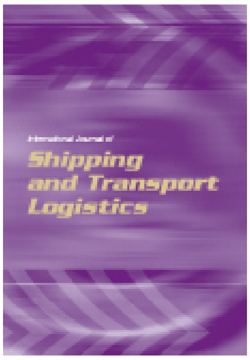

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(*r*, *Q*) inventory management in complex distribution systems of the One Belt One Road initiative

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Abstract: The paper addresses the inventory management problem in logistic systems with a networked structure in the context of new transit corridors arising from the One Belt One Road initiative. An inventory control framework for the distribution of resources in complex multi-echelon networks governed by the (*r*, *Q*) inventory policy has been presented. In addition to an arbitrary topology with lateral transshipments, the demand may be imposed on any controlled node, not just end-points. The proposed framework is applied to investigate crude oil supplies for China in the presence of uncertain demand variations. The multifaceted study gives practical insights into the policy parameter selection to secure a sufficient level of resources under operational constraints. As demonstrated in numerical experiments, the constructed framework can be flexibly adapted to examine the effects of structural changes, e.g., caused by regional blockages, that enforce the reorganisation of the distribution system.

Keywords: distribution networks; inventory control; supply chain management; uncertain demand; One Belt One Road; OBOR; Belt and Road Initiative; BRI.

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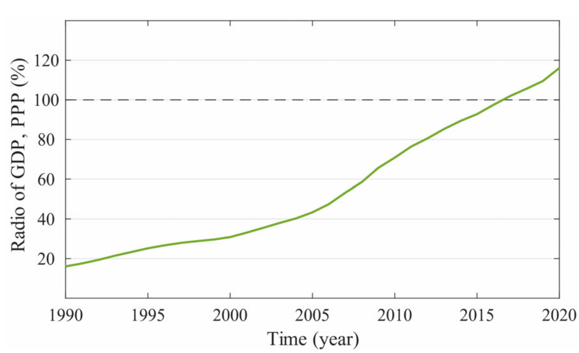
1 Introduction

The global order established after the Second World War paved the way for globalisation. The post-war international trade agreements enabled the free movement of goods and services throughout the world. During the Cold War, two large spheres of political and economic influence were formed around the USA and the Soviet Union. With the collapse of the latter, the US-based trade agreements have been revised and extended to other countries and regions. As a consequence, globalisation and business internationalisation have progressed even faster. Many enterprises have delocalised their manufacturing facilities into regions with lower labour costs and cheaper production opportunities. Numerous overseas supply chains have thus been created, enabling the economic growth of developed and developing countries. However, in recent years, the polarity in the influence spheres has changed again with China emerging as probably the biggest beneficiary of globalisation. Its national economy has experienced substantial growth through a series of socio-economic reforms initiated by Deng Xiaoping in 1978. Those reforms opened China to external markets and capital inflows. The comparison of the national economies of China and the USA (the world's largest economy at the time), illustrated in Figure 1, supports this fact. While in 1980 the Chinese economy accounted for 11% of the US-one, it subsequently rose from 16% in 1990 through 31% in 2000 to 71% in 2010. In 2017, it surpassed that of the USA and maintains the rising trend, though the impact of the COVID-19 crisis is yet to be determined. The graph from Figure 1 presents the data from the World Bank (n.d.) and the International Monetary Fund (n.d.) reflecting the gross domestic product at purchasing power parity which is a common metric used to compare national economies. The depicted trend heralds the prospect of another breakthrough in the global economic order that may reformulate the past trade agreements and decouple the existing supply chains (Kaveh et al., 2021).

Figure 1 The ratio of the Chinese national economy to the USA (see online version for colours)



Nowadays, owing to saturation effects and existing international agreements, China is facing a slowdown in economic growth. Hence, the current president, Xi Jinping, announced in 2013 the One Belt One Road (OBOR) initiative, also called the Belt and Road Initiative (BRI), which refers to the ancient Silk Road (Cui and Song, 2019). This geopolitical project aims at restoring and extending the onshore and offshore communication channels called the New Economic Silk Belt and the 21st Century Maritime Silk Road, respectively. The former involves the transit corridors linking China to Europe through the Eurasian landmass. The latter connects China to both Southwest and Southeast Asia as well as Africa and Southern Europe by combining the sea routes in the Indian Ocean, the Red Sea, and the Mediterranean Sea (Flint and Zhu, 2019). Therefore, large-scale multimodal supply chains emerge, increasing the volume of flowing resources both from and into China. Due to their geographical spread, diversity of regional markets, and dependence on the internal policies of the member countries, the resulting logistic networks are characterised by longer lead-time delays (LTDs), uncertain demand variations, and disturbance risk, e.g., as a result of regional lockdowns. Thus, establishing an efficient resource distribution scheme and inventory control in those systems becomes a challenging task (Zhao et al., 2020; Esmizadeh and Parast, 2021).

The contribution of this work is twofold. First, the inventory control framework destined for multi-echelon logistic networks exhibiting complex topologies, suitable for the analysis of dynamic and economic phenomena, is proposed. It allows for the transshipments between intermediate nodes leading to a networked architecture that cannot be untangled into separate, parallel paths. Neither simplifications nor restrictions in the way in which the interconnections are established are required. Unlike similar frameworks that have been considered so far, the external demand, satisfied up to the resource level with the lost-sales condition, may be imposed on any node in the network, not just conveniently chosen end-points. Moreover, the nonlinear (r, Q) inventory management policy, rather than the typically studied in similar problems linear order-up-to policy, is examined according to the economic and operational measures. From a practical perspective, the model complements and generalises the existing frameworks used to study the resource reflow in the OBOR-related networks (Sheu and Kundu, 2018) by incorporating both the operational costs (transportation and holding cost) and customer satisfaction (quantified through the demand fill rate). Therefore, the second paper objective is to give a new perspective on the potential of the OBOR initiative in deploying sustainable transportation solutions in non-trivial logistic architectures. As China became the world's largest energy consumer in 2011, which ushered in diversified acquisition (Li et al., 2018), the effectiveness of the proposed framework has been demonstrated using China's external crude oil supplies. In addition to the typical cases, it is shown how the proposed framework can be used to investigate the impact of structural changes, e.g., arising as a result of inopportune political decisions.

The rest of the paper is organised in the following way. Section 2 gives an account of related works concerning the application of the (r, Q) policy and supply chain formation in the OBOR context. The proposed inventory control framework and a networked (r, Q) policy are detailed in Section 3. Practical case studies are analysed in Section 4. Finally, the results and perspectives are discussed in Section 5.

2 Related works

2.1 (r, Q) inventory management policy

Inventory management in modern supply networks that have non-trivial topologies is a challenging task (Dominguez et al., 2021). Despite a substantial body of literature addressing the inventory control problem, the real-life supply chains are treated via simplified models destined for single-echelon systems, not adequate in the current context (Grob, 2019). The proposed control policies aim at reducing excess operational costs while guaranteeing a high service level (Jalali and Van Nieuwenhuyse, 2015). In this paper, the primary emphasis is given to the popular among practitioners (r, Q) policy due to its advantage over others in the systems operating under the lost-sales assumption (Taleizadeh et al., 2020). Until now, the (r, Q) policy has been investigated in systems with various structural limitations. First, Axsäter (2006) proposed a procedure to determine the order quantities under a fill-rate constraint for a single-echelon configuration with positive lead time and normally distributed demand. Olsson (2009) extended that model to a two-locations setting with lateral transshipments. The (r, Q) policy was found reasonable for a relatively low demand rate. Meanwhile, Bai et al. (2012) highlighting the common presence of demand inaccuracy in the industry investigated the policy robustness in the systems assuming incomplete demand knowledge. Afterward, Hajiaghaei-Keshteli et al. (2011) examined a three-echelon serial configuration with a singular retailer facing independent Poisson demand. Hu and Yang (2014) extended that structure by multiple intermediate echelons; however, the market demand was placed on the last stage node, only. Chen and Li (2015) applied the guaranteed service approach in serial inventory systems to optimise the policy parameters selection. Next, Varyani et al. (2014) aimed to find optimal parameters for the (r, Q) strategy in a three-echelon system with an assembly structure with stochastic demand imposed on a central warehouse. However, all those systems assume certain topological constraints that disallow applying them in distribution networks with arbitrary structures. Li and Wu (2019) scaled their structure up to multiple echelons and performed numerical studies on randomly generated topologies. On the other hand, Andersson and Marklund (2000) studied a two-level distribution model with one warehouse and multiple retailers. Atan et al. (2018) proposed a similar structure, yet allowing transshipments among the retailers to handle the customer demand. Although various system topologies have been studied so far, contemporary real-life supply networks are organised in more complex architectures, with arbitrary interconnection topologies (Dominguez et al., 2021). Following that observation, Mousavi et al. (2019) proposed a two-echelon vendor-buyer model that contains multiple nodes in each layer. However, the buyer was supplied by a single warehouse, only. Gao and Wang (2008) considered a three-echelon system with an additional layer of distribution centres. They applied simulation-based optimisation for adjusting the policy parameters to minimise the total system cost. Nevertheless, their model did not allow transshipments between the nodes within the same layer. Xiao-Jian et al. (2013) considered a similar model, albeit permitting a specified amount of backorders. In addition, they employed an adaptive genetic algorithm to solve the numerical cases.

