Towards a Secure Two-stage Supply Chain Network: A Transportation-Cost Approach

Camelia-M. Pintea¹, Anisoara Calinescu², Petrica Pop¹, Cosmin Sabo¹

¹ North University Center at Baia-Mare, Technical University Cluj-Napoca, Romania
² Department of Computer Science University of Oxford, Oxford OX1 3QD, UK
dr.camelia.pintea@ieee.org, ani.calinescu@cs.ox.ac.uk
petrica.pop@cunbm.utcluj.ro, cosmin_sabo@prime-tech.com

Abstract. The robustness, resilience and security of supply chain transportation is an active research topic, as it directly determines the overall supply chain resilience and security. In this paper, we propose a theoretical model for the transportation problem within a two-stage supply chain network with security constraints called the Secure Supply Chain Network (SSCN). The SSCN contains a manufacturer, directly connected to several distribution centres DC, which are directly connected to one or more customers C. Each direct link between any two elements of Secure Supply Chain Network is allocated a transportation cost. Within the proposed model, the manufacturer produces a single product type; each distribution centre has a fixed capacity and a security rank. The overall objective of the Secure Supply Chain Network is 100% customer satisfaction whilst fully satisfying the security constraints and minimizing the overall transportation costs. A heuristic solving technique is proposed and discussed.

1 Introduction

Supply Chain Networks as well as other transportations and logistics nowadays are facing security threats. These threats could be natural disasters, such as earthquakes or floods, or human-related threats, such as market uncertainty and computer attacks [27].

As stated by Rice et al. [15]: "The supply network is inherently vulnerable to disruption, and the failure of any one element in it could cause the whole network to fail". Furthermore, Lee et al. [16] highlight the need to create a "secure freight system", across all transportation stages between supply chain partners.

The transport-related problems are combinatorial optimization problems. The researchers use in general heuristic approaches [24, 7, 17, 19], approximation algorithms [3] or hybrid algorithms [8] to solve transportation problems.
It is inherently difficult to model real-world transportation problems: due to the large number of constraints and parameters, often characterised by variability, uncertainty and interdependence, as well as many local optimal or suboptimal solutions. There are supply chains with the transportation cost directly proportional to the number of units transported [1]. Some transportation problems can be described as fixed-charge transportation problems [2, 24].

The problem described in this paper assumes a fixed-charge transportation. The Secure Supply Chain Network (SSCN) problem involves two different supply chain configurations. The first supply chain consists of a manufacturer directly linked to all distribution centers. The second chain is from each of the distribution centres to one or more customers. The novelty is introducing secure constraints for distribution centers into the existing two-stage Supply Chain Network with fixed-charge transportation.

The objective function is to minimize the whole transportation cost, from manufacturer to customers, based on several intermediary costs and other parameters, whilst fully satisfying the customers and meeting the security constraints. The manufacturer supplies a single type of product. The objective function takes into account opening fixed costs and transportation costs.

A mathematical model of the problem is given using the SSCN parameters and additional security constraints. The applicability of linear algorithms for solving real-world transportation problems is limited due to their inherent complexity. Heuristics or hybrid algorithms have been successfully used to solve these type of problems [18, 24]. Previous work solved this problem using the nearest neighbour in [12], a hybrid approach in [11], a genetic algorithm in [14] and further research with a reverse distribution system in [13].

The paper is organized as follows. Section 2 includes some prerequisites. Section 3 introduced the SSCN problem with its formulation and mathematical model. In Section 4 is described the new problem Secure Supply Chain Network with the security constraints. The last section discusses the strengths and limitations of the SSCN problem and concludes with future work suggestions.

2 Prerequisites

The Supply Chain Network (SCN) problem is formulated based on a particular Supply Chain Network presented in [6, 11–13], with fixed-charged capacity.

