chain react to a disruption while regaining its prior operational state or better, supply chain resilience lessens the impact of disruptions. Being more responsive to unforeseen variables in the corporate environment has drawn increasing attention recently as one of a firm's key features [5]. In other words, the competence of a corporation to endure a disruption, return to its pre-disturbance state after the disruption, can even move in the direction of a more ideal state subsequently to the disruption is what is meant by resilience in a supply chain. There is a plentiful of studies that have reached this matter; the author chose to focus on the most recent ones. [6] investigated a hybrid methodology to supply chain risk reduction that made use of both process flexibility and finished goods inventories. Modeling of the interaction between inventory and process flexibility involved a two-stage robust optimization issue. According to authors, prior to a disruption, the company allocates inventory in the first stage; in the second stage following a disruption, to prevent demand loss, the corporation determines the production amounts at each plant. They give a formula for the ideal inventory solution based on analysis for flexibility designs, which enables to investigate the efficacy of various degrees of flexibility. Furthermore, they discover that firms should allocate more inventory to high variability products when flexibility is low.

[7] developed planning for supply chain risk management based on metrics for risk readiness and resiliency, while integrating a mathematical model that took into account the selected risk variables, containment strategies, and expected benefits for supply chain planning. In order to achieve the intended performance goals, their research additionally led to the suggestion of a method for conducting what-if evaluations of the many trade-off possibilities relevant to different levels of risk preparation and resiliency. In a similar content, [8] investigated a holistic approach to supplier choice, demand distribution, and transportation selection for channels in a situation with delivery reliability and hazards of supplier and geographical disruption. The authors claimed that their proposed model helped stakeholders understand how supply chain risk management uses the aforementioned elements to improve reaction to different kinds of disruption. Utilizing a decision tree and two-stage mixed-integer coding model, the importance of considering contingency planning in order to decrease the negative consequences of disruptions was investigated. Also highlighted were the effects of geographical and supplier reliability, along with the delay cost parameter, on management decisions about demand allocation.

A hierarchy-based framework for supply chain resilience was developed by [9], supporting the interactions between the 13 enablers that were taken into consideration and empirically validating the model. The path analytical model was tested and the hierarchical model was validated using structural equation modeling. The authors used Matrix of Cross Impact Multiplications Applied to Classification methodology to classify the enablers according to their driver power and dependence. Their main finding was that by altering their strategic assets and using the suggested strategy, businesses can boost their resilience potential. Their concept uses a single quantitative index to measure resilience, while comparison is done using the coefficient of similarity. Additionally, [10] investigated the durability of physical internet-based inventory models in the face of disturbances at supply chain facilities. An experimental quantitative investigation was presented to answer the topic using an optimisation model based on simulation. Their experimental findings demonstrated that for demand uncertainties and supply chain disruptions, the physical internet inventory model outperforms conventional pre-determined inventory control approaches. Additionally, as product value, penalty costs, and disruption frequency rise, the performance gap widens. They argue that the advantages are mostly due to the improved agility, flexibility, and delivery alternatives made possible by the connected logistics services.

All businesses must be responsive to consumers and markets. By looking at the main causes and impacts of supply chain agility at the strategic as well as operational levels through the prism of resources, [11] made an attempt to address this problem. They contended that two organizational flexibility aspects are the essential precursors to supply chain agility. Additionally, manufacturing flexibility, strategic flexibility, and supply chain agility are all important aspects of company performance. Through an empirical study of a few chosen industrial practitioners, they developed and evaluated a conceptual framework for the arguments. Structural equation modeling was used to examine data from a sample of 141 clothing manufacturing firms. Their findings showed that supply chain agility was positively influenced by both strategic and manufacturing flexibility. However, manufacturing flexibility had no effect on a firm's performance, whereas strategic flexibility did.

Following a similar conceptual framework, [12] examined the effects of supply risk and demand risk on a supply chain with numerous locations, transportation routes, and product projection over a number of time periods. They used a quantitative example to illustrate the link amongst three measurable features related to responsiveness, risk, and the cost of new and seasonal commodities before looking at how flexibility and agility may be employed to lessen supply chain disruptions. In order to show a trade-off between objective functions in their quantitative example, they used three multi-objective optimization techniques to decompose the multi-objective mixed integer programming model.

3 Supply chain risks and the importance of risk management: defining the problem

Supply chain risks could have some potentially severe consequences if they are not swiftly mitigated. Risks to employee health and safety, hacking, criminal activity, issues with suppliers, along with natural disasters could have an impact on the company's supply chain. A company's financial stability, standing in the market, and the well-being of the people and things associated with the production cycle are all subject to risks. If risks materialize and affect final goods or services, the company may experience a deluge of disgruntled clients, which could hurt sales and image. So, supply chain risk management is crucial if the company is to successfully protect its brand and bottom line. Risks should be evaluated at each step of the production flow, and safety precautions should be put in place to guard against weaknesses or interruptions.

A supply chain network strategic-tactical planning issue is the topic of the suggested study. The best risk management approaches must be chosen at the strategic level from a blend of robust and resilient approaches. The author concentrates on two leading supply-side disruption risks: extreme weather and ban on exports disruptions. The author considers the three following approaches, which are probably successful in reducing risks associated with these two types of disruption [12,13][1]:

(i) Supply diversification (SD) - Utilizing a single supplier concentrates risks, and any problems with the supplier increase the likelihood that the complete supply chain will be disrupted. The company can spread risks and lessen risk effect by diversifying its supplier base. Increased supply chain resilience may be aided by a larger supplier network. Engaging several suppliers, and if practical, suppliers in various areas, can help lower the risk of locally specific problems, regardless of whether the company has a global supply chain or a relatively contained production flow. Choosing vendors and contractors with particular expertise, finding goods and services at the best costs while simultaneously maintaining the highest quality and profitability are all made possible by working with many suppliers.