All the mentioned papers have made a substantial contribution to the field of inventory control. However, the network complexity grows, violating the topological restrictions considered so far. This work addresses the inventory control problem in multi-echelon distribution networks with arbitrary topology. The interconnection structure permits transshipments among network nodes with the uncertain demand imposed on any node in the system. A primary contribution is a consistent framework to evaluate the regulatory potential of the (*r*, *Q*) policy in such multi-dimensional sophisticated architectures.

2.2 OBOR initiative

Xi Jinping's proposal for the OBOR initiative announced in 2013 incited much scientific interest with a growing number of papers. By describing the contemporary relationship between the USA and China, Clarke (2018) expounded the China's motivations for promoting OBOR among Eurasian countries. He noted both its importance for the Middle Kingdom's international position as well as emphasised economic desirability for the less developed countries that would experience rapid growth of their industries. Rasel et al. (2020) performed a literature review, covering 97 papers, addressing the OBOR initiative from various perspectives. The review concluded the study with the message that each member country should devote all available political and economic resources to support this initiative as despite direct profits all the members would gain diverse benefits for the infrastructure development, trading, bilateral agreements, etc. Numerous other researchers have investigated the OBOR from the participant perspective, including China's closest neighbours, e.g., Russia (Makarov and Sokolova, 2016), Mongolia (Li et al., 2019), Pakistan (Sher et al., 2019), other Asian countries, e.g., Malaysia (Woan-Lin et al., 2018), Sri Lanka (Zhu, 2015), as well as European ones (e.g., Bartosiewicz and Szterlik, 2019). Moreover, Chen et al. (2021) analysed more than 170 studies and classified them on the basis of the countries they concern. Due to the proposed methodology, it was indicated that the vast majority of them have a supportive attitude toward the initiative. A significant part of the literature is focused on the potential investments that ought to be realised to ensure OBOR sustainability, e.g., in maritime infrastructure (Huo et al., 2019; Wang et al., 2021). They involve diverse subjects that may constitute a driving as well as hampering factor, e.g., geological phenomena (Peng et al., 2016), renewable energy resources (Xu et al., 2017), and carbon emission (Liu and Hao, 2018), etc. On the other hand, Wang et al. (2018) studied cross-border e-commerce business over the OBOR initiative from the Chinese market perspective and indicated supply chain management as a key activity to achieve a competitive advantage. Ghanem et al. (2021) analysed in detail the potential benefits coming from the China-Pakistan Economic Corridor, which is one of the most relevant components of the OBOR initiative. The performed simulations revealed that all the examined metrics, i.e., transportation cost, shipping time, and distance, would be reduced significantly. However, relatively few scientific works consider OBOR from the perspective of logistic practitioners. For instance, studying a two-stage serial chain composed of a single provider and one integrator, Liu et al. (2018) analysed the impact of cost-sharing contracts on the chain performance. Fang et al. (2018) considered a three-stage logistic system with an arborescent structure that distributes perishable resources under cost and carbon emission regulations. Lei et al. (2021) also designed the transnational supply chain as an arborescent structure. Their model assumed multiple suppliers and manufacturers, however, did not allow for transshipments between the nodes in the same layer. Wei and Dong (2019) studied integrated cross-border logistic systems, combining both land and maritime subnetworks, yet again without transshipments permitted. In a recent study, Sheu and Kundu (2018) investigated the time-varying logistics distribution flows in a three-layer supply chain based on a real-life case of China's multimodal crude oil supplies. Later, their model was formally analysed for resistance to perturbations in the transport channels (Ignaciuk, 2021). However, the proposed three-layer framework does not allow transshipments between the transport layer nodes. Ignaciuk (2022) addressed this issue and developed that supply chain structure to a networked system governed using the classical order-up-to inventory management policy. Nevertheless, the external demand has been applied to the end nodes, only. As noted by Cattani et al. (2011), such topological simplifications might lead to an overoptimistic system view and non-optimal distribution flows.

This paper gives a new perspective on complex logistic systems arising from the OBOR initiative. The constructed framework, assuming no topological restrictions, permits analysis of resource exchange under uncertain demand and disruptive factors, e.g., lockdowns. According to the recent studies in the OBOR context (Lee et al., 2020), such disruptions place new requirements on the constructed models so that they could be applied in practical situations. The model proposed in this work answers those requirements by incorporating the concepts of robust control theory.

3 Network model

Table 1 contains the main symbols and mathematical notation that have been used to describe the model structure and entity interactions.

3.1 Network structure

The structure of the considered class of logistic systems encompasses three types of entities. The first one is an external source with infinite stock that only supplies the network with resources. The second one reflects a controlled node whose reserves are regulated by the (r, Q) inventory policy. The stock at the controlled node is used to satisfy the external demand imposed by customers, as well as to respond to the internal requests, i.e., the replenishment orders coming from other controlled nodes. The last group of entities conveys customers generating the external demand that may be imposed on any controlled node in each period and should be satisfied immediately, i.e., no backordering is allowed. External sources and controlled ones are interconnected using unidirectional links and form an arbitrary multi-dimensional structure. There are neither restrictions nor limitations in the way that the structure is created, however, there are no separated nodes, i.e., without any suppliers, and also any node cannot supply itself.

Each interconnection between any two nodes is characterised by three attributes:

- the nominal supplier fraction (NSF) determining the part of the needed resources that the controlled node orders from the supplier
- the LTD quantifying the time from order to receiving the resources from the supplier
- the transportation unit cost (TUC) denoting the cost of transporting one unit of resources through the route.