The Supply Chain Network problem considers two stages of a supply chain network: The manufacturer and distribution centres (DCs), and the DCs and customers (C). The first supply chain includes the manufacturer that provides items to distribution centres (DCs); the second supply chain uses these DCs to deliver to the customers, according to their demands. An ideal manufacturer, with no capacity limitation in production is considered. Each potential distribution centre has a different capacity to support the customers [6]. The time constraints are not considered. The total cost includes the transportation costs from the manufacturer to potential distribution centres, the opening cost of these DCs, and the transportation cost from the DCs to the customers.
In [10, 22, 23] was introduced and developed a security constraint model for jobs scheduling. The security modes considered are the secure mode, as a conservative approach, the Risky mode, the aggressive approach, and the \( \gamma\)-risky mode, considering a probability measure of risk. In general the risky or the \( \gamma\)-risky modes are used. The secure mode includes supplementary costs and it allows less flexibility, and therefore it is rarely used.

3 The Secure Supply Chain Network: Problem formulation and Mathematical model.

The Secure Supply Chain Network problem is a Supply Chain Network with security constraints. Each supply chain is endowed with a security constraint set, which includes the security demand and security rank, denoted \( SC = \{sd, sr\} \) (see section 4 and Figure 1).

The objective of the problem is to optimize the transportation cost, from manufacturer to customers, subject to satisfying the security risk constraints of distribution centers.

The mathematical model of the fixed-charged transportation problem with security constraints uses \( m \) DCs and \( n \) customers. Table 1 shows the input and output data with notations and descriptions; the input data includes besides the SCN input, the security demand \( (sd) \) for a DC, the security rank \( (sr_i) \) for each \( DC_i \) and the security levels values: from very low \( (vl) \) to very high \( (vh) \).

![Fig. 1. An example of a two-stage Secure Supply Chain Network (SSCN) with an infinite-capacity manufacturer, \( m \) available distribution centres (DCs) and \( n \) customers.](image)

The total cost, \( Z \), includes fixed costs, \( Z_f \), and transportation costs, \( Z_{tc} \). The aim is to minimize the total \( SSCN \) cost while meeting the security constraints and fully satisfying the customers. Two types of fixed costs are involved: the opening cost \( f_i \) for \( DC_i \) and the fixed transportation cost from \( DC_i \) to customer \( j \), denoted \( f_{ij} \).
Symbol | Description
--- | ---
input |  
\(sd\) | the security demand for a DC  
\(sr_i\) | the security rank of \(DC_i\)  
\(vl\) to \(vh\) | the security levels values: from very low to very high  
\(f_i\) | the opening cost for \(DC_i\)  
\(f_{ij}\) | the fixed transportation cost from \(DC_i\) to \(C_j\)  
\(c_i\) | the transportation cost from \(M\) to \(DC_i\)  
\(c_{ij}\) | the transportation cost from \(DC_i\) to \(C_j\)  
\(a_i\) | the capacity of \(DC_i\)  
\(d_j\) | the demands of \(C_j\)  
output |  
\(x_{ij}\) | a part of the demand of \(C_i\) supplied by \(DC_i\)  
\(x_i\) | a part of the quantity of \(M\) supplied to \(DC_i\)  
\(y_i\) | a binary variable; 1, if \(DC_i\) is opened as potential location  
\(y_{ij}\) | a binary variable; 1, if \(DC_i\) is opened for customer \(C_j\)  
\(Z_{fc}\) | the total of the fixed costs  
\(Z_{tc}\) | the total cost of transportation  
\(Z\) | the total cost: the sum of the total fixed and transportation costs.

Table 1. Secure Supply Chain Network parameter description.

The transportation cost per unit includes the transportation cost from the manufacturer to distribution centre \(i\), \(c_i\), and the transportation cost per unit \((c_{ij})\) from \(DC_i\) to a customer \(j\).

Due to the two stages of the supply chain network, the following objectives are specified, in order to minimize the total cost:

- Identify the distribution centre to be opened that satisfies the security requirements, as a function of its security demand, \(sd\), and security rank, \(sr\), as presented in Section 4.
- Identify the optimal set of DCs for each customer. The demands of all the customers should be met; a customer could receive products from one or more distribution centres.