(ii) Supply Chain Risk Management Plans (SCRMP) - As with all other parts of risk management, risk evaluations are essential to supply chain risk management. The company must determine, evaluate, and finally be ready for any risks that could disrupt the supply chain. Outline the precautions that should be taken to limit risks throughout the production process and be ready to take action in the event of foreseeable occurrences or risks that could have a negative effect on the supply chain. The firm should make processes adaptable so they may be changed as needed to minimize supply chain disruptions. It's critical to remember that not every circumstance can be predicted and planned for. Therefore, the supply chain risk management strategy should prioritize based on frequency and probable consequences and set restrictions and backup plans in place

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[1] Apart from the approaches unfolded here, the author would suggest as future research two more approaches: (a) Monitor market trends, namely keep track of the latest market trends, such as the availability of wheat, prices, and demand. This helps anticipate changes that may affect supply, including weather, political instability, or other factors and (b) invest in technology, since technology can help optimize supply chain efficiency and resilience. For instance, using predictive analytics or blockchain technology can enhance traceability and transparency, enabling better data management across the supply chain.

for scenarios that are most likely to happen or that will significantly harm business.

(iii) Backup Suppliers (BS) - Precautionary action is essential in risk management for effective risk assessment and strategic risk mitigation. Risk management in the supply chain is also crucial. The business must take a proactive stance. By preparing for probable outcomes of an incident, the organization can ensure business continuity and protect itself from threats both inside and outside. Any time could come when one of the company's business partners would be unable to carry out their responsibilities in the supply chain. Vendors could be unable to complete an order for a number of different reasons. For example, they might be dealing with unusually high demand or problems in their own supply chain. For one cause or another, such as a supplier's bankruptcy, they may even decide to stop operations. By rapidly bringing on alternative business partners, the company can avoid significant disruptions and delays if it encounters problems with any of its suppliers. Therefore, the company should confirm that it has backup vendors prepared before any issues arise. The same procedures it would use to select a main supplier should be used to find suitable suppliers. After choosing a supplier, to reserve production capacity in case it's needed during a business disruption, the company ought to optimally negotiate an agreement with them. This will make it possible for the business to respond more quickly to issues. As an alternative, it can merely inform suppliers that they will be kept on file in case of emergencies, but the company runs the risk of their availability being limited.

(iv) Risk acceptance ($\boldsymbol{r_0}$) - The author takes into account a risk acceptance approach for comparison's sake. A managerial choice to forgo taking major action to mitigate a particular risk is known as risk acceptance. It refers, in more detail, to the process by which a specific risk is accepted by an entity. When someone or something accepts a risk, they are acknowledging that there is a possibility of losing money. The most common defense is that other risk management approaches, including risk avoidance or risk restriction, might be more expensive than the risk itself.

To represent perishability, the author uses a fractional formulation. However, the proportion employed is commodity-dependent rather than fixed or time-dependent, as indicated by $\boldsymbol{\rho(c)}$. The perishability function relies on the following factors in addition to the perishability fraction: c is the commodity's type; $\boldsymbol{t_0}$ denotes the moment at which it enters a specific level of the network; and $\boldsymbol{\Delta_t}$ demonstrates the length of time it stays there. The author takes homogenous perishability into account because such a network frequently uses air-cool storage. The definition of the perishability metric can be seen in (1):

$$\lambda_n(c, t_0, \Delta_t) = \lambda_{yz}(c, t_0, \Delta_t) = \lambda(c, t_0, \Delta_t) = \prod_{t=t_0}^{t_0\Delta_t}(1-\rho(c)) = (1-\rho(c))^{\Delta_t}, \tag{1}$$

where:

$y \in Y$: is one (y) of the supply sites Y, comprising a collection of growers, packing and storage facilities.

$z \in Z$: is a demand location z, for example a demand market within the set of demand locations Z.

$\lambda_y(c, t_0, \Delta_t)$: is the supply-side storage $y \in Y$ for product $c \in C$ that enters in period $t_0 \in T$ for Δ_t periods' unperished fraction function.

$\lambda_z(c, t_0, \Delta_t)$: is the demand-side storage $z \in Z$ for product $c \in C$ that enters in period $t_0 \in T$ for Δ_t periods' unperished fraction function.

$\lambda_{yz}(c, t_0, \Delta_t)$: is the transportation storage yz ($y \in Y, z \in Z$) for product $c \in C$ that enters in period $t_0 \in T$ for Δ_t periods' unperished fraction function.

With a constant exponential product dependent loss rate, the only factor affecting the unperished fraction is the length of time that inventory is held or shipped. This is a good spot to start because businesses almost always have outdated inventory. Inventory that is out of date must be identified as such. Contrary to wine, goods or basic materials kept in storage do not get better with age. When something has been kept for six months or longer and a short-term use is not anticipated, it should be thrown away [14]. Because their management does not want to disclose the ensuing loss on their financial statements, troubled companies are hesitant to do this. The author does set an upper-bound on the maximum duration, though. All items that are older than six months will be deemed perished.