Table 1 Nomenclature and mathematical preliminaries

Symbol	*Description*
$[\cdot]'$	Transpose operator
$t \in \{1, \ldots, T\}$	Time period, with the planning horizon $T \in \mathbb{N}$
$\Omega_N = \{1, \ldots, N\}$	The set of controlled node indices, where N denotes the number of controlled nodes
$\Omega_S = \{N + 1, \ldots, N + S\}$	The set of external source indices, where S denotes the number of external sources
$\Omega = \Omega_N \cup \Omega_S$	The set of indices of all the nodes in the supply network
$P = N + S$	The number of all the nodes (both external sources and controlled nodes) in the supply network
$\alpha_{ij} \in [0, 1]$	The NSF between nodes i and j that determines the part of the ordered quantity at node i to be requested from supplier j
$\beta_{ij} \in \mathbb{N}$	The LTD between nodes i and j, counted from order placement to shipment delivery
B	The highest value of LTD between any two nodes in the supply network
$\gamma_{ij} \in \mathbb{R}_+^*$	The TUC charged for one unit of resources passing from node i and j
$x_i(t)$	The on-hand stock level at node i in period t
$o_i(t)$	The number of resources sent in outgoing shipments by node i in period t
$u_i(t)$	The number of resources received in incoming shipments by node i in period t
$q_i(t)$	The replenishment signal generated by node i to its suppliers in period t
$d_i(t)$	The external demand imposed on node i in period t
$h_i(t)$	The external demand satisfied by node i in period t
$y_i(t)$	The inventory position of node i in period t
r_i	The reorder point (RP) at node i
Q_i	The order quantity (OQ) at node i
$\mathbf{\Gamma}$	The matrix containing TUCs at the network interconnections
$\mathbf{x}(t) = [x_i(t), \ldots, x_N(t)]'$	The vector of on-hand stock levels at the controlled nodes in period t
$\mathbf{q}(t) = [q_i(t), \ldots, q_N(t)]'$	The replenishment signals generated in period t
$\mathbf{d}(t) = [d_i(t), \ldots, d_N(t)]'$	The vector of external demands imposed on the controlled nodes in period t
$\mathbf{h}(t) = [h_i(t), \ldots, h_N(t)]'$	The vector of demands satisfied by the controlled nodes in period t
$\mathbf{y}(t) = [y_i(t), \ldots, y_N(t)]'$	The vector of inventory positions in period t
$\mathbf{r} = [r_i, \ldots, r_N]'$	The vector of RPs
$\mathbf{Q} = [Q_i, \ldots, Q_N)]'$	The vector of OQs

The considered model assumes full order partitioning, i.e., the NSFs sum up to one. Then, denoting the NSF from node *i* to *j* as α_{ij},

$$\forall_{j} \sum_{i \in \Omega} \alpha_{ij} = 1. \tag{1}$$

In this work, the considered class of logistic networks is applied to represent a three-stage supply network containing multiple suppliers, multiple manufacturers with transshipments allowed as well as multiple customers that may impose a demand on any controlled nodes during the entire distribution process. Figure 2 illustrates the interconnection structure between the nodes of all the layers in the considered system, where the transshipments among the controlled nodes are marked in red and the dashed lines denote the flow of resources is performed among multiple intermediate nodes.

Figure 2 The three-stage interconnection model (see online version for colours)

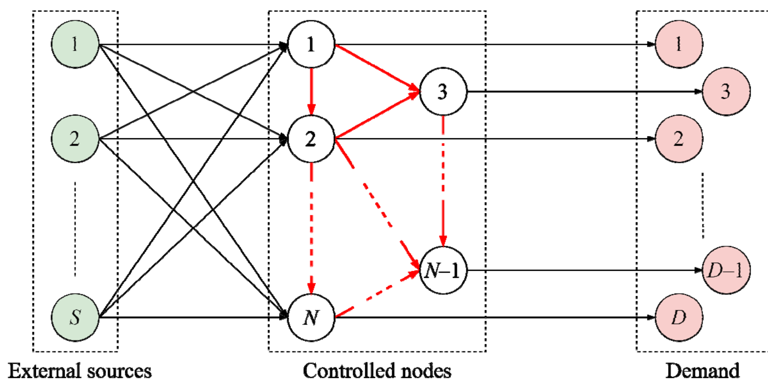
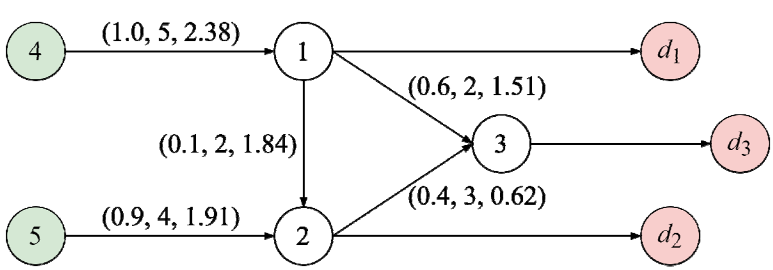


Figure 3 illustrates the example structure of the logistic system under consideration to facilitate an understanding of the resource distribution process. The network is composed of three controlled nodes (1–3) and two external sources (4–5). For instance, node 2 has two suppliers – an external source and a controlled node. It orders 90% of the needed resources from external source 5 and the rest – 10% – from controlled node 1. Then, the transportation of shipments from node 5 to 2 lasts 4 periods and costs 1.91 per unit of resources. Moreover, node 2 satisfied external demand d_2 and fulfils the replenishment signals from node 3, if possible.

Figure 3 Example structure (see online version for colours)



3.2 Interactions

The proposed model assumes the fixed sequence of operations executing at the controlled node in each period. First, the incoming shipments are registered at the on-hand stock. Then, the imposed external demand is satisfied, if possible. Afterward, the replenishment signals from the neighbours are fulfilled, if possible. Finally, the replenishment signals are generated and requested from the suppliers. Note that both the incoming and outgoing shipments are related to the flow of resources internal to the network, i.e., the resource exchange among the nodes. Contrarily, satisfying the customer demand imposed on the controlled nodes reflects the outflow of resources from the system. Taking as an example the structure illustrated in Figure 3, connections 1–3 and 2–3 are channels for the 'incoming shipments' flowing towards controlled node 3 from nodes 1 and 2, respectively. Meanwhile, connections 1–2 and 1–3 denote the paths of the outgoing shipments sent by node 1.

Let $u_i(t)$ and $o_i(t)$ be the number of resources in incoming and outgoing shipments processed by node i in period t, respectively, while $h_i(t)$ denotes the demand satisfied by node i in that period. Then, according to the described operational sequence, the on-hand stock level at node i in period $t + 1$ may be expressed by

$$x_i(t+1) = x_i(t) + u_i(t) - h_i(t) - o_i(t). \tag{2}$$

There are neither damages nor losses of the in-transit shipments and thus all the resources in outgoing shipments sent by the suppliers of node i are delivered, i.e.,

$$\sum_{j\in\Omega} o_{ji}\left(t-\beta_{ji}\right) = u_i(t). \tag{3}$$

Taking into account that the controlled nodes dispose of a finite stock and may not be able to fulfil all the replenishment signals from their neighbours, the supplier fraction between any two nodes i and j may be expressed as time-varying function $\alpha_{ij}(t)$ that satisfies

$$0 \le \alpha_{ij}(t) \le \alpha_{ij}. \tag{4}$$

Let $q_i(t)$ denote the replenishment signals, i.e., the number of resources that are needed by node i and ordered from its suppliers in period t. It means that $q_i(t)$ is a time-varying function generated by the controlled node in each period during the whole distribution process. Then, the number of resources in incoming shipments received by node i in period t may be calculated as

$$u_i(t) = \sum_{j\in\Omega} \alpha_{ji}\left(t-\beta_{ji}\right) q_i\left(t-\beta_{ji}\right). \tag{5}$$

In the considered model, the external demand is an arbitrary, bounded function of time. The satisfied demand is equal to the imposed one whenever the on-hand stock level at the controlled node is sufficient to fulfil the entire one. Otherwise, it is satisfied as much as possible that yields a loss of sales (no backordering allowed). This assumption causes a model nonlinearity, in contrast to the typical backorder approach, which may be expressed by

$$h_i(t) = \min\left(x_i(t) + u_i(t), d_i(t)\right). \tag{6}$$

Finally, with an analogy to (5), the number of resources in outgoing shipments sent by node i to its neighbours can be established according to

$$o_i(t) = \sum_{j\in\Omega} \alpha_{ij}(t) q_j(t). \tag{7}$$

3.3 State-space representation

Further analysis of the considered supply network model requires a state-space representation. Thus, all the system interactions and dependencies should be transformed into a matrix-vector form and grouped to formulate the state-space equation. First, let the detailed information about the in-transit shipments, i.e., the time-varying supplier fractions in periods $k = 1, \ldots, B$, be collected into a set of matrices

$$\mathbf{A}_k(t) = \begin{bmatrix} \sum_{i:\beta_{i1}=k} \alpha_{i1}(t) & \cdots & \delta_{1N}(t) \\ \vdots & \ddots & \vdots \\ \delta_{N1}(t) & \cdots & \sum_{i:\beta_{iN}=k} \alpha_{iN}(t) \end{bmatrix}, \tag{8}$$

where

$$\delta_{ij}(t) = \begin{cases} -\alpha_{ij}(t), & \beta_{ij} = k \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