The main objective of the problem is to minimize the function \(Z\).

\[
Z = Z_{fc} + Z_{tc}
\]  

\[
Z_{tc} = \sum_{i=1}^{m} c_i x_i + \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij}, \quad Z_{fc} = \sum_{i=1}^{m} f_i y_i + \sum_{i=1}^{m} \sum_{j=1}^{n} f_{ij} y_{ij},
\]  

The following equations (3) are the constraints for the quantities to be transported.

\[
x_{ij} \geq 0, \; \forall i = 1, \ldots m, \; \forall j = 1, \ldots n, \quad x_i \leq a_i, \; \forall i = 1, \ldots m,
\]
where

\[
y_i = \begin{cases} 
1, & \sum_{j=1}^{n} x_{ij} \geq 0, \forall i = 1 \ldots m, \\
0, & \sum_{j=1}^{n} x_{ij} = 0, \forall i = 1 \ldots m,
\end{cases}
\]

\[
y_{ij} = \begin{cases} 
1, & x_{ij} \geq 0, \forall i = 1 \ldots m, \\
0, & x_{ij} = 0, \forall j = 1 \ldots n.
\end{cases}
\]

(4)

The secure fixed-charge transportation problem is about to minimize the function \(Z\), equation (1), when satisfy the security constraints, equation (5). The security objective should be satisfied on both stages of the supply chain network.

In the next section the new constraint (equation (5)) of the SSCN is introduced.

4 The Secure Supply Chain Network: the Security Constraint

In this section, we propose a security constraint for the Supply Chain Network based on the security constraint model for data-intensive jobs running on distributed computing environments [10, 22, 23].

A distribution is assigned to an available unit, for example a distribution centre in our particular problem, only if the condition \(sd \leq sr\) is met. Three security modes are considered:

- **Secure mode**: the fully secure mode permits transportation only on the units satisfying the security requirements.
- **Risky mode**: the risky mode takes all possible risks by transporting the products on any available unit, \(DC\) in our case.
- **\(\gamma\)-risky mode**: use a probability measure of risk, the \(\gamma\)-risky mode, the transportation will be available to the unit taking at the most \(\gamma\)-risk. The secure mode is obtained for \(\gamma = 0\), and the risky mode when \(\gamma = 1\).

The current approach of SSCN uses the \(\gamma\)-risky mode. The security levels are assessed in distributed environments [21] in terms of a qualitative/fuzzy scale with five levels: very high (\(vh\)), high (\(h\)), medium (\(med\)), low (\(l\)), very low (\(vl\)).

- A transportation is secure if it is made to a completely safe unit, when \(sd \leq sr\).
- The risk must be less than 50% in the security constraint model if a distribution is assigned to a unit with a failure risk (when \(sd > sr\)).
- The transport is possible if \(0 < sd - sr \leq vl\), where \(vl\) represents the very low security level.
- The transport will be delayed when \(vl < sd - sr \leq l\), but should be made before the execution deadline [25]; \(vl\) and \(l\) are the very low and low security levels.
- A transport operation is not feasible if \(l < sd - sr \leq vh\) based on [21], where \(l\) and \(vh\) are the low and very high security levels.
The risk probability, equation (5), for the proposed security constraint model is defined as in [10] and represented in Figure 1. The $sr_i$ is the security risk of the $i$-th distribution center, $DC_i$.

$$P(risk) = \begin{cases} 
0, & sd - sr_i \leq 0 \\
1 - e^{-\frac{sd - sr_i}{2}}, & 0 < sd - sr_i \leq vl \\
1 - e^{-\frac{sd - sr_i}{2}}, & vl < sd - sr_i \leq l \\
1, & l < sd - sr_i \leq vh 
\end{cases} \quad \forall i = 1, \ldots, m. \quad (5)$$

5 Discussions on the proposed problem

A hybrid algorithm based on the nearest neighbour searching technique [3], was used in [12] to solve the fixed-charged transportation problem; an improved hybrid algorithm for the problem was introduced in [11]. An efficient reverse distribution system for solving a sustainable SCN was proposed in [13].

The Nearest Neighbour transportation model could be applied to minimize the transportation cost in the two-stage supply chain network with security constraints on DCs, based on [12, 11, 13]. The model is used when choosing a distribution centre and a connection between DCs and customers.