The author refers to a wheat sack as a product unit in this issue[2]. As a result, wheat sacks are used to quantify all quantity-related parameters and variables. All factors and variables related to unit cost and price are calculated per wheat sack. Following [15], the algorithm makes the following presumptions as well: (i) at the expiration of a time period, all shipments ($\boldsymbol{x_{yzct_\psi}}$) are fulfilled; (ii) the sales price is obtained from the market and is used as an input parameter; it is the price of product c in market z at time t under event ψ; (iii) only during the phases of

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[2] The weight of one sack of wheat is considered 85kg (1 bushel = 27kg).

inventory holding and shipping, denoted by $\boldsymbol{\lambda_z(c, t-1, 1)}$ and $\boldsymbol{\lambda_y(c, t+d(y,z)-1, 1)}$ for supply-side and demand-side inventory holding, respectively, and by $\boldsymbol{\lambda_{yz}(c, t, d(y,z))}$ for shipping (where $\boldsymbol{d(y,z)}$ denotes the delivery lead-time between y and z) is the decomposition process taken into account on the supply; (iv) at the expiration of a time period, products that have perished or are older than six months are thrown away; (v) at every supply domain, disruptions happen one at a time.

The two-stage stochastic programming approach, in which the degree of uncertainty is only partially exposed, is the most common type of stochastic programming. The choice variables in these issues are divided into two groups, the first-stage and the second-stage decisions [16,17]. This study's two-stage stochastic model follows this pattern. The first-stage decisions are made before the identification of the uncertain parameters, which occurs in the second stage, i.e. shipment, inventory combined in $\boldsymbol{X_{\psi t}}$ prior to $\boldsymbol{\tilde{t}(\psi)}$, where:

$\boldsymbol{g_r}$: Binary variable for choosing approach r.
$\boldsymbol{X_{\psi t}}$, t< $\boldsymbol{\tilde{t}(\psi)}$: Set of tactical variables prior to event completion.

In this instance, the second-stage decisions or recourse actions have a corrective effect in addition to reducing the impossibilities imposed on by the identification of the uncertain parameters. The overall purpose is to maximize both the objective function of the first-stage costs and the expected return of the random second-stage costs. These variables are established after an event is realized. These are tactical supply chain judgments $\boldsymbol{(X_{\psi t})}$ in time-periods after $\boldsymbol{\tilde{t}(\psi)}$, where:

$\boldsymbol{X_{\psi t}}$, t≥ $\boldsymbol{\tilde{t}(\psi)}$: Set of tactical variables following event completion.

Following [18] and [19], given each event $\psi \in \Psi$, equation (2) defines the profit $(V_\psi(X_\psi))$ under event-dependent tactical choices of $X_\psi \equiv \{X_{\omega t}, t \in T\}$:

$$V_\psi(X_\psi) = \sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} v(z,c,t,\psi)h_{zct\psi} - \sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^m(z,c,t)m_{zct\psi} - \sum_{y\in Y}\sum_{c\in C}\sum_{t\in T}\sum_{r\in\xi^\kappa\cup\{r_0\}} s^\kappa(y,c,t,\rho)\kappa_{yct\psi r} - \sum_{y\in Y}\sum_{c\in C}\sum_{t\in T} s^m(y,c,t)m_{yct\psi} - \sum_{y\in Y}\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^x(y,z,c,t)x_{yzct\psi} \tag{2}$$

where:
$z \in Z$: is a demand spot *z*, for example a demand market within the set of demand locations *Z*.
$c \in C$: is a commodity *c* within the set of commodities *C*.
$t \in T$: is one of the times *t* in the group of periods *T*.
$y \in Y$: is one (*y*) of the supply sites *Y*, comprising a collection of growers, packing and storage facilities.
$r \in \xi^\kappa \cup \{r_0\}$: is a approach *r* within the group of all approaches *ξ*.
ξ^κ : is the set of risk management approaches related to supply status.
$v(z,c,t,\psi)$: is the market value for commodity $c \in C$ at demand spot $z \in Z$ in period $t \in T$, under event $\psi \in \Psi$.
$s^m(y,c,t)$: is the storage cost per unit of commodity $c \in C$, when held at supply spot $y \in Y$ for one period, from period $t \in T$.
$s^\kappa(y,c,t,\rho)$: is the purchase cost per unit of commodity $c \in C$ at supply spot $y \in Y$, in period $t \in T$, in approach $r \in \xi$.
$s^x(y,z,c,t)$: is the shipping cost between $y \in Y$ and $z \in Z$ per unit of commodity $c \in C$ in period $t \in T$.
$h_{zct\psi}$: is the sales of commodity $c \in C$ at demand spot $z \in Z$ in period $t \in T$, under event $\psi \in \Psi$.
$x_{yzct\psi}$: is the transportation of commodity $c \in C$ from supply spot $y \in Y$ to demand spot $z \in Z$ in period $t \in T$, under event $\psi \in \Psi$.
$m_{yct\psi}$: is the inventory of commodity $c \in C$ held at supply spot warehouse $y \in Y$ in period $t \in T$, under event $\psi \in \Psi$.
$m_{zct\psi}$: is the inventory of commodity $c \in C$ held at demand spot warehouse $z \in Z$ in period $t \in T$, under event $\psi \in \Psi$.
$\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} p(z,c,t,\psi)h_{zct\psi}$: denotes the sales revenue, namely the money the company makes from selling products.
$\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^m(z,c,t)m_{zct\psi}$: denotes the storage cost at demand spots, namely the sum of money expended on storing (holding) inventory at demand spots.
$\sum_{y\in Y}\sum_{c\in C}\sum_{t\in T}\sum_{r\in\xi^\kappa\cup\{r_0\}} s^\kappa(y,c,t,\rho)\kappa_{yct\psi r}$: denotes the supply expenses, namely the cost of consumables used during a reporting time.
$\sum_{y\in Y}\sum_{c\in C}\sum_{t\in T} s^m(y,c,t)m_{yct\psi}$: denotes the storage cost at supply spots, namely the sum of money expended on storing (holding) inventory at supply spots.
$\sum_{y\in Y}\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^x(y,z,c,t)x_{yzct\psi}$: denotes the shipping cost, namely physical transportation, handling, customs, tariffs, inspection, storage, insurance, and taxes, as well as all related fees and expenses.