Then, using (8) all the system dependencies may be expressed as

$$\mathbf{x}(t+1) = \mathbf{x}(t) + \underbrace{\sum_{k=1}^{B} \mathbf{A}_k(t)\mathbf{q}(t-k)}_{\text{incoming- outgoing shipments}} - \mathbf{h}(t), \tag{10}$$

where the matrix product $\mathbf{A}_k(t)\mathbf{q}(t)$ contains all the information about in-transit shipments (both incoming and outgoing ones). Assuming zero initial input, i.e., $q(t) = 0$ for $t < 0$, the on-hand stock level at any period of time during distribution phase ($t > 0$) may be calculated as

$$\mathbf{x}(t) = \mathbf{x}(0) + \sum_{m=0}^{t-1} \sum_{k=1}^{B} \mathbf{A}_k(m)\mathbf{q}(m-k) - \sum_{m=0}^{t-1} \mathbf{h}(t). \tag{11}$$

Moreover, according to (6) and denoting the vector of the highest expected values of the external demand imposed on the controlled nodes during the entire distribution process as $\mathbf{d}_{\max}$, the following dependency is always satisfied

$$0 \le \mathbf{h}(t) \le \mathbf{d}(t) \le \mathbf{d}_{\max}. \tag{12}$$

In addition, let $\mathbf{y}(t)$ denote the vector containing the inventory positions of the controlled nodes, i.e., the sum of the resources at on-hand stock and in-transit shipments,

$$\mathbf{y}(t) = \mathbf{x}(t) + \sum_{k=1}^{B} \mathbf{A}_k(t)\mathbf{q}(t-k). \tag{13}$$

3.4 Inventory control

To ensure an efficient flow of resources in the considered class of logistic systems, the classical (r, Q) inventory management policy has been applied. The policy is deployed in a fully distributed way, i.e., at each node independently. According to this strategy, the controlled node generates replenishment signals based on a defined pair of attributes r and Q that denote RP and OQ, respectively. Then, in each period the controlled node checks whether its inventory position is lower than the RP and if so, the replenishment signal of size Q is requested from its suppliers. Hence, the replenishment signals in period t may be expressed collectively as:

$$\mathbf{q}(t) = [q_1(t), ..., q_N(t)]', \tag{14}$$

where

$$q_i(t) = \begin{cases} Q_i, & y_i(t) < r_i \\ 0, & \text{otherwise,} \end{cases} \tag{15}$$

in which $y_i(t)$ denotes the inventory position of node i in period t.

3.5 Quality metrics

In order to evaluate the quality of the distribution process, three metrics, commonly used in this class of logistic problems, are defined. They take into account the operational costs involving both holding and transportation costs, and the customer satisfaction that is understood as the part of the imposed external demand actually satisfied (Arora et al., 2010; Safaeian et al., 2019).

The holding cost determines the spending incurred by the controlled nodes for resource storage, i.e., the cost of storing a unit of resources at a controlled node,

$$HC = \sum_{t=1}^{T} \mathbf{x}(t). \tag{16}$$

The transportation cost is treated as the cost incurred by the replenished node for the orders obtained from its suppliers. Note that the number of resources in the incoming shipments might not be equal to the generated replenishment signals, e.g., in the case of insufficient on-hand stock at the suppliers. The transportation cost is calculated by

$$TC = \sum_{t=1}^{T} \mathbf{\Gamma} \circ \mathbf{A}_E(t)\mathbf{q}(t), \tag{17}$$

where $\mathbf{\Gamma} \circ \mathbf{A}_E$ is the Hadamard product of $P \times N$ matrices $\mathbf{\Gamma}$ and $\mathbf{A}_E(t)$. The first one stores the information about TUCs of each system interconnection, i.e.,

$$\mathbf{\Gamma}=\begin{bmatrix} 0 & \gamma_{12} & \cdots & \gamma_{1N} \\ \gamma_{21} & 0 & \cdots & \gamma_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{N1} & \gamma_{N2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{P1} & \gamma_{P2} & \cdots & \gamma_{PN} \end{bmatrix}, \tag{18}$$

while matrix $\mathbf{A}_E(t)$ contains the corresponding supplier fractions in period t,

$$\mathbf{A}_E(t)=\begin{bmatrix} 0 & \alpha_{12}(t) & \cdots & \alpha_{1N}(t) \\ \alpha_{21}(t) & 0 & \cdots & \alpha_{2N}(t) \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{N1}(t) & \alpha_{N2}(t) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{P1}(t) & \alpha_{P2}(t) & \cdots & \alpha_{PN}(t) \end{bmatrix}. \tag{19}$$

Note that, since the external sources are assumed uncapacitated, the associated supplier fractions are always equal to the nominal values, i.e., $\alpha_{ij}(t) = \alpha_{ij}$ for $i \in \Omega_S$. In addition, both holding and transportation costs are expressed via a generic measure, which may be replaced by any currency. Similarly, there is no specific unit for resources, which can be defined by any quantitative measure, e.g., barrels, gallons, litres, etc.

Finally, in contrast to the operational costs that need to be contained, customer satisfaction should be maximised to provide a high service level. This metric is calculated by

$$CS=\frac{\sum_{t=1}^{T}\mathbf{h}(t)}{\sum_{t=1}^{T}\mathbf{d}(t)}, \text{ thus } CS\in[0,1], \tag{20}$$

where $CS = 1$ means full customer satisfaction, i.e., the case in which the entire imposed demand is satisfied.

Overall, the quality of the goods distribution process will be quantified through the cost function

$$J=\left(1-\frac{HC}{HC_{\max}}\right)^{F}\left(1-\frac{TC}{TC_{\max}}\right)^{G}CS^{H}, \tag{21}$$

where F, G, and H are non-negative parameters enabling one to emphasise the reduction of holding and transportation costs or improving customer satisfaction. $HC_{\max}$ and $TC_{\max}$ are the expected costs when a full-service rate is to be ensured under persistent maximum demand. Under a time-varying demand the costs will be lower and the ratios – HC / $HC_{\max}$ and TC / $TC_{\max}$ – confined within the range [0, 1]. As a result, one avoids the scaling issues and may smoothly balance all the quality metrics (without typical abrupt transitions).

The considered cost function allows one to handle the three-objective optimisation problem as a single-objective one. Thus, it is possible to efficiently apply computational intelligence techniques to find a near-optimal solution, such as a genetic algorithm, which is the case of this research. Moreover, increasing the parameters F, G, or H, enables one to drive the optimisation process rewarding solutions of small safety stock, low transportation cost, and high customer satisfaction, respectively. The performed research indicates that by increasing one parameter by an order of magnitude over the others leads to proper prioritisation.

4 Numerical studies

The constructed model has been examined in numerous resource distribution scenarios. This section reports on its application in the context of external crude oil supplies for China arising from the OBOR initiative. Two groups of tests have been considered for a detailed analysis. In each case, a network is designed and evaluated under diverse conditions and structural modifications, e.g., regional lockdowns. In the first group of tests, the model considered by Sheu and Kundu (2018) is extended by allowing transshipments among the nodes of the transport layer. Moreover, the external demand may be imposed on all the controlled nodes, i.e., any intermediate node may be influenced by the local market. The second group of tests investigates the potential of extending the transit corridors related to the OBOR initiative. The analysed system has a complex, networked structure covering goods exchange among 18 member countries.

The interconnections parameters – supplier fractions, delays, transportation costs – have been established using open-access resources. The networks assume three transport modes, i.e., maritime, pipeline, and rail, which allow one to estimate TUCs by applying the example cost structure proposed for Chinese oil transport by Erickson and Collins (2018). In order to emphasise the impact of structural modifications, all the controlled nodes face the external demand within a similar range (although varying differently for each node). The numerical studies are conducted with the following assumptions:

- time horizon: 1 year, i.e., 365 periods
- the initial stock level ($t = 0$) at the controlled nodes equals the corresponding RP, i.e., $\mathbf{x}(0) = \mathbf{r}$
- the external demand has been generated using the gamma distribution with the shape and scale parameters equal to 5 and 10, respectively.

