A Robust Supply Chain Model for a National Economy with Many Goods, Multiple Import Routes, and Compulsory Stockpiling

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1 Introduction

Robust supply chains can mitigate supply disruption risks, be these due to operational issues, natural disasters, or deliberately inflicted damage. The extant literature has mostly reviewed the construction of such robust supply chains from a private sector perspective. It therefore focuses on minimizing business losses and on the trade-off between supply chain resilience and related investment cost (e.g., [4–6, 10, 13]). In particular, this literature advises producers to make their supply chains more robust by targeted investments in their suppliers, by integrating redundant capacity, by diversifying suppliers, and by simulating threat scenarios and implied disruption probabilities [3, 7–9, 11, 12, 14, 15]. Quite often, these authors make strong assumptions that do not necessarily hold for complex supply chains. For example, both [8] and [7] assume suppliers have unlimited capacities, while [9] assume an evenly distributed demand.

This chapter proposes both an alternative view and a different level of analysis. A complete national economy is modeled as a supply chain, and supply chain disruption risk is conceived of as a threat to the effective delivery of goods and

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services to the population. This viewpoint makes the modeling of disruption risks and scenarios more demanding since a national economy typically imports many different goods (e.g., food, medical supplies, or fossil fuels). In such a setting, supply chain risk is not only related to the domestic distribution of goods, but also to the risk of import disruption, i.e. the risk that goods produced abroad cannot be delivered as a consequence of transportation shortage or blockage of import routes.

Moreover, many nations have implemented a system of compulsory stockpiling, whereby the state stores some quantity of essential goods in order to guarantee emergency supplies whenever significant disruptions occur. Any optimization procedure would have to take into account the existence of such additional stocks. To account for all of these issues, an extension of the model by Garcia-Herreros et al. [2] is proposed and specified by a mixed integer linear program (MILP).

2 Model Specification

The model proposed by Garcia-Herreros et al. [2] is a useful starting point for two reasons. First, it includes distribution centers (which are referred to as transshipment platforms in the remainder of this chapter) as a design decision. Second, it employs a Benders decomposition algorithm that reduces the computational complexity of finding optimal solutions for large-scale supply chains (see [1] for an extensive discussion). All in all, the model significantly improves supply chain resilience at a reasonable cost.

In this contribution, the original model is extended by relaxing some of its assumptions and by introducing novel elements. Moreover, the wording is slightly adapted to a setting where demand originates from different regions in the national economy. In the original model, supply is delivered to these regions by transshipment platforms which, in turn, receive their goods from different import routes which may be disrupted. Whenever an import route or transshipment platform cannot satisfy any particular demand, alternative routes and platforms are used. If, after this re-routing, there is any remaining (uncovered) demand, this demand is satisfied by a fictitious import route and a fictitious transshipment platform at a penalty cost.

The authors [2] assume that there exists only one producer of the goods that are to be distributed. Since firms in a national economy source goods and services from many different suppliers, the extension proposed in this chapter considers multiple producers. Further, they also assume a world of only two goods whose cost functions are interrelated. This assumption is relaxed by considering multiple and mutually independent goods produced by multiple suppliers. Finally, they assume production to be safe, whereas all supply chain risk is modeled at the distribution center stage. This restriction is relaxed here by modeling the possibility that not only transshipment centers, but also import routes themselves can be disrupted, e.g. as a consequence of war, natural disasters, technical failure, pandemics, or sanctions. The probability that any such disruption may occur is captured by different scenarios, each of which is given a particular probability.

Very few national economies operate in autarchy. This means that import is an important element of national supply, and therefore even a temporary disruption of import routes constitutes a significant supply risk. Further, both the structure and the number of different means of transport differ by country in terms of capacity, speed and cost. For example, water-bound flows of goods should take into account the fleet of ships available. The extension proposed here therefore considers the maximum capacity of each import route by factoring the speed and costs of different means of transport into total transport cost. Moreover, the flows from import routes to transshipment platforms are modeled, and new boundary conditions are proposed since goods can be imported by more than one import route.