After the list $(L)$ of selected DCs is specified, based on quantities and security risks, the second supply chain is considered. The reverse technique [13] could be used by starting from the customer demand, and the objective is to use the secure DCs from list $L$ by optimizing the transportation costs, equation (1). In real life there could be different threats on the second supply chain, so the risk parameters could be different from those in the first supply chain.

The threats could come from several internal technical issues, manageable factors, or from external factors. Some of the technical problems could be staffing capacity of distribution centres, and the product design and manufacturing [4, 20]. External threats could be increases in raw material price, or natural disasters. A natural disaster could lead, for example, to a transportation delay. An external threat over a supply chain could be controllable if there are some previous contingency plans in case of the specific threat [27], such as spare manufacturing capacity and/or transportation links.

The controllable threats are quantified as mathematical parameters, as already described in section 4. Being the most expensive, due to major costs, the secure mode which allows transportation only when $sd \leq sr$, is very rare used. Either the risky mode or the $\gamma$-risky mode are used, instead.

For the risky mode, when all possible risks are taken by transporting the products on any available unit, DC or customer, the SSNC problem is reduced to the initial SNC problem without any secure conditions.

As specified in section 4, in the $\gamma$-risky mode the transportation will be available to an unit, in our case the distribution centre for both supply chains, taking at most $\gamma$-risk.
We consider a numerical example involving four $DC_i, i=1,4$. The values for security demand, $sd = 10$, the security risk values for each $DC$ are $sr = \{11, 8, 15, 12\}$ and the levels of security from the very low $vl$ to the very high $vh$ are: $vl=1, l=2, med=3, h=4$ and $vh=5$.

| DC   | Security level of a DC | Symbolic representation | $P(\text{risk})$ | Risk description for a DC |
|------|------------------------|-------------------------|------------------|--------------------------|
| $DC_2$ | High Security Level   | $sd - sr \leq 0$       | 0                | No risk is involved in the distribution to/from DC |
| $DC_1$ | Medium Security Level  | $0 < sd - sr \leq 1$   | $1 - e^{-16}$   | Distribution to/from DC is possible, has no a major risk |
| $DC_4$ | Low Security Level     | $1 < sd - sr \leq 2$   | $1 - e^{-27}$   | Delayed distribution to/from DC due to security risks |
| $DC_3$ | Very Low Security Level| $2 < sd - sr \leq 5$   | 1                | Distribution to/from DC it is not possible |

Table 2. The influence of security levels of distribution centre when distributing the products from manufacturer to distribution centres, and from distribution centres to customers (based on [21, 25]), for security demand $sd = 10$, $DC$ security risk values $sr = \{11, 8, 15, 12\}$ and the levels of security $vl=1, l=2, med=3, h=4$ and $vh=5$.

Based on Table 2 the distribution will be possible just on $DC_1$, $DC_2$ and $DC_4$, where the security risk is acceptable. The risk probability is computed based on equation 5.

The current ongoing work is on implementing the proposed algorithm for solving the $SSCN$ problem in terms of security constraints. The tests consider different values for the security parameters. The Secure Supply Chain Problem could be extended to include time constraints. Furthermore could be useful to develop a component-based system, for example modelled as a finite automaton as in [5, 26]. In perspective a security approach using intelligent mobile multi-agent systems [9] could be used to enhance the $SSCN$.

6 Conclusions and future work

The security of product distribution is nowadays a challenging problem. The paper proposes a security-based model for a fixed-charged transportation problem within a two-stage supply chain network. The complexity of the initial supply chain problem increases due to the security constraints. Several discussions about the solution for the optimization function based on diverse security levels are presented. Future work will include other constraints, such as time constraints and a dynamic approach of the supply chain problem.