Following [12], the cost of implementing a risk management plan (g_r) is a fixed cost (f_r). Equation (3) gives the overall cost of putting risk management approaches $F(g_r)$ into practice. The choice of a mixed collection of robust/resilient approaches comes with technical challenges. The author categorizes all robust/resilient approaches as being supply-based $(r \in \xi^{\kappa})$ and probability-based $(r \in \xi^{pr})$ in order to surmount the difficulties. At least one of these two sets must include the specified approach. A risk acceptance approach (r_0) can be used regardless of the specified approach sets [20].

$$F(g_r) = \sum_{r\in\xi} f_r g_r \tag{3}$$

As shown in Equations (4) and (5), both the supply cost $s^{\kappa}(y,c,t,\rho)$ and the supply bounds are impacted by supply-based approaches. Supply bounds are multiplied by a term (g_r) associated with the author's approach-selection decision variable wherever they occur in the model constraints.

$$\underline{b}(y,c,t,\psi,r_0)\left(1-\sum_{r\in\xi^{\kappa}} g_r\right) \le b_{yct\psi r_0} \le \overline{b}(y,c,t,\psi,r_0)\left(1-\sum_{r\in\xi^{\kappa}} g_r\right) \tag{4}$$

$$\underline{b}(y,c,t,\psi,r)g_r \le b_{yct\psi r} \le \overline{b}(y,c,t,\psi,r)g_r \tag{5}$$

where:

$\underline{b}(y,c,t,\psi,r_0)$: is the lower bound for supply $c \in C$ at supply spot $y \in Y$ at period $t \in T$ under event $\psi \in \Psi$ when employing approach $r \in \xi^{\kappa} \cup \{r_0\}$.

$\overline{b}(y,c,t,\psi,r_0)$: is the upper bound for supply $c \in C$ at supply spot $y \in Y$ at period $t \in T$ under event $\psi \in \Psi$ when employing approach $r \in \xi^{\kappa} \cup \{r_0\}$.

Although this may happen in reality, the model does not permit the selection of more than one supply-based approach due to the interaction of supply bounds. To deal with this constraint, the author outlines a joint approach $BS = BS \cap SD$ in the supply-based approach set. On the other hand, the chance of a disruption (*Pr*(ψ)) is decreased by probability-based approaches $r \in \xi^{pr}$, while the likelihood of the base event (*Pr*(ψ_0)) is increased. Therefore, there are probability changes *ΔPr*(ψ,*r*) for each $r \in \xi^{pr}$ for every $\psi \in \Psi$ that have an impact on the anticipated overall profit. A risk management plan can only choose one probability-based approach to avoid the interaction of the probability adjustments (Hopkin, 2018). This can be transformed to equation (6).

$$\begin{aligned}&\sum_{r\in\xi} l_r g_r + \left[Pr(\psi_0) + \sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r) g_r\right] V_{\psi_0}(X_{\psi_0}) + \sum_{\psi\in\Psi\setminus\{\psi_0\}}\left[Pr(\psi) - \sum_{r\in\xi^{pr}} \Delta Pr(\psi,r) g_r\right] V_{\psi}(X_{\psi}) = \\ &= \sum_{r\in\xi} l_r g_r + \sum_{\psi\in\Psi} \Pr(\psi) V_{\psi}(X_{\psi}) + \sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r) g_r V_{\psi_0}(X_{\psi_0}) - \sum_{\psi\in\Psi\setminus\{\psi_0\}} \sum_{r\in\xi^{pr}} \Delta Pr(\psi,r) g_r V_{\psi}(X_{\psi})\end{aligned} \tag{6}$$

where:

$\sum_{r\in\xi} l_r g_r$: the fixed cost for risk management.

$\left[Pr(\psi_0) + \sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r) g_r\right] V_{\psi_0}(X_{\psi_0})$: the adjusted performance for base alternative

$\sum_{\psi\in\Psi\setminus\{\psi_0\}}\left[Pr(\psi) - \sum_{r\in\xi^{pr}} \Delta Pr(\psi,r) g_r\right] V_{\psi}(X_{\psi})$: the adjusted performance for other alternatives

$\sum_{\psi\in\Psi} \Pr(\psi) V_{\psi}(X_{\psi})$: unadjusted performance for all alternatives

$\sum_{r\in\xi^{pr}} \Delta \Pr(\psi_0,r)\, g_r V_{\psi_0}(X_{\psi_0})$: adjustment to ψ_0

$\sum_{\psi\in\Psi\setminus\{\psi_0\}} \sum_{r\in\xi^{pr}} \Delta Pr(\psi,r) g_r V_{\psi}(X_{\psi})$: adjustment to other alternatives

$\sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r) g_r V_{\psi_0}(X_{\psi_0})$ - $\sum_{\psi\in\Psi\setminus\{\psi_0\}} \sum_{r\in\xi^{pr}} \Delta Pr(\psi,r) g_r V_{\psi}(X_{\psi})$: the method for obtaining the efficient adjustment to the anticipated profit for $r \in \xi^{pr}$.

As discussed before, two steps of decision-making are required for two-stage optimization. As a result, there are two sets of variables, the set of first-stage and the set of second-stage variables that have feasible solutions respectively, depending on the first-stage answer that has been selected [21]. The method used in this paper permits the automatic selection of one alternative for certain and uncertain two-stage events based on several choice variables. It is possible to utilize this technique to address any two-stage multi-objective optimization problem, even though the author presents it in the context of supply disruptions.