Finally, the model by Garcia-Herreros et al. [2] does not consider external storage of goods (e.g., in warehouses). While this assumption may be acceptable for the case of private firms which try to minimize storage cost at all times, it may not apply to a national economy where stockpiling is a significant element of the security of supply. The purpose of a compulsory stockpile is to secure nationwide supplies by bridging bottlenecks in the case of longer interruptions. Hence, stockpiling typically concentrates on durable goods that can be stocked in large quantities and for longer periods of time, such as staple foods and fuels.

The extended model is specified by the following mixed integer linear program.

Sets

S scenarios
E import routes
U transshipment platforms
K regions
G goods

Parameters

N number of time periods
D_{kg} demand of region k for good g per time period
H_{ug} storage cost of good g in transshipment platform u per time period
F_e^1 fixed cost of import route e
F_u^2 fixed cost of transshipment platform u
V_{eg}^1 variable (capacity) cost per import route e and good g
V_{ug}^2 variable (capacity) cost per transshipment platform u and good g
T_{eug}^1 transport costs of import route e to transshipment platform u per good g
T_{ukg}^2 transport costs of transshipment platform u to region k per good g
C_{eg}^{max1} maximum capacity of import route e per good g
C_{ug}^{max2} maximum capacity of transshipment platform u per good g
C_g^{max3} maximum capacity of stockpile for good g
C_g^{min} minimum capacity of stockpile for good g
PL_g^1 stockpiling cost per thousand units of good g
PL_g^2 cost for requiring stockpiled goods per thousand units of good g
Π_s probability of scenario s

M_{seu} availability vector of import route e and transshipment platform u under scenario s
q number of import routes e
r number of transshipment platforms u

Decision Variables

$* w_e$ $= \begin{cases} 1, \text{ if import route } e \text{ was selected} \\ 0, \text{ else} \end{cases}$
$* x_u$ $= \begin{cases} 1, \text{ if transshipment platform } u \text{ was selected} \\ 0, \text{ else} \end{cases}$
$* d_{eg}$ storage capacity of good g in import route e
$* c_{ug}$ storage capacity of good g in transshipment platform u
$* z_{seug}$ quantity of good g transported from import route e to transshipment platform u under scenario s
$* y_{sukg}$ quantity of good g transported from transshipment platform u to region k under scenario s
$* l_g$ compulsory stock of good g
$* t_{skg}$ quantity of good g transported from stockpile to region k under scenario s

The model is formulated as follows

$$\begin{aligned}
\text{Min.}\ & \sum_{e=1}^{E-1} F_e^1 \cdot w_e + \sum_{u=1}^{U-1} F_u^2 \cdot x_u + \sum_{e=1}^{E-1}\sum_{g=1}^{G} V_{eg}^1 \cdot d_{eg} + \sum_{u=1}^{U-1}\sum_{g=1}^{G} V_{ug}^2 \cdot c_{ug} \\
& + N \cdot \sum_{s=1}^{S} \Pi_s \cdot \sum_{e=1}^{E}\sum_{u=1}^{U}\sum_{g=1}^{G} z_{seug} \cdot T_{eug}^1 \\
& + N \cdot \sum_{s=1}^{S} \Pi_s \cdot \sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{g=1}^{G} y_{sukg} \cdot T_{ukg}^2 \\
& + N \cdot \sum_{s=1}^{S} \Pi_s \cdot \sum_{u=1}^{U}\sum_{g=1}^{G} H_{ug} \cdot \left(c_{ug} - \sum_{k=1}^{K} y_{sukg} \right) \\
& + \sum_{g=1}^{G} \left(l_g \cdot PL_g^1 + \sum_{s=1}^{S} \Pi_s \cdot \sum_{k=1}^{K} t_{skg} \cdot PL_g^2 \right) \\
& - \sum_{s=1}^{S} \Pi_s \cdot \sum_{g=1}^{G} \cdot \left(\sum_{k=1}^{K} t_{skg} \cdot \sum_{e=E}^{E}\sum_{u=U}^{U} T_{eug}^1 \right)
\end{aligned} \tag{1}$$