Moreover, the parameters of the (r, Q) inventory policy have been established using the continuous genetic algorithm (Wieczorek and Ignaciuk, 2018; Ignaciuk and Wieczorek, 2020), which has already succeeded in adjusting the classical order-up-to policy (Ignaciuk and Wieczorek, 2019). According to the guidelines in Ignaciuk and Wieczorek (2020), 200 generations of a population containing randomly generated candidates have been performed to find a near-optimal solution. The genetic operations involved the two-point crossover, the 15-way tournament selection, and the mutation probability of 15%. The applied cost function (21) been parametrised by $F = 1$, $G = 1$, $H = 20$ to guarantee high customer satisfaction that is crucial in the initial phase of the system's operation and allows one to gain trust in the market – from both stakeholders and end users.

4.1 8-node network

4.1.1 Baseline scenario

Figure 4 depicts an eight-node logistic network involving 13 routes through which the crude oil is transferred toward China. The network has two external sources – Saudi Arabia and Angola – which were the first and the fourth biggest Chinese oil suppliers in 2019, and six controlled nodes. The parameters of node interconnections are detailed in Table A1. The external demand is randomly established within the range [7, 150] units. Function $d_i(t)$ imposed at the nodes has been presented in Figure 5.

Figure 4 Baseline scenario – resource distribution network (see online version for colours)

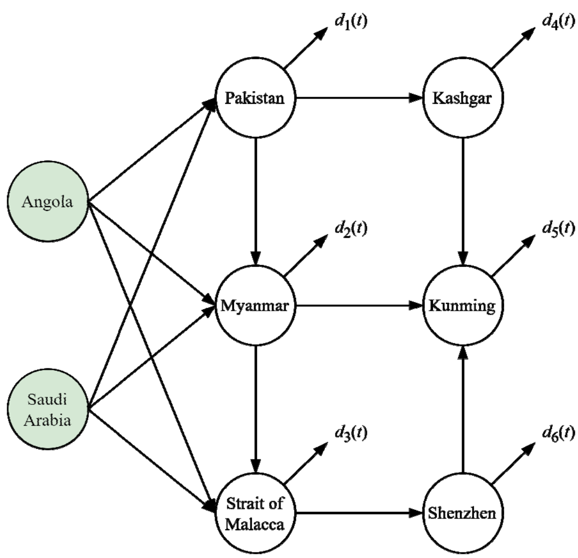
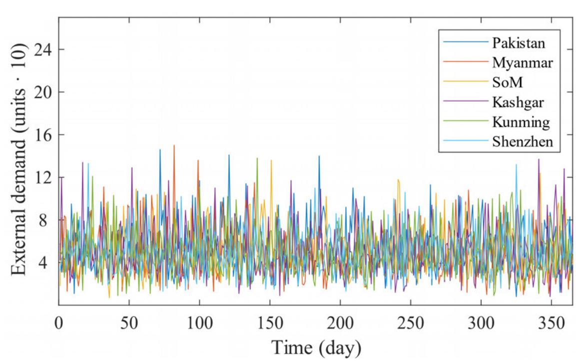


Figure 5 External demand imposed on the controlled nodes (see online version for colours)



According to the data about the network topology (Table A1), in the nominal case, i.e., when the flow of resources is not additionally perturbed by insufficient on-hand stock, matrix $\mathbf{A}(t) = const.$,

$$\mathbf{A} = \begin{bmatrix} 1.0 & -0.1 & 0.0 & -1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & -0.1 & 0.0 & -0.8 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & -1.0 \\ 0.0 & 0.0 & 0.0 & 1.0 & -0.1 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & -0.1 & 1.0 \end{bmatrix}. \quad (22)$$

Using the continuous genetic algorithm, the following policy parameters have been selected:

$$\mathbf{r}_{\text{opt}} = [1099, 1725, 2288, 1057, 316, 889]', \quad (23)$$

$$\mathbf{Q}_{\text{opt}} = [99, 193, 105, 151, 127, 74]'. \quad (24)$$

The plot in Figure 6 presents the stock level at the controlled nodes during the performed resource distribution. During the initial phase, i.e., until the first replenishment orders are realised, all the controlled nodes had surplus inventory accumulated to be able to satisfy the external demand. Then, they tend to reduce the excessive stock (their levels are close to the horizontal axis), at the same time, they accumulate enough resources for achieving high customer satisfaction.

Figure 6 Stock level at the controlled nodes (see online version for colours)

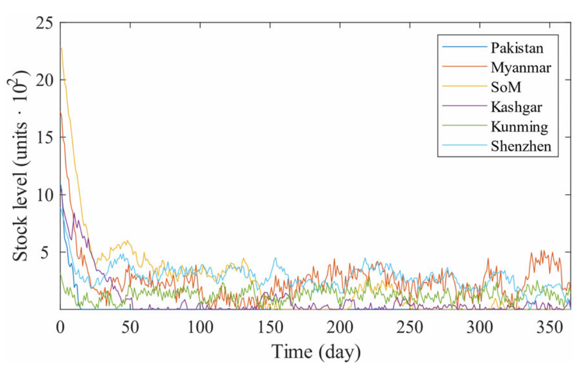


Table 2 groups the holding and transportation costs incurred by the controlled nodes. They indicate Pakistan, being an intermediate node with two suppliers and two replenished nodes, can immediately utilise the acquired resources (both satisfying the external demand and supplying the neighbouring nodes), which reduces its holding cost significantly. Moreover, Kashgar, having only one supply route with a relatively expensive transportation cost, faces high prices for the incoming shipments. The quality metrics of the scenarios related to the supply network discussed in this subsection are collected in Table 6.

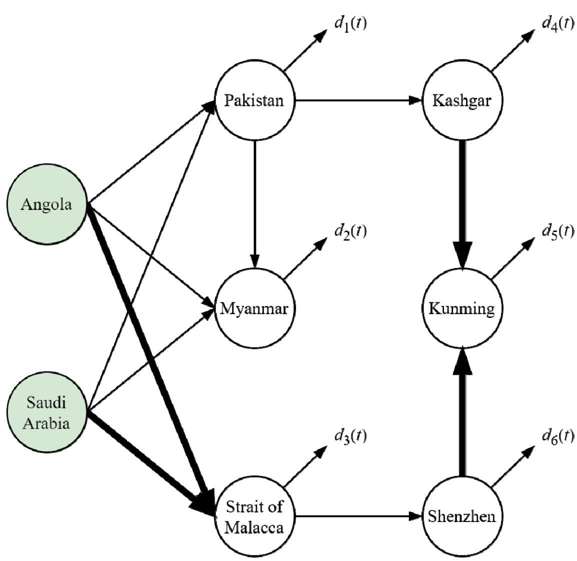
Table 2 Baseline scenario – detailed operational costs

Node	*Holding cost (units)*	*Transportation cost (units)*
Pakistan	5,825	36,036
Myanmar	92,145	75,523
Strait of Malacca	81,449	66,456
Kashgar	29,436	147,680
Kunming	44,874	27,944
Shenzhen	103,332	10,728

4.1.2 The unilateral lockdown of Myanmar

This scenario reflects the partial lockdown which may be caused by various reasons, e.g., pandemic, political sanctions, atmospheric phenomena, etc. As a result, no shipments are sent from Myanmar, however, the external demand is still imposed and should be satisfied. Figure 7 illustrates the resultant logistic system taking into account the described situation, where the node interconnections whose supplier fractions are affected by the lockdown are marked in bold.

Figure 7 The logistic network resulting from the unilateral lockdown of Myanmar (see online version for colours)



The selected vectors of RPs and OQs are as follows:

$$\mathbf{r}_{\text{opt}} = [1143, 1982, 2751, 1626, 696, 1201]', \tag{25}$$

$$\mathbf{Q}_{\text{opt}} = [229, 46, 159, 51, 123, 154]'. \tag{26}$$

The quality metrics collected in Table 6 indicate that both holding and transportation costs have considerably risen with respect to the baseline – unperturbed – scenario. This cost increase is caused by two reasons. The first one, Myanmar cannot forward the acquired resources to the further nodes, which influences the overall holding cost, as shown in Table 3. The second reason, related to the transportation cost, is the extension of the transit distance from external sources to Kunming. However, the increase in the operational costs enabled high customer satisfaction to be maintained.