Acknowledgements. The study was conducted under the auspices of the IEEE-CIS Interdisciplinary Emergent Technologies TF.
References

1. Diaby, M., Successive linear approximation procedure for generalized fixed charge transportation problems. J Oper Res Soc 42:991–1001, 1991
2. Adlakha, V., Kowalski, K., On the fixed-charge transportation problem. OMEGA: The International Journal of Management Science, 27:381–388, 1999
3. Arya, S., et al., An Optimal Algorithm for Approximate Nearest Neighbor Searching in Fixed Dimensions. Jnl ACM, 45(6):891–923
4. Calinescu, A., et al., Applying and assessing two methods for measuring complexity in manufacturing. J Oper Res Soc, 723–733, 1998
5. Fanea A, Motogna S, Diosan L. Automata-based component composition analysis. Studia Universitas Babes-Bolyai, Informatica.50(1):13–20, 2006
6. Molla-Alizadeh-Zavardehi S. et al., Solving a capacitated fixed-charge transportation problem by artificial immune and genetic algorithms with a Prüfer number representation, Expert Sys App 38:10462–10474, 2011
7. Chira C., Dumitrescu D., Pintea C-M., Learning sensitive stigmergic agents for solving complex problems, Computing and Informatics, 29(3):337–356, 2010
8. Pintea C-M., Crià n G-C., Chira C., Hybrid Ant Models with a Transition Policy for Solving a Complex Problem, Logic Jnl IGPL, 20(3):560-569, 2012
9. Iantovics B, Crainicu B.: A Distributed Security Approach for Intelligent Mobile Multiagent Systems. Studies in Computational Intelligence 486:175–189, 2014
10. Liu H., Abraham A., Snášel V., McLoone S., Swarm scheduling approaches for work-flow applications with security constraints in distributed data-intensive computing environments. Information Sciences 192:228–243, 2012
11. Pintea C-M., Pop P.C., An improved hybrid algorithm for capacitated fixed-charge transportation problem. Logic Jnl IGPL 23(3):369–378, 2015
12. Pintea C-M., et al., A hybrid classical approach to a fixed-charged transportation problem. LNCS 7208: 557–566, 2012
13. Pop P.C., et al., An Efficient Reverse Distribution System for Solving Sustainable Supply Chain Network Design Problem. Jnl Applied Logic, 13(2):105–113, 2015
14. Pop P.C., et al., A hybrid based genetic algorithm for solving a capacitated fixed-charged transportation problem. Carpathian J. Math. 32(2):225–232, 2016
15. Rice, J. B., F. Caniato. Building a secure and resilient supply network. Supply Chain Management Review, 7(5):22–30, 2003
16. Lee, H.L., Wolfe M., Supply chain security without tears. Supply Chain Management Review, 7(3):12–20, 2003
17. Matei O. Evolutionary Computation: Principles and Practices. Risoprint, 2008.
18. Mes, M. et al., Comparison of agent-based scheduling to look-ahead heuristics for real-time transportation problems. Eur J Oper Res 181(1):59–75, 2007
19. Nechita, E. et al.: Cooperative Ant Colonies for Vehicle Routing Problem with Time Windows. A Case Study in the Distribution of Dietary Products. WMSCI 5:48–52, 2008
20. Sivadasan, S., et al., Advances on measuring the operational complexity of supplier–customer systems. Eur J Oper Res 171(1):208–226, 2006
21. Song S., Hwang K., Zhou R., Kwok Y., Trusted P2P transactions with fuzzy reputation aggregation, IEEE Internet Computing 9(6):24–34, 2005
22. Song S., Kwok Y., Hwang K., Security-driven heuristics and a fast genetic algorithm for trusted grid job scheduling, Int. Parallel & Distributed Processing, IEEE CS, 65:4–12, 2005
23. Song S., Hwang K., Kwok Y., et al, Risk-resilient heuristics and genetic algorithms for security-assured grid job scheduling, IEEE Trans Comp 55(6):703, 2006
24. Sun, M., et al., A tabu search heuristic procedure for the fixed charge transportation problem. Eur J Oper Res 106(2):441–456, 1998
25. Venugopal S., Buyya R., A deadline and budget constrained scheduling algorithm for eScience applications on data grids, LNCS 3719:60–72, 2005
26. Vescan A., Motogna S., Overview and architecture of a component modeling tool. Creative Math.Inf.16:159–165, 2007
27. Xiangyang Li, Charu Chandra, Toward A Secure Supply Chain: A System’s Perspective. Human Systems Management, 27(1):73–86, 2008