$$\text{s.t.}\ \sum_{u=1}^{U} y_{sukg} + t_{skg} = D_{kg} \tag{2}$$

$$\{s = 1, \ldots, S, k = 1, \ldots, K, g = 1, \ldots G\}$$

$$\sum_{k=1}^{K} y_{sukg} = \sum_{e=1}^{E} z_{seug} \tag{3}$$

$$\{s = 1, \ldots, S, u = 1, \ldots, U, g = 1, \ldots, G\}$$

$$\sum_{e=1}^{E} z_{seug} \leq C_{ug}^{max2} \tag{4}$$

$$\{s = 1, \ldots, S, u = 1, \ldots, U, g = 1, \ldots, G\}$$

$$d_{eg} \leq C_{eg}^{max1} \cdot w_e \tag{5}$$

$$\{e = 1, \ldots, E, g = 1, \ldots, G\}$$

$$c_{ug} \leq C_{ug}^{max2} \cdot x_u \tag{6}$$

$$\{u = 1, \ldots, U, g = 1, \ldots, G\}$$

$$z_{seug} \leq M_{seu} \cdot d_{eg} \tag{7}$$

$$\{s = 1, \ldots, S, e = 1 \ldots, E, u = 1, \ldots, U, g = 1, \ldots, G\}$$

$$\sum_{u=1}^{U} z_{seug} \leq d_{eg} \tag{8}$$

$$\{s = 1, \ldots, S, e = 1, \ldots E, g = 1, \ldots, G\}$$

$$\sum_{k=1}^{K} y_{sukg} \leq c_{ug} \tag{9}$$

$$\{s = 1, \ldots, S, u = 1, \ldots, U, g = 1, \ldots, G\}$$

$$\sum_{u=1}^{U} c_{ug} \leq \sum_{e=1}^{E} d_{eg} \tag{10}$$

$$\{g = 1, \ldots, G\}$$

$$w_e \leq \sum_{g=1}^{G} d_{eg} \tag{11}$$

$$\{e = 1, \ldots, E\}$$

$$\sum_{k=1}^{K} t_{skg} \leq l_g \tag{12}$$

$$\{s = 1, \ldots, S, g = 1, \ldots, G\}$$

$$t_{skg} \leq y_{sukg} \tag{13}$$

$$\{s = 1, \ldots, S, u = 1, \ldots, U, k = 1, \ldots, K, g = 1, \ldots, G\}$$

$$l_g \leq C_g^{max3} \tag{14}$$

$$\{s = 1, \ldots, S, g = 1, \ldots, G\}$$

$$l_g \geq C_g^{min} \tag{15}$$

$$\{s = 1, \ldots, S, g = 1, \ldots, G\}$$

$$w_e, x_u \in \{0, 1\} \tag{16}$$

$$\{e = 1, \ldots, E, u = 1, \ldots, U\}$$

$$c_{ug}, d_{eg}, z_{seug}, y_{sukg}, t_{skg} \in \mathbb{Z} \geq 0 \tag{17}$$

$$\{s = 1, \ldots, S, e = 1, \ldots, E, u = 1, \ldots, U, k = 1, \ldots, K, g = 1, \ldots, G\}$$

The structure of the program follows the approach of [2] by partitioning the objective function (1) into different cost blocks. For the sake of readability, they are organized by lines. The first line aggregates fixed and variable investment costs. The second line sums up all transport costs for deliveries from import routes to transshipment platforms, and the third line sums up those from transshipment platforms to regions. The fourth line sums up all storage costs in the transshipment centers. These are caused whenever the inflow of goods in particular scenarios is well below the maximum capacity of any particular transshipment platform. This lack of capacity utilization implies costs, e.g. for maintenance and electricity. The fifth line totals the cost of stocking goods in the stockpile and the cost of any deliveries from the stockpile to the regions. The sixth line corrects total cost for opportunity benefits since any delivery of goods from the stockpile substitutes for another delivery by an alternative import route or transshipment platform. Since the third line considers flows from transshipment platforms to regions but not those from import routes to transshipment platforms, this correction avoids an erroneous double consideration of the implied costs.