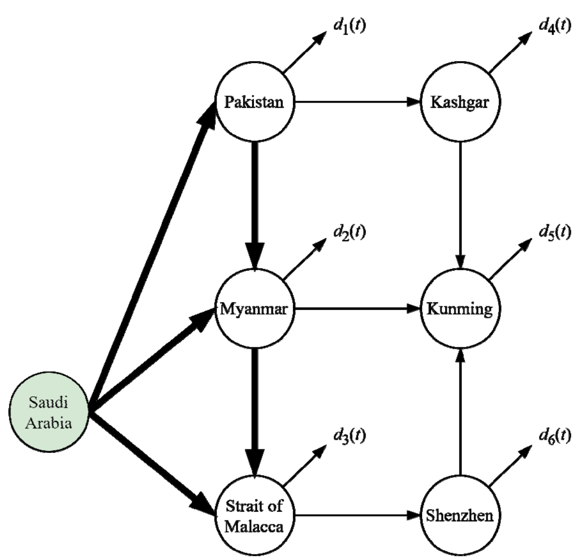
Table 3 The unilateral lockdown of Myanmar – detailed operational costs

Node	*Holding cost (units)*	*Transportation cost (units)*
Pakistan	53,783	38,701
Myanmar	202,904	48,475
Strait of Malacca	76,900	95,113
Kashgar	26,876	165,111
Kunming	82,315	43,516
Shenzhen	99,941	17,734

4.1.3 The lockdown of Angola

Next, this scenario assumes the lockdown regarding one of the external sources, i.e., Angola does not supply the network with resources. Thus, the remaining source – Saudi Arabia – is responsible for providing the crude oil for the entire system. The reconfigured interconnection structure is illustrated in Figure 8, where the bolded routes have been affected by the considered situation.

Figure 8 The logistic network resulting from the lockdown of Angola (see online version for colours)



The following policy parameters:

$$\mathbf{r}_{\text{opt}} = [532, 1714, 1387, 964, 358, 862]', \tag{27}$$

$$\mathbf{Q}_{\text{opt}} = [111, 319, 123, 152, 58, 109]', \tag{28}$$

allow one to perform an effective resource distribution which quality metrics are gathered in Table 6. Owing to the assumption of infinite stock at external sources and the system structure (note that both external sources supply the same intermediate nodes), the considered situation does not affect the logistic network considerably. Both the operational costs and customer satisfaction are similar to the primary system. Also, the detailed cost structure gathered in Table 4 does not deviate from the baseline scenario.

Table 4 The lockdown of Angola – detailed operational costs

Node	*Holding cost (units)*	*Transportation cost (units)*
Pakistan	765	10,505
Myanmar	110,608	92,523
Strait of Malacca	38,869	43,226
Kashgar	50,795	171,810
Kunming	41,237	29,182
Shenzhen	110,820	10,865

4.1.4 The lockdown of the Strait of Malacca

The last scenario in this group is related to the blockade of the Strait of Malacca which may be caused by both political decisions as well as natural disasters. As a result, neither incoming nor outgoing shipments are allowed through that region. Figure 9 depicts the reconfigured supply network where the interconnection between Kunming and Shenzhen has to be reversed to allow Shenzhen to satisfy the external demand (until now, the Strait of Malacca has been its only supplier).

The considered situation caused there are only five controlled nodes, then the policy parameters are simplified to five-element vectors:

$$\mathbf{r}_{\text{opt}} = [1348, 2374, 1276, 487, 1037]', \tag{29}$$

$$\mathbf{Q}_{\text{opt}} = [111, 358, 186, 243, 51]'. \tag{30}$$

The quality metrics grouped in Table 6 indicate that removing one of the controlled nodes from the logistic network causes a significant reduction in the holding cost. On the other hand, the connection complexity has decreased and thus the flow of resources requires covering longer distances (therefore, the increase in the transportation cost) to maintain high customer satisfaction. Moreover, the detailed operational costs presented in Table 5 show the excess stock in Myanmar, since it is supplied by three other nodes (including two external sources); however, it replenishes only one neighbouring node – Kunming.

Figure 9 The logistic network resulting from the lockdown of the Strait of Malacca (see online version for colours)

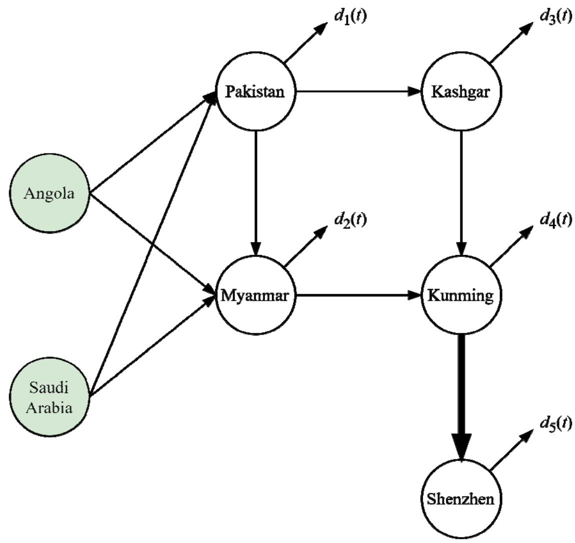


Table 5 The lockdown of the Strait of Malacca – detailed operational costs

Node	*Holding cost (units)*	*Transportation cost (units)*
Pakistan	7,750	40,404
Myanmar	161,063	101,555
Kashgar	35,216	184,087
Kunming	42,406	59,542
Shenzhen	82,319	34,604

Table 6 8-node network – quality metrics

Scenario	*Holding cost (units·10⁵)*	*Transportation cost (units·10⁵)*	*Customer satisfaction*	*Cost function value*
Baseline scenario	3.57	3.64	0.97	0.091
The unilateral lockdown of Myanmar	5.43 (+52%)	4.09 (+12%)	0.97	0.106
The lockdown of Angola	3.53 (–1%)	3.58 (–2%)	0.99	0.152
The lockdown of the Strait of Malacca	3.29 (–8%)	4.2 (+15%)	0.97	0.111

4.2 32-node network

4.2.1 Baseline scenario

In order to examine the proposed inventory control methodology in large-scale scenarios, the 18-country supply network has been designed based on the potential OBOR transit corridors. It consists of 32 nodes – eight external sources and 24 controlled nodes.

According to Trade Map (n.d.), all the assumed external sources are the main crude oil suppliers of China (together, they generated almost 70% of the total Chinese crude oil imports in 2019). The controlled nodes combine two sets of actors, i.e., the OBOR member countries as well as Chinese cities. Note that external demand may be imposed on any controlled node during the whole resource distribution which illustrates the local market demand imposed on intermediate countries. Figure 10 depicts the designed supply network through the OBOR transit corridors (see Table A2 for the node interconnections details).

Figure 10 The considered large-scale crude oil supply network (see online version for colours)

Similarly to the previous group of scenarios, the continuous genetic algorithm allows one to establish the optimal policy parameters as follows:

$$\mathbf{r}_{\text{opt}} = \begin{bmatrix} 1020, 421, 2130, 2297, 289, 1001, 2089, 6847, 3047, 783, 670, 486, \\ 1151, 625, 2234, 205, 2105, 1974, 1205, 614, 520, 426, 394, 665 \end{bmatrix}', \tag{31}$$

$$\mathbf{Q}_{\text{opt}} = \begin{bmatrix} 69, 102, 279, 103, 146, 193, 55, 387, 309, 180, 149, 71, \\ 205, 137, 406, 125, 102, 239, 170, 158, 106, 124, 90, 130 \end{bmatrix}'. \tag{32}$$

Table 7 presents the operational costs incurred by the controlled nodes. They indicate that the nodes distant from the external sources, e.g., Shenzhen, Shanghai, and Chongqing, need to store an excess amount of resources in order to provide high customer satisfaction. Table 10 contains the quality metrics of the resource distributions performed in this group of tests.