The two-stage stochastic optimization model may now be constructed using the definitions provided above. Following [18] and [22], the goal function in equation (7) optimizes anticipated profit in the event of a supply-side disruption.

$$\begin{aligned}&\sum_{r\in\xi} -l_r g_r + \sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r) g_r V_{\psi_0}(X_{\psi_0}) - \\ &- \sum_{\psi\in\Psi\setminus\{\psi_0\}} \sum_{r\in\xi^{pr}} \Delta Pr(\psi,r) g_r V_{\psi}(X_{\psi}) + \sum_{\psi\in\Psi} \Pr(\psi) V_{\psi}(X_{\psi})\end{aligned} \tag{7}$$

The event-dependent profit has a linear formula in limitation (8).

$$V_\psi(X_\psi) = \sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} v(z,c,t,\psi)h_{zct\psi} - \sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^m(z,c,t)m_{zct\psi} - \sum_{y\in Y}\sum_{c\in C}\sum_{t\in T}\sum_{r\in\xi^\kappa\cup\{r_0\}} s^\kappa(y,c,t,\rho)\kappa_{yct\psi r} - \sum_{y\in Y}\sum_{c\in C}\sum_{t\in T} s^m(y,c,t)m_{yct\psi} - \sum_{y\in Y}\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^x(y,z,c,t)x_{yzct\psi} \tag{8}$$

By taking into account inventory holding, shipment, and supply in balance, limitations (9) and (10) balance the movement of goods in supply-side spots.

$$\sum_{r\in\xi^\kappa\cup r_0}\xi_{yc1\psi r} = m_{yc1\psi} + \sum_{z\in Z,t+d(y,z)\le|T|} X_{yzc1\psi} \tag{9}$$

$$\sum_{r\in\xi^\kappa\cup r_0}\xi_{yct\psi r} + \lambda(c,t-1,1)\, m_{yct-1\psi} = m_{yct\psi} + \sum_{z\in Z,t+d(y,z)\le|T|} X_{yzct\psi} \tag{10}$$

The flow of goods in demand-side spots is similarly balanced by limitations (11) and (12) by taking inventory holding, shipment, and sales into account.

$$\sum_{y\in Y,d(y,z)=0}\lambda(c,t-d(y,z),d(y,z))\, x_{yzct-d(y,z)\psi} = h_{zct\psi} + m_{zct\psi} \tag{11}$$

$$\sum_{y\in Y,t>d(y,z)}\lambda(c,t-d(y,z),d(y,z))\, x_{yzct-d(y,z)\psi} + \lambda(c,t-1,1)m_{zct-1\psi} = h_{zct\psi} + m_{zct\psi} \tag{12}$$

Limitations in (13) establish the supply range for a risk-acceptance approach.

$$\underline{b}(y,c,t,\psi,r_0)\left(1-\sum_{r\in\xi^\kappa} g_r\right) \le b_{yct\psi r_0} \le \bar{b}(y,c,t,\psi,r_0)\left(1-\sum_{r\in\xi^\kappa} g_r\right) \tag{13}$$

A supply-based risk management approach has bounds on the supply that are set by the limitations in (14).

$$\underline{b}(y,c,t,\psi,r)g_r \le b_{yct\psi r} \le \bar{b}(y,c,t,\psi,r)g_r \tag{14}$$

Limitation (15) guarantees that only one supply-based approach will be chosen out of all possible alternatives.

$$\sum_{r\in\xi^\kappa} g_r \le 1 \tag{15}$$

A market capacity limitation is limitation (16).

$$\sum_{c\in C(e)} h_{zct\psi} \le \bar{j}(z,e,t) \tag{16}$$

where:
$e \in E$: a product e contained by a group of products E
$\bar{j}(z,e,t)$: the upper threshold of product $e \in E$ demand, in demand spot $z \in Z$, at time $t \in T$.

Limitation (17) guarantees that a maximum of one probability-related approach is chosen.

$$\sum_{r\in\xi^{pr}} g_r \le 1 \tag{17}$$

The limitations in (18) specify the transport capabilities.

$$\sum_{z\in Z,t+d(y,z)\le|T|} X_{yzct\psi} \le \bar{x}(y,c,t) \tag{18}$$

A non-anticipatory limitation (19) makes sure that choices made in various yield disruption situations are consistent before a disruption actually happens.

$$X_{\psi t<\tilde{t}(\psi)} = X_{\psi_0 t} \tag{19}$$

Finally, non-negative and binary variables are defined by limitation (20).

$$\underline{b}(y,c,t,\psi,r) \ge 0$$
$$h_{zct\psi} \ge 0$$
$$X_{yzct\psi} \ge 0$$
$$m_{\delta ct\psi} \ge 0$$
$$g_r \in \{0,1\}$$

where:
$\delta \in \Delta$: a location δ contained by group of all spots $\Delta \equiv Y \cup Z$.

This issue is known as a Mixed Integer Quadratic Program (MIQP) since the objective functions contain a quadratic term. A Mixed Integer Linear Program (MILP) is a problem that has an objective function (a linear objective) without any quadratic terms. According to [23] and [24], relevant quadratic terms like the aforementioned linear formula (8) could be dealt using the Big-M method to convert the model from a MIQP to MIPL. The Big M method is a version of the Simplex Algorithm that foremost observes a breadth-first search (BFS) algorithm by including artificial variables to the problem. The objective function of the original linear programming ought to be altered to guarantee that the artificial variables are all equal to 0 at the conclusion of the simplex algorithm.