An optimal solution to this problem must take the following boundary conditions into account. First, constraint (2) ensures that the demand of all regions can be delivered by either traditional import routes or the stockpile. Constraint (3) specifies that the number of goods delivered to a transshipment platform must correspond to the number of goods shipped by this platform. Constraint (4) specifies that any quantity of goods delivered to a transshipment platform must not exceed its maximum capacity.

Constraints (5) and (6) guarantee that the capacities allocated to import routes and transshipment platforms do not exceed this maximum capacity, subject to the consideration of whether or not the model selected these import routes and transshipment platforms at all.

Constraints (7)–(9) guarantee that the quantities transported from one import route to all transshipment platforms and from one transshipment platform to all regions do not exceed their respective capacities. They also ensure that goods are only transported if the import route and transshipment platform in question are not disrupted. Constraint (10) specifies that any quantity of goods distributed to the regions must not exceed the quantity of goods imported by the import routes, and constraint (11) guarantees that the selection of import routes takes the storage capacity limits of these routes into account.

Constraints (12)–(15) refer to the compulsory stockpile. They stipulate that the total quantity transported from the compulsory stockpile to the regions must never exceed its total stock, and that any quantity transported from the compulsory stockpile to any region must never exceed the quantity delivered from the transshipment platform to the same region. In addition, the stockpile of each good must be above any minimum and below any maximum level of stock. Further, the costs of requiring goods from the compulsory stockpile must exceed the costs of requiring these from any transshipment platform since the stockpile must not be used to realize cost savings, but only as a lender of last resort. Also, the costs of delivering any goods from the compulsory stockpile should not exceed the penalty cost of any disrupted import route or transshipment platform. Finally, constraints (16) and (17) define all binary variables and the non-negativity and integer conditions of the decision variables. In addition, constraint (17) forbids reverse flows of any good from any region to any transshipment platform.

3 Application

A simple case provides a basic illustration of the model. It comprises two scenarios, one without and one with disruption, two import routes, one transshipment platform, three regions and one good (Sect. 3.1). The scalability of the model is demonstrated by considering a more complex case with 15 scenarios that might occur with different probabilities, nine import routes, ten transshipment platforms, four goods, six regions, and one compulsory stockpile per good (Sect. 3.2). Finally, a contingency analysis is provided within this complex case by considering different stockpile configurations (Sect. 3.3).

3.1 Simple Illustration

The model is illustrated using the national economy of Switzerland. This country is landlocked, but goods can be delivered from the seaport of Rotterdam to the river port of Basel by way of the river Rhine (water-bound import route). Once they arrive, the goods are either transferred to trucks and freight trains for subsequent inland transport, or added to a compulsory stockpile. In addition, an alternative import route by road exists. Demand for a single good g originates from region 1 (3 million units), region 2 (7 million units) and region 3 (4 million units). Import capacities for good g are 4 million units (water-bound route) and 6 million units (alternative route).

Normal operations are now affected by a distortion. Due to severe dryness over several weeks, the water level of the Rhine has dropped so much that all shipping traffic is stopped. In addition, an important sluice is out of operation due to maintenance work. Since the water-bound import route is now completely blocked, its import capacity is reduced to zero, whereas the alternative import route is not affected. Hence, any demand originating from the regions must now be satisfied by the alternative import route and by the compulsory stockpile. If their combined capacity cannot fully satisfy all demand, the remaining uncovered demand is delivered by a fictitious import route E and a fictitious transshipment platform U at a penalty cost. This scenario is parameterized with the following data (Tables 1, 2, 3, 4 and 5).

Figure 1 below provides a diagram of the optimal solution. The import capacity of the blocked water-bound route can be partially substituted by the alternative import route and the stockpile, but some uncovered demand remains that is delivered via fictional import route E and fictional transshipment platform U at a penalty cost.

