Reliability Engineering and System Safety 138 (2015) 93–104

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Protection of warehouses and plants under capacity constraint

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ARTICLE INFO

Article history:
Received 1 June 2014
Received in revised form
11 December 2014
Accepted 4 January 2015
Available online 3 February 2015

Keywords:
Protection
Warehouse
Game theory
Capacity
Attack
Damage
Defense

ABSTRACT

While warehouses may be subjected to less protection effort than plants, their unavailability may have substantial impact on the supply chain performance. This paper presents a method for protection of plants and warehouses against intentional attacks in the context of the capacitated plant and warehouses location and capacity acquisition problem. A non-cooperative two-period game is developed to find the equilibrium solution and the optimal defender strategy under capacity constraints. The defender invests in the first period to minimize the expected damage and the attacker moves in the second period to maximize the expected damage. Extra-capacity of neighboring functional plants and warehouses is used after attacks, to satisfy all customers demand and to avoid the backorders. The contest success function is used to evaluate success probability of an attack of plants and warehouses. A numerical example is presented to illustrate an application of the model. The defender strategy obtained by our model is compared to the case where warehouses are subjected to less protection effort than the plants. This comparison allows us to measure how much our method is better, and illustrates the effect of direct investments in protection and indirect protection by warehouse extra-capacities to reduce the expected damage.

1. Introduction

1.1. Importance of warehouses

Warehouses are commonly used by manufacturers for conservation of stocks for production or distribution. It is widely recognized that the efficiency and effectiveness in any distribution network is largely determined by the good operation of warehouses. They are fundamental elements in the supply network and they play a vital role in the success or failure of businesses today [13], and in determining a company's competitiveness. There are in fact many situations where it is not suitable to supply directly to customers. For example, some customers require to be served from warehouses rather than from plants because the supplier lead times cannot be reduced cost effectively to the short lead times required by customers [14]. Warehouses offer a same-day or next-day lead-time to customers from inventory [15], and they need to reach this objective reliably within high tolerances of speed, precision and safety. They must be able to properly receive the goods and ship them back to areas of applications as efficiently as possible, respecting the promised delivery dates to customers who are increasingly demanding [12]. Warehouses have a critical impact not only on customer service levels, but also on logistics costs [11,16,17].

1.2. Protection of warehouses

In a supply network, if one or many warehouses are unavailable, substantial losses may be incurred. Therefore, it is imperative to the success of businesses that warehouses are designed and protected so that they function reliably and cost effectively. In this paper, we consider warehouses as critical facilities that need to be protected against malevolent acts. Considering the plant and warehouse location problem [33], the objective is to define how to allocate optimally the protective resources among the plants and the warehouses, knowing that they are both exposed to external attacks.

The total procurement cost of warehouses is generally less expensive than the costs of plants. One reason is that a plant often requires much more technological production equipment and machines. It results that the protection of warehouses may receive less attention than plants by the designer, and much more protection effort is 'naturally' put on the plants. However, the impact of losing the functionality of warehouses may cause substantial damage. Knowing that an intelligent adversary may choose to attack the most vulnerable element (weak point) of the supply network in order to paralyze this network and to cause maximum damage, warehouse protection becomes essential when considering the attacker as a fully strategic optimizing agent.

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http://dx.doi.org/10.1016/j.ress.2015.01.003
0951-8320/

Nomenclature

n_p number of plants in the system
n_w number of warehouses in the system
n_k number of customers in the system
β index that refers to plant or warehouse, $\beta=1, 2, \ldots, n_p+n_w$
i ith potential plant location, $i=1, 2, \ldots, n_p$
j jth potential warehouse location, $j=n_p+1, n_p+2, \ldots, n_p+n_w$
k jth demand location, $k=1,2, \ldots, n_k$
I the set of candidate plant locations, indexed by i
J the set of candidate warehouse locations, indexed by j
K the set of customer locations, indexed by k
D_k the demand at customer location $k \in K$
h_i the total capacity acquisition cost function at plant $i \in I$
g_j the total capacity acquisition cost function at warehouse $j \in J$
CP_i the fixed cost of locating a plant at candidate site $i \in I$
CW_j the fixed cost of locating a warehouse at candidate site $j \in J$
CAP_i the maximum capacity that can be built-in at plant at candidate site $i \in I$
CAP_j the maximum capacity that can be built-in at warehouse at candidate site $j \in J$
Uc_{ij} the cost of producing and shipping one unit from candidate plant site $i \in I$, to candidate warehouse site $j \in J$
Uc_{jk} the cost of shipping one unit from candidate warehouse site $j \in J$ to customer location $k \in K$
X_i 1 if a plant is to be located at candidate site i, and 0 otherwise
Y_j 1 if a warehouse is to be located at candidate site j, and 0 otherwise
ψ_{ij} the quantity shipped from candidate plant site $i \in I$, to candidate warehouse site $j \in J$
Z_{jk} the quantity shipped from candidate warehouse site $j \in J$ to customer location $k \in K$
δ_β number of protection types for facility β
p index of protection type, $p=1, 2, \ldots, \delta_\beta$
F_p investment effort to protect a facility located at site β using protection type p
$f_{\beta p}$ unit cost of effort to protect a facility located at site β using protection type p
$\overline{F}_{\beta p}$ investment expenditure to protect a facility located at site β using protection type p
π_β value from $p=1, 2, \ldots, \delta_\beta$
π_β^{opt} optimal defence strategy value from $p=1, 2, \ldots, \delta_\beta$
$\mathbf{P}$ vector of protection strategy, $\mathbf{P}=\left(\pi_\beta\right)$
$\mathbf{P}_{\text{opt}}$ vector of the optimal protection strategy, $\mathbf{P}_{opt}=\left(\pi_\beta^{opt}\right)$
$\mathbf{F}$ vector of investments to protection strategy $\mathbf{P}, \mathbf{F}=\left(F_{\beta\pi_\beta}\right)$
$\mathbf{F}_{\text{opt}}$ vector of investments to protection strategy $\mathbf{P}_{opt}, \mathbf{F}_{opt}=\left(F_{\beta\pi_\beta^{opt}}\right)$
$F_{\beta\pi_\beta}$ element of investments vector $\mathbf{F}$
$F_{\beta\pi_\beta^{opt}}$ element of investments vector $\mathbf{F}_{\text{opt}}$
$\lambda_{\beta p}$ binary variable which is equal to 1 if a protection of type p is used for facility β
$\boldsymbol{\lambda}$ matrix, $\boldsymbol{\lambda}=(\lambda_{\beta p})$
$\rho_\beta Z$ number of extra-capacity options for each facility β
e index of extra-capacity options, $e=1,2 \ , \ldots, \ \rho_\beta$
$\tau_{\beta e}$ proportion of the acquired capacity associated with the facility located at site β using extra-capacity option e
C_β^* capacity acquired associated with the facility located at site β
Ac_β capacity acquisition cost at facility location β per unit
$CE_{\beta e}$ investment of extra-capacity associated with the facility located at site β using extra-capacity option e, $CE_{\beta e}=Ac_\beta \tau_{\beta e} C_\beta{}^*$
$\mathbf{E}$ vector of extra-capacity strategy, $\mathbf{E}=\left(\theta_\beta\right)$
θ_β