The author defines additional variables $\boldsymbol{C_{\psi_0 r}}$ and $\boldsymbol{C_{\psi r}}$ as the adjustments in the anticipated profit, when $\boldsymbol{r} \in \boldsymbol{\xi^{pr}}$ if used in base-case and disruption events, respectively. The (8) is the re-ordered in (20):

$$\sum_{r\in\xi^{pr}} l_r g_r + \sum_{\psi\in\Psi}\Pr(\psi)\, V_\psi(X_\psi) + \sum_{r\in\xi^{pr}} C_{\psi_0 r} - \sum_{r\in\xi^{pr}}\sum_{\psi\in\Psi\backslash\psi_0} C_{\psi r} \tag{20}$$

The model transformation is dependent on the following extra limitations (21), (22), (23), (24).

$$C_{\psi r} - \Delta \Pr(\psi, r) V_{\psi} X_{\psi} \leq B(1 - g_r) \quad (21)$$

$$C_{\psi r} - \Delta \Pr(\psi, r) V_{\psi} X_{\psi} \geq -B(1 - g_r) \quad (22)$$

$$C_{\psi r} \leq B g_r \quad (23)$$

$$C_{\psi r} \geq -B g_r \quad (24)$$

where B is such a big number to impose Big-M limitations.

When an integer viable solution is available, the Branch-and-Cut method typically runs more quickly. An upper bound on the cost of the solution enhances the algorithm's capacity to prune branches from the search tree, and this solution is also utilized by local search MIP heuristics. Several heuristics are used by MIP solvers to automatically generate these solutions; however, they are not always effective. The author employed Python-MIP, which enables the creation of better Branch-&-Cut algorithms by connecting routines tailored for particular applications to the general algorithm built into the solver engine. Given that there aren't many possible occurrences in this study's problem, the Branch-&-Cut algorithm eventually solves the stochastic model's deterministic equivalent.

4 Results - numerical application and case study illustration

4.1 Production and supply of wheat in India

In India, wheat is the second most popular grain after rice. The nation is ranked as the second-largest wheat producer in the world. Commercial foods like wheat are farmed over a huge amount of land. Wheat is regarded as the food with the highest protein content for humans. India's economy depends 40% on wheat exports. India produces 70 million tonnes of wheat annually since it is the main agricultural product in the nation. Statistics show that about 12% of the world's wheat is produced in India. The decrease in wheat production in the United States (May 2022) made wheat export from India possible. However, India uses contemporary technology to meet the rising demand for wheat. India's wheat export industry is hampered by a lack of quality control, adequate processing facilities, storage space, and transportation infrastructure [25].

Incorporated in 1975, the wheat producing company Shri Mahavir Agritech (a division of the Mahavir Group) has become a leader in the production of whole wheat flour, the processing of wheat, and the supply of goods including chickpeas, semolina flour, durum wheat, milling wheat, all-purpose flour, and others. The company's cutting-edge infrastructural facility is divided into units. These units, each having particular duties and accountability are processing, quality assurance, warehousing & packaging, logistics, and administrative. It also offers this assortment in a variety of packaging solutions to match the clients' varied needs. Its ability to serve orders quickly has allowed it to build up a sizable clientele. Specifically, the company has built up a clientele network, providing services to almost 700 clients, including well-known companies like ITC Ltd., Ruchi Soya Ltd., Louis Dreyfus, Allana Group, and more [26].

Shri Mahavir Agritech keeps an annual supply of 850,000 wheat sacks on an annual basis, while exporting its wheat products to 85 countries worldwide, mainly through its client Allana Group, one of the major exporters of the country . These three markets are taken into account in this case study: Asia, Africa and Middle East, with sales prices averaging \$24.42, \$28.11 and \$31.43 per wheat sack respectively [27]. The planning horizon spans a total of 12 months. In India, wheat is collected in March, April, May, and June. These months make up our hypothetical base harvest period. The states of Haryana, Punjab, Rajasthan, Uttar Pradesh, West Bengal, Madhya Pradesh, Gujarat, Maharashtra, Tamil Nadu, Andhra Pradesh, and Bihar are the ones that produce the most wheat, comprising the agri-food production cluster in this case . Supply upper-bounds are shown in Table 1 for the basic event ψ_0 and risk acceptance approach r_0 respectively. Even if all wheat kinds are combined into a single product, the commodity is differentiated by the sources of its supply and the timing of its harvest. The case study is a multi-commodity model as a result. The author considers two supply locations, Uttar Pradesh , UP (S1) and other Indian suppliers (S2).

Table 1 Supply upper-bound (thousands of sacks)
Source: Author's calculations & compilation

Supply location	Commodity	Risk management	March	April	May	June
y	$c = (y, e, \hat{t})$	Strategies r	t=3	t=4	t=5	t=6
1	(1 ,1 ,3)	$\forall r \in \xi \backslash \{SD\}$	227	0	0	0
1	(1 ,1 ,4)	$\forall r \in \xi \backslash \{SD\}$	0	227	0	0
1	(1 ,1 ,5)	$\forall r \in \xi \backslash \{SD\}$	0	0	67	0
1	(1 ,1 ,6)	$\forall r \in \xi \backslash \{SD\}$	0	0	0	38
2	(2 ,1 ,3)	$\forall r \in \xi$	56	0	0	0
2	(2 ,1 ,4)	$\forall r \in \xi$	0	56	0	0
2	(2 ,1 ,5)	$\forall r \in \xi$	0	0	18	0
2	(2 ,1 ,6)	$\forall r \in \xi$	0	0	0	7

Moreover, in Table 2, data for demand upper-bounds are estimated.

Table 2 Demand upper-bound (thousands of sacks), Source: Author's calculations & compilation

Demand location	Product	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
z	e	*t=1*	*t=2*	*t=3*	*t=4*	*t=5*	*t=6*	*t=7*	*t=8*	*t=9*	*t=10*	*t=11*	*t=12*
1	1	61	61	61	61	61	58	58	43	43	43	43	43
2	1	56	56	56	56	27	27	27	14	14	14	7	7
3	1	58	58	58	58	57	33	33	18	18	14	14	14

Estimated lead times and sack prices for transport are shown in Table 3.

Table 3 Supply to market shipping lead-time and costs
Source: Author's calculations & compilation

Supply location y	Demand location z		
	1	2	3
1	2 ($3.23)	1 ($3.11)	1 ($3.11)
2	2 ($3.23)	1 ($3.11)	1 ($3.11)
3	2 ($3.23)	1 ($3.11)	1 ($3.11)

Supply costs paid to growers and inventory holding cost characteristics are shown in Table 4.

Table 4 Purchase cost ($ per sack) and inventory storage cost
Source: Author's calculations & compilation

Variable	Location	Value
Supply cost $s^{\kappa}(y,c,t,\rho_0)$	∀y=1,2	$4.23
Supply cost $s^{\kappa}(y,c,t,\rho_0)$	∀y=3	$4.05
Supply side inventory storage cost $s^{m}(y,c,t)$	∀y=1,2	$3.11
Supply side inventory storage cost $s^{m}(y,c,t)$	∀y=3	$3.04
Demand side inventory storage cost $s^{m}(z,c,t)$	∀z∈ Z	$4.05

During 2022, India experienced the warmest March in 122 years, which led to a low yield of wheat [28]. The harvest in UP (S1) is delayed by a month in the author's extreme weather disruption event, but the yield is unaffected. The likelihood of a disruption is 30%. On the other hand, the likelihood of the basic event is 70%. Shri Mahavir Agritech is concerned about this disruptive event since any delay in getting new season wheat into its key markets results in significant revenue losses. The author makes the fixed cost assumption that it will cost $14 million to implement an approach for moderating disruption probability in order to minimize the likelihood of a significant weather disruption by 10%. The author marks the particular realization during considerable weather disturbance with r= 〖SCRMP〗 ^M.

On Friday, May 13, 2022, the Indian government imposed a restriction on wheat exports, citing worries about India's food security raised by the sudden rise in global wheat prices. Exemptions had been granted for shipments to other countries that the government had authorized in order to meet those countries' obligations for food security after receiving requests from those governments, as well as export agreements with customs registration or an irrevocable letter of credit on or before May 13, 2022. The Government of India's capacity to distribute wheat under its domestic food assistance/security programs was impacted by the lower-than-anticipated 2022 wheat harvest, rising food inflation, and low government acquisition of wheat under its Minimum Support Price program [29].

According to the author, a disruption at the UP (S1) caused by a ban on exports would cause an output reduction of 70% in either March or April. Since most of the wheat is harvested during these two months, and since UP serves as its main source of supplies, these two eventualities worry Shri Mahavir Agritech the most. The likelihoods of the base event and two disruption events involving ban on exports are 50% (base), 25%, and 25% respectively. The worst-case event would involve a ban on exports in March, which would have a bigger negative effect on financial performance. The chance of ban on exports disruption in March and April would be decreased by 5% (from 25% to 20%) and 20% (from 25% to 5%) respectively, by using supply chain risk management plans (SCRMP). However, a fixed cost of $3M is anticipated to accompany the implementation of the approach. The author designates the precise realization subject to ban on exports disruption as r= 〖SCRMP〗 ^H.

The most important distributor of Shri Mahavir Agritech in the USA is Parmar Dhanraj Inc. based in Hayward, California, serving the entire West Coast of USA. The fixed cost of reserving an extra backup supply of ten million sacks from California in March is projected to be $7 million if the author employs the backup suppliers method (r=BS). Moreover, the author replaces five million sacks from the UP supply with the Californian source as part of the supply diversification plan (r=SD). Instead of a fixed cost, this approach has an additional variable cost of \$3.67 each sack. The costs are increased for the BS=BS∩SD joint approach.

4.2 *Model evaluation and risk mitigation strategies*

Since the author has used Python-MIP before, that allows the development of improved Branch-&-Cut algorithms, he uses Python-PuLP which is a high-level modeling package that makes the most of its potential by letting users write programs using expressions that are native to the language and, if possible, avoiding extra syntax and keywords. This software has been used to solve this study's case problem. The predicted earnings and the worst-case (extreme weather disruption) profits for various risk management approaches are shown in Table 5.

Table 5 Outcomes of efficiency enhancement under extreme weather disruption
Source: Author's calculations & compilation, Note: EAT is short for Earnings After Taxes

Offered approach	Estimated EAT (in \$mn.)	Enhanced efficiency (%)	Worst EAT (in \$mn.)	Enhanced efficiency (%)
No approach	174,35	n/a	166,53	n/a
SD, BS, $SCRMP^M$	181,54	4,12	175,47	5,37
SD, $SCRMP^M$	179,41	2,90	168,21	1,01
SD, BS	177,85	2,01	175,47	5,37
BS, $SCRMP^M$	177,14	1,60	174,23	4,62
$SCRMP^M$	176,46	1,21	166,53	0,00
SD	176,39	1,17	168,21	1,01
BS	176,12	1,02	174,23	4,62

In the first cost settings, a risk acceptance method serves as a baseline for comparison. To accomplish the largest enhancement in the predicted profit, all strong and resilient approaches are used in the ideal solution. The result of combining all three approaches is an enhancement of 4.12%. 2.90% represents the best enhancement over subsets of two approaches. The r= 〖SCRMP〗 ^M yields the best results when only one option is available (either BS, SD, or 〖SCRMP〗 ^M), although the gains from the other two approaches are close (1.21% versus 1.17% and 1.02%). When all three (or both BS, SD) approaches are employed, the best profit increase is 5.37% in the worst-case event. The 〖SCRMP〗 ^(M)does not have an impact on the worst-case event because it only influences the likelihood of the disruption event and not the profit when the event occurs.

As observed, while there is some replaceability between the approaches, the significance is rather small (the enhancement of the joint approaches is lower than the total of the individual enhancements). That is, by putting the approaches into practice simultaneously, a sizable benefit can be realized. Approaches BS, SD exhibit the least substitution loss, whilst BS, 〖SCRMP〗 ^(M) exhibit the most. As a result, it is rather biased to draw a broad conclusion on the substitution impacts of solid against sustainable approaches.

The outcomes for the ban on wheat exports disruption are displayed in Table 6. In contrast to an extreme weather disruption, implementing the two approaches of BS and SD is nearly as effective as implementing all three approaches (2.80% vs. 2.88%).

Table 6 Outcomes of efficiency enhancement under ban on wheat exports disruption
Source: Author's calculations & compilation, Note: EAT is short for Earnings After Taxes

Offered approach	Estimated EAT (in \$mn.)	Enhanced efficiency (%)	Worst EAT (in \$mn.)	Enhanced efficiency (%)
No approach	180,12	n/a	175,46	n/a
SD, BS, $SCRMP^H$	185,31	2,88	185,27	5,59
SD, $SCRMP^H$	184,11	2,22	178,69	1,84
SD, BS	185,17	2,80	185,27	5,59
BS, $SCRMP^H$	181,54	0,79	182,81	4,19
$SCRMP^H$	181,45	0,74	175,46	0,00
SD	182,16	1,13	182,42	3,97
BS	181,51	0,77	182,81	4,19

The〖SCRMP〗 ^(H)approach is therefore ineffective, despite its \$3 million relatively modest cost. Additionally, when just one approach is permitted, SD is twice as effective as BS under yield disruption (1.13% versus 0.77% profit enhancement). However, both SD and BS perform similarly when extreme weather occurs (profit enhancement of 1.17% vs. 1.02%). Similar to Table 5, there is some degree of replaceability between the approaches, although the magnitude is still quite small. Again, approaches BS and SD exhibit the lowest replaceability loss, while approach BS with approach 〖SCRMP〗 ^(M)exhibits a sizable replaceability loss.

5 Conclusions

The world has been made aware of the interdependence of nations' basic food supplies thanks to COVID and related initiatives, the dangers of lean supply chains, where inventories are reduced or eliminated, and the susceptibility of this global agrifood supply chain architecture to disruptions. The environmental impact of these worldwide agrifood supply chains as well as the environmental impact of the average person's diet are both being questioned by the present climate change agenda, which is being implemented by various governments.

Some governments, such as the Netherlands, have begun purchasing farmland from farmers to reduce farming activities and, as a result, the country's agri-food production after identifying farmers as the biggest contributors to climate change. Mega food production hubs are spreading environmental effect (and contributing to climate change) to the countries that import food from them. The allocation of resources may be preferable from the perspectives of efficiency and the environment at large, but for the major agri-food production hubs that are now located in the Americas and Europe, this strategy is not advantageous at the national level under the current calculating methodology.

By creating a two-stage stochastic programming model, this study attempts to propose robust and resilient risk management approaches in the supply chain of agricultural foods. The model is used in a case study of Shri Mahavir Agritech wheat supply chain to examine how well a number of strong and adaptable solutions work when faced with risks related to extreme weather and ban on exports disruptions. The modeling outcomes and conclusions provide crucial managerial insights into a number of overarching supply chain risk management principles.

As further research, the author believes that new KPIs like the amount of time containers spend in ports (dwell time) should be introduced in this study’s model. The 2021–22 supply chain crisis' lingering effects, the implications of Russia's invasion of Ukraine on logistics in Europe, the acceleration of wealthier economies in port productivity, and the digitalization of end–to–end supply chains all contribute to the fact that emerging economies typically experience shorter delays than industrialized economies. Middle-income nations could outperform both their peers and more developed nations if they exhibit consistent performance across all supply chain components [30,31]. Moreover, agri-food production self-sufficiency at the national level will be a significant KPI; in other words, the extent to which the nation can provide for the requirements of its own people through domestic farming, including, of course, foreign tourists, despite potentially greater expenses. Over the past 50 years, many countries' levels of self-sufficiency have declined as a result of the existence of large-scale international agri-food production hubs [32].

Eventually, a limitation of the current study is the absence of any environmentally sustainable logistics options; options for logistics that are environmentally friendly can reduce supply networks' carbon footprints while facilitating trade. Environmentally sound decisions include switching to fewer carbon-intensive freight modes, warehousing that uses less energy, or employing more of the available capacity. Furthermore, price unpredictability is outside the purview of this study. Despite the fact that price unpredictability is important in some other supply chain problem settings, in the current instance that include a supply chain for premium fresh produce, price is taken into consideration as an established component and no price promotion is recommended; as a result, if product quality declines below the desired level, products are disposed of. Additionally, market capabilities for premium goods are typically higher than supply, reducing the possibility of a drop in demand.

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Review process

Single-blind peer review process.