More specifically, the demand originating from region 1 can be fully satisfied by the alternative import route. The stockpile can cover 50% of the demand originating from region 2, but the remaining uncovered demand of 3.5 m units is delivered at a penalty cost. The demand originating from region 3 can be partially satisfied by the alternative import route. After delivering 3 m units, this alternative route is at its maximum capacity of 6 m units since another 3 m units are shipped to region 1 via this route. The stockpile can cover an additional 0.5 m units, but since it delivers 3.5 m units to region 2 already, its capacity is now exhausted. As a result, the remaining uncovered demand of 0.5 m units is delivered at a penalty cost. The total cost for this optimal solution is approx. 491.8 m Swiss francs.

Table 1 Parameters and sets for the basic example

Parameter	Value	Unit
N	365	Days
D_1	3000	Units (thousands) per period
D_2	7000	Units (thousands) per period
D_3	4000	Units (thousands) per period
H_1	0.1	Swiss francs (thousands)
H_2	0	Swiss francs (thousands)
F_1^1	1000	Swiss francs
F_2^1	500	Swiss francs
F_1^2	500	Swiss francs
V_1^1	2	Swiss francs (thousands)
V_2^1	3	Swiss francs (thousands)
V_1^2	5	Swiss francs (thousands)
C_1^{max1}	6000	Units (thousands) per period
C_2^{max1}	8000	Units (thousands) per period
C_3^{max1}	1,000,000,000	Units (thousands) per period
C_1^{max2}	20,000	Units (thousands) per period
C_1^{max2}	1,000,000	Units (thousands) per period
C_g^{max3}	1,000,000	Units (thousands) per period
C_g^{min}	0	Units (thousands) per period
PL_g^1	50	Swiss francs (thousands)
PL_g^2	100	Swiss francs (thousands)
Π_1	0.7	
Π_2	0.3	
q	3	Import routes
r	2	Transshipment platforms

Table 2 Transportation cost from import routes to transshipment platforms

T_{eug}^1	u	
e	1	2
1	10	500
2	5	500
3	500	500

Table 3 Transportation cost from transshipment platforms to regions

T_{ukg}^2	k		
u	1	2	3
1	5	5	5
2	500	500	500

Table 4 First scenario without disruption

M_{1eu}	u	
e	1	2
1	1	1
2	1	1
3	1	1

Table 5 Second scenario with disruption of the water-bound import route

M_{2eu}	u	
e	1	2
1	1	1
2	0	1
3	1	1

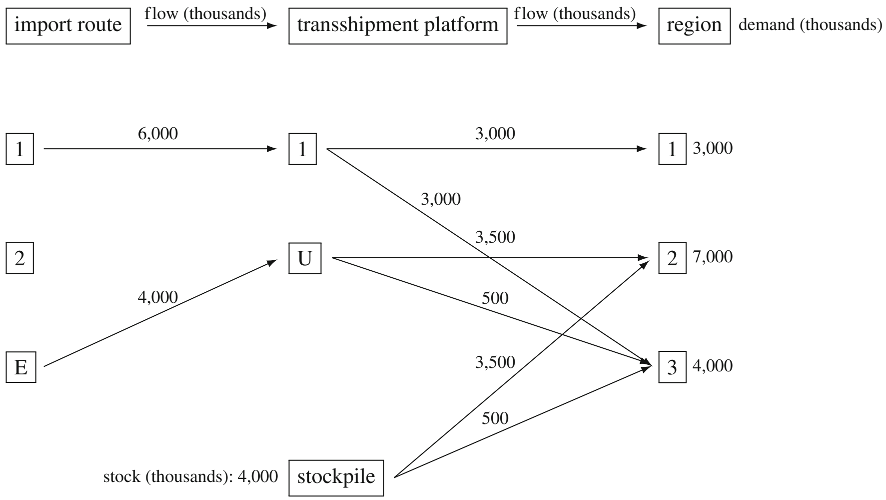

Fig. 1 Supply chain network with compulsory stockpiling and two import routes, one of which is disrupted