Table 7 Baseline scenario – detailed operational costs

Node	*Holding cost (units)*	*Transportation cost (units)*
Uzbekistan	6,817	181,289
India	341	10,025
Nepal	27,301	251,470
Pakistan	85,116	30,836
Mongolia	28,015	141,876
Tajikistan	45,333	127,032
Kazakhstan	48,957	222,622
Strait of Malacca	508,628	204,983
Myanmar	18,801	171,263
Kashgar	26,623	177,629
Lhasa	15,842	160,477
Guilin	58,125	9,870
Harbin	117,864	55,432
Xining	102,046	27,588
Shenzhen	208,860	33,763
Shenyang	36,556	88,347
Shanghai	133,231	34,804
Kunming	43,006	57,072
Ürümqi	214,327	71,129
Wuhan	127,732	17,232
Chengdu	116,392	11,712
Nanning	58,799	74,137
Beijing	35,274	51,129
Chongqing	169,555	10,760

4.2.2 Blockage of three external sources

First, taking into consideration the situation in which three external sources are disabled, the others have to take responsibility for supplying the network with resources. Figure 11 illustrates a regional lockdown influencing Iraq, Iran, and Kuwait. As a consequence, there are only five external sources that supply the entire logistic system.

The policy parameters allowing an effective flow of resources are equal:

$$\mathbf{r}_{\text{opt}} = \begin{bmatrix} 1160, 2517, 2175, 1918, 421, 839, 1157, 5194, 3645, 1051, 840, 506, \\ 945, 673, 4567, 346, 1475, 2609, 1116, 468, 258, 501, 483, 321 \end{bmatrix}' \tag{33}$$

$$\mathbf{Q}_{\text{opt}} = \begin{bmatrix} 224, 153, 270, 336, 87, 264, 116, 305, 354, 82, 46, 160, \\ 254, 104, 205, 75, 160, 123, 205, 131, 106, 88, 138, 164 \end{bmatrix}'. \quad (34)$$

Table 8 The lockdown of three external sources – detailed operational costs

Node	*Holding cost (units)*	*Transportation cost (units)*
Uzbekistan	11,252	14,620
India	28,533	15,037
Nepal	231,615	337,431
Pakistan	206,238	53,424
Mongolia	62,951	147,574
Tajikistan	86,377	226,008
Kazakhstan	2,998	469,531
Strait of Malacca	44,206	192,617
Myanmar	234,246	234,515
Kashgar	15,144	93,231
Lhasa	5,804	76,392
Guilin	126,600	10,520
Harbin	56,401	54,813
Xining	110,449	27,750
Shenzhen	319,989	29,589
Shenyang	74,068	88,438
Shanghai	145,819	36,813
Kunming	77,999	57,308
Ürümqi	164,408	67,312
Wuhan	70,082	17,072
Chengdu	26,340	10,947
Nanning	65,423	104,252
Beijing	77,168	53,759
Chongqing	51,373	10,805

The quality metrics stored in Table 10 indicate that operational costs have slightly increased. The holding one has risen by 3% due to the necessity to secure higher safety stocks by the controlled nodes. The transportation cost has gone up by 9%. According to the detailed operational costs presented in Table 8, this increase is due to some controlled nodes, i.e., Tajikistan and Uzbekistan, being further from the external sources than before, and consequently, their replenishments are more dependent on the neighbouring intermediate nodes and have to cover larger distances. However, customer satisfaction has been maintained at the same level.

Figure 11 The large-scale supply network with the blockage of three external sources (see online version for colours)

Figure 12 The large-scale supply network with the lockdown of four controlled nodes (see online version for colours)

4.2.3 Lockdown of four controlled nodes

Finally, the lockdown influencing the central region of the supply network is analysed. As a result, four controlled nodes – Xining, Kunming, Chengdu, and Chongqing – are excluded from the system. The external demand imposed on them is not taken into account. Moreover, this situation requires redefining the interconnection structure in the neighbourhood of the excluded nodes. The case is visualised in Figure 12.

Due to reducing the number of the controlled nodes, the vectors of RPs and OQs contain 20 elements, only,

$$\mathbf{r}_{\text{opt}} = \begin{bmatrix} 627, 1233, 1797, 841, 536, 731, 1772, 5504, 3221, 428, \\ 678, 390, 1540, 2072, 261, 1125, 576, 496, 548, 501 \end{bmatrix}', \tag{35}$$

$$\mathbf{Q}_{\text{opt}} = \begin{bmatrix} 73, 137, 260, 221, 187, 156, 49, 346, 106, 69, \\ 139, 112, 116, 247, 102, 118, 124, 108, 202, 108 \end{bmatrix}'. \tag{36}$$

Table 9 The lockdown of four controlled nodes – detailed operational costs

Node	*Holding cost (units)*	*Transportation cost (units)*
Uzbekistan	4,485	191,418
India	5,417	13,464
Nepal	65,683	350,487
Pakistan	69,623	24,856
Mongolia	133,538	137,632
Tajikistan	75,178	82,698
Kazakhstan	29,982	198,336
Strait of Malacca	78,847	199,927
Myanmar	123,941	86,728
Kashgar	1,586	87,502
Lhasa	67,292	97,022
Guilin	93,526	8,604
Harbin	184,269	53,836
Shenzhen	85,281	34,309
Shenyang	53,665	86,166
Shanghai	89,643	31,298
Ürümqi	96,831	35,768
Wuhan	110,524	12,578
Nanning	94,360	86,947
Beijing	108,257	40,189

Table 9 stores the detailed operational costs of the analysed resource distribution. The quality metrics grouped in Table 10 indicate that the considered lockdown had caused the operational costs to decrease. For the holding one, it is obvious, since the logistic system contains fewer controlled nodes. However, the transportation cost has changed differently from the case of the lockdown of the Strait of Malacca discussed earlier. The reason is that the excluded region is far from the external sources and the other nodes are not significantly dependent on the removed ones. Moreover, the excluded region generated substantial transportation costs due to its distance from sources and also that cost is reduced.

Table 10 32-node network – quality metrics

Quality metric	*Holding cost (units·10^6)*	*Transportation cost (units·10^6)*	*Customer satisfaction*	*Cost function value*
Baseline scenario	2.23	2.22	0.97	0.109
The lockdown of external sources	2.3 (+3%)	2.43 (+9%)	0.97	0.12
The lockdown of controlled nodes	1.57 (–30%)	1.86 (–16%)	0.97	0.086

5 Result discussion and policy implications

In general, the proposed methodology allows one to study both the dynamical and economic performance of multi-echelon logistic networks with complex interconnection structures. The considered model permits transshipments between the transport layer nodes and placing the external, uncertain demand at any node. The presented methodology is generic and may be easily applied by practitioners to analyse the resource distribution in supply systems with networked topologies. In addition, any topological changes may be efficiently handled in the analysed model. Thus, it enables one to tackle multifaceted logistic situations, e.g., regional lockdowns, which have been studied in this paper in the context of China's external oil supplies through the potential transit corridors arising from the OBOR initiative. The performed studies elaborate on different types of blockages and highlight the adaptability of the proposed control framework to various structural changes in the distribution system. The first scenario involves a blockage of the outgoing shipments from a selected controlled node. The second one addresses the loss of an external source. Next, the lockdown of the Strait of Malacca reflects the loss of an intermediate node that supplies both the neighbouring nodes and responds to the local demand. The second group of scenarios concerns large-scale logistic systems in which regional lockdowns may occur. From the inventory control perspective, the constructed model enables one to analyse multi-channel distribution systems that involve transport modes with different cost and delay characteristics, and operate under demand uncertainty.