3.2 Complex Disruption Case

To illustrate the usability of the extended model and to demonstrate the importance of a resilient supply chain, fifteen different scenarios are specified, each of which has a particular probability. The scenarios cover situations from minor disturbances to complete network failure (viz. Table 6). Since complete breakdowns are less likely or occur less frequently, the probability with which a particular scenario occurs decreases as the number of interruptions increases. However, the probability also includes the geographical proximity of import routes. A major disruption in Basel may block multiple Basel-bound import routes, while import routes bound to other areas (e.g., Geneva) should not be affected. While the number of scenarios is limited to 15 in order to keep the model computable in this particular example, any

Table 6 Interruption scenarios and probabilities for the complex illustration

Scenario (S)	Probability (Π)	Disrupted U	Disrupted E	Example
1	50%	0	0	Normal operations
2	25%	1	0	Transshipment platform in Basel disrupted
3	15%	0	1	E_1 Waterbound import route to Basel disrupted
4	5%	0	1	E_2 Railway import route to Basel disrupted
5	2.5%	2	0	
6	1%	3	0	
7	0.6%	4	0	
8	0.4%	0	2	
9	0.2%	0	3	
10	0.165%	1	2	
11	0.1%	1	3	
12	0.01%	0	3	
13	0.01%	2	3	
14	0.01%	2	4	
15	0.005%	5	0	

supply chain can be modeled as long as the probabilities of interruptions are not underestimated.

These scenarios are applied to a fictitious national economy that has nine import routes and ten transshipment platforms. In this economy, demand for four discrete goods originates from six discrete regions, and one compulsory stockpile per good exists, the respective stock of which can range from zero to a specified maximum capacity.

First, a baseline case is calculated which assumes that no interruptions will ever occur. In the optimal solution for this baseline case, all compulsory stockpiles have an optimal stock of zero since all demand originating from the regions can be met by extant import routes and transshipment platforms. The values of the decision variables from this baseline case are then transferred into a scenario-based model which assumes that interruptions will occur according to the scenarios specified in Table 6. To simplify calculations, it is assumed that if an import route is interrupted, there is either no alternative import route (implying the goods cannot be delivered at all) or that delivery is only possible by a fictitious import route at a penalty cost. The same simplification applies to any interruption of any transshipment platform. This scenario-based model has an optimal solution. Calculation took less than 0.1 seconds on a 2016 Macbook Pro with a 3.1 GHz Intel Core i5 processor and 16 GB RAM. The model was implemented in AMPL (https://ampl.com) using a Gurobi solver. Table 7 below compares the optimal solution for the scenario-based model with the baseline case.

Table 7 Comparison of a scenario-based approach versus a baseline case without disruption

	Scenario-based	Baseline
# Binary variables	21	21
# Linear variables	11,008	816
# Conditions	10,234	770
Calculation time (seconds)	0.1	0.02
# Selected import routes[a]	8	6
# Selected transshipment platforms	9	7
Investment costs (Swiss francs)	1,620,140	809,038
Transport costs to transshipment platforms (Swiss francs)	251,993,000	283,714,000
Transport costs to regions (Swiss francs)	216,680,000	176,988,000
Storage costs (Swiss francs)	745,390	0
Stockpiling costs (Swiss francs)	395,536	0
Stockpiling savings (Swiss francs)	2,349,720	0
Penalty costs (Swiss francs)	71,481,600	319,585,000[b]
Total cost (Swiss francs)	540,565,946	781,096,038

[a]In the respective optimal solution, excluding the fictitious import route and transshipment platform.
[b]Upon implementation of the optimal solution for the baseline model into the scenario-based model.

The scenario-based model selects a larger number of import routes and transshipment platforms as it considers possible interruptions. In comparison to the baseline model, this consideration implies higher investment into compulsory stockpiling and transportation costs, but the supply chain is made significantly more robust. This result is reflected by the total penalty cost which is significantly lower than in the baseline case. In the baseline case, there is no storage and transportation cost for stockpiling. However, no penalty cost can be avoided by rerouting transport or using stockpiled goods once a disruption unexpectedly occurs. Hence, the modeling of interruption scenarios is productive since the investments in stockpiling are more than offset by saved penalty cost. All in all, my findings corroborate those of [2] by suggesting that while operators incur higher investment costs as they hedge supply chain risk, they can offset these investments by opportunity benefits which come as saved penalty costs.

3.3 Contingency Analysis for Different Stockpile Configurations

Table 7 illustrates the effect that a stockpile saves more costs than it causes. Hence, the impact of stockpiled goods on supply chain robustness is analyzed in greater detail. The optimal solution of the above scenario-based model is compared and contrasted with two alternative modifications of the compulsory stockpile. In the

Table 8 Contingency analysis for different stockpile inventory configurations

	Optimal	Maximum inventory	Minimum inventory
Calculation time (seconds)	0.1	0.4	0.3
# Import routes selected	8	8	8
# Transshipment platforms selected	9	9	9
Stockpile inventory for good 1 (thousands)	4024	1000	5000
Stockpile inventory for good 2 (thousands)	18,594	1000	19,000
Stockpile inventory for good 3 (thousands)	1644	999	2000
Stockpile inventory for good 4 (thousands)	14,880	1000	15,000
Stockpiling costs	395,536	40,399	413,916
Stockpiling savings	2,349,720	239,940	2,349,720
Total penalty costs	71,481,600	135,654,000	71,481,600

first modification, the stockpile inventory can range between a minimum of zero and a maximum of one million units per good. In the second modification, a minimum stockpile inventory must be maintained at all times. Models for this second modification were calculated with different minimum inventories. Table 8 compares the optimal solution from Sect. 3.2 with the optimal solutions for both modifications.

As the compulsory stockpile is not used for cost-saving purposes, a minimum or maximum level of stock has no influence on the choice of import routes and transshipment platforms and their capacities. Accordingly, the associated costs of these elements do not change. However, the effect of stockpile inventories on stockpile penalty costs is significant. Savings and penalty cost reductions are equally high for the optimal stockpile and any higher level of stock per good. It should be noted that for every good, the respective optimal inventories exceed the arbitrarily defined maximum of 1 million units per good that the first modification introduces.

Finally, the fact that penalty cost savings increase with increased stockpile inventories indicates that stockpiling creates redundancies which mitigate the effects of a disruption. However, the increase in stockpiling costs signals that this mitigation comes at the price of capital lockup. Hence, every increase in stockpile inventory should be justified by a corresponding interruption scenario.

4 Outlook

The proposed extension of the model by Garcia-Herreros et al. [2] is productive in several ways. It considers supply disruptions on two levels of the supply chain and introduces compulsory stockpiling. Further, the proposed extension is scalable to complex disruption cases, multiple goods and multiple import routes. Still, it is important to note that the results of the proposed extended model significantly depend on the specification of the disruption scenarios, as well as on the correct estimation of any probabilities associated with such scenarios. Future research also needs to find acceptable trade-offs between the number and the exhaustiveness of the disruption scenarios since a very large number of scenarios makes the assignment of specific probabilities difficult. Further, interdependencies between import routes and transshipment platforms must be modeled realistically in order to correctly estimate the extent to which (if any) imports can be rerouted.

Future research may further develop the extension proposed here by removing some of its limitations. In the model proposed computation time grows exponentially with the number of scenarios specified, the number of import routes, and the number of transshipment platforms. Hence, novel approximation algorithms and super-computing power may be required to adapt the extension proposed here to the analysis of highly complex supply chains. Finally, whenever a blocked import route implies an out-of-stock situation in any transshipment platform, the capacities of other import routes may be over-utilized as these platforms attempt to reroute imports. Hence, if blockages of import routes occur iteratively, a cascading effect may be caused that affects not only the focal, but also many other transshipment platforms. Future research should introduce additional elements into the extension proposed here to capture such dynamic effects.

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