The performed studies have also indicated a few practical insights related to resource distribution in logistic networks. First, the blockage of external sources may be easily compensated by connecting alternative sources to the nodes that lose access to their suppliers. Although LTDs and transportation costs may be higher, the desired service level will be maintained. The second observation concerns regional lockdowns of intermediate nodes. Although the interconnection complexity is lowered, the resources need to cover larger distances and the costs raise. In order to mitigate this effect, additional interconnections among the remaining nodes should be established, leading to increased structural complexity. In general, the higher the connection complexity of the network, the smaller the negative effects of regional disturbances – the neighbouring nodes assume responsibility for the excluded ones. Finally, from the transportation cost perspective, the maritime routes seem the most cost-efficient transport corridor for crude oil. Meanwhile, creating an oil pipeline network is preferable for the onshore routes, rather than maintaining rail routes. Nevertheless, diversification of transport modes may be necessary in the case of severe regional perturbations that cut selected channels off.

6 Further research perspectives

The proposed model, although well-reflecting the complexity of current international logistic systems, may be extended in a few dimensions. First of all, one may assess the influence of damage or partial loss of transported goods. The considered class of systems concentrates on the single-item distribution process. Thus, adjusting the system model to support multiple item types might be a valuable area for future development. Also, it could be adapted to analyse the flow of perishable resources by employing the formal studies on networked supply chains, e.g., Ignaciuk (2015). Moreover, the constructed framework may be extended to cover systems with time-varying interconnection properties. Particularly interesting insights may provide a study of transportation channel perturbations. In turn, owing to the geopolitical nature of the OBOR initiative, the robustness against international regulations may be crucial to arriving at stable resource distribution. In terms of the optimisation procedures, the presented approach involving continuous genetic algorithms requires one to predefine a single cost function representing a trade-off among the quality metrics. Such composite cost function may be difficult to tune to leverage the actual objectives. Therefore, multi-objective optimisation techniques might be more suitable for systems with elevated complexity.

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Appendix

Table A1 First network – interconnection details

Node	*Supplier*	*Transport mode*	*NSF (fraction)*	*LDT (days)*	*TUC (cost per unit)*
Pakistan	Saudi Arabia	Maritime route	0.6	4	0.26
Pakistan	Angola	Maritime route	0.4	18	2.11
Myanmar	Saudi Arabia	Maritime route	0.6	12	1.30
Myanmar	Angola	Maritime route	0.3	21	2.41
Myanmar	Pakistan	Oil pipeline/rail	0.1	12	14.29
Strait of Malacca	Saudi Arabia	Maritime route	0.5	15	1.44
Strait of Malacca	Angola	Maritime route	0.4	22	2.47
Strait of Malacca	Myanmar	Maritime route	0.1	4	0.36
Kashgar (China)	Pakistan	Oil pipeline/rail	1.0	7	9.13
Kunming (China)	Myanmar	Oil pipeline	0.8	3	1.28
Kunming (China)	Kashgar (China)	Oil pipeline	0.1	11	4.48
Kunming (China)	Shenzhen (China)	Oil pipeline	0.1	9	1.95
Shenzhen (China)	Strait of Malacca	Maritime route	1.0	10	0.54

Table A2 Second network – interconnection details

Node	*Supplier*	*Transport mode*	*NSF (fraction)*	*LDT (days)*	*TUC (cost per unit)*
Uzbekistan	Iraq	Oil pipeline/rail	0.8	8	8.93
Uzbekistan	Kazakhstan	Oil pipeline	0.2	3	0.64
India	United Arab Emirates	Maritime route	0.4	4	0.33
India	Oman	Maritime route	0.6	2	0.23
Nepal	India	Rail	0.9	6	11.86
Nepal	Kashgar (China)	Rail	0.1	5	10.79
Pakistan	Saudi Arabia	Maritime route	0.5	4	0.26
Pakistan	Angola	Maritime route	0.3	18	2.11
Pakistan	Kuwait	Maritime route	0.2	5	0.32
Mongolia	Russia	Rail	1.0	3	5.75
Tajikistan	Iran	Oil pipeline	0.7	6	1.39
Tajikistan	Uzbekistan	Oil pipeline	0.1	3	0.49
Tajikistan	Pakistan	Oil pipeline/rail	0.2	7	7.74
Kazakhstan	Russia	Oil pipeline/rail	1.0	9	11.12
Strait of Malacca	Saudi Arabia	Maritime route	0.6	15	1.44
Strait of Malacca	Angola	Maritime route	0.4	22	2.47
Myanmar	Saudi Arabia	Maritime route	0.4	12	1.30
Myanmar	Angola	Maritime route	0.2	21	2.41
Myanmar	India	Maritime route/rail	0.4	8	9.21
Kashgar (China)	Uzbekistan	Oil pipeline/rail	0.3	4	4.37
Kashgar (China)	Pakistan	Oil pipeline/rail	0.2	7	9.13
Kashgar (China)	Tajikistan	Oil pipeline/rail	0.5	2	1.79
Lhasa (China)	Nepal	Rail	0.8	3	5.03
Lhasa (China)	Kashgar (China)	Rail	0.2	6	12.94
Guilin (China)	Shenzhen (China)	Oil pipeline	0.7	2	0.41
Guilin (China)	Kunming (China)	Oil pipeline	0.2	3	0.56
Guilin (China)	Nanning (China)	Oil pipeline	0.1	2	0.30
Harbin (China)	Russia	Oil pipeline	1.0	7	1.50

Table A2 Second network – interconnection details (continued)

Node	*Supplier*	*Transport mode*	*NSF (fraction)*	*LDT (days)*	*TUC (cost per unit)*
Xining (China)	Lhasa (China)	Oil pipeline	0.2	5	0.98
Xining (China)	Ürümqi (China)	Oil pipeline	0.7	5	1.13
Xining (China)	Beijing (China)	Oil pipeline	0.1	5	1.09
Shenzhen (China)	Strait of Malacca	Maritime route	1.0	10	0.54
Shenyang (China)	Harbin (China)	Rail	1.0	2	4.31
Shanghai (China)	Strait of Malacca	Maritime route	0.8	10	0.94
Shanghai (China)	Shenzhen (China)	Oil pipeline	0.2	4	0.94
Kunming (China)	Myanmar	Oil pipeline	1.0	6	1.28
Ürümqi (China)	Russia	Oil pipeline	0.6	6	1.28
Ürümqi (China)	Kazakhstan	Rail	0.1	6	12.94
Ürümqi (China)	Kashgar (China)	Oil pipeline	0.3	4	0.83
Wuhan (China)	Guilin (China)	Oil pipeline	0.2	3	0.56
Wuhan (China)	Shenzhen (China)	Oil pipeline	0.4	4	0.71
Wuhan (China)	Shanghai (China)	Oil pipeline	0.4	3	0.56
Chengdu (China)	Lhasa (China)	Oil pipeline	0.3	5	0.98
Chengdu (China)	Xining (China)	Oil pipeline	0.2	3	0.53
Chengdu (China)	Kunming (China)	Oil pipeline	0.3	3	0.49
Chengdu (China)	Beijing (China)	Oil pipeline	0.1	6	1.20
Chengdu (China)	Chongqing (China)	Oil pipeline	0.1	1	0.23
Nanning (China)	Myanmar	Oil pipeline/rail	0.6	6	6.75
Nanning (China)	Shenzhen (China)	Oil pipeline	0.2	2	0.45

Table A2 Second network – interconnection details (continued)

Node	*Supplier*	*Transport mode*	*NSF (fraction)*	*LDT (days)*	*TUC (cost per unit)*
Nanning (China)	Kunming (China)	Oil pipeline	0.2	3	0.49
Beijing (China)	Mongolia	Oil pipeline/rail	0.3	5	5.56
Beijing (China)	Harbin (China)	Oil pipeline	0.1	4	0.83
Beijing (China)	Shenyang (China)	Oil pipeline	0.1	3	0.49
Beijing (China)	Shanghai (China)	Oil pipeline	0.4	4	0.83
Beijing (China)	Wuhan (China)	Oil pipeline	0.1	4	0.83
Chongqing (China)	Kunming (China)	Oil pipeline	0.8	3	0.49
Chongqing (China)	Wuhan (China)	Oil pipeline	0.2	3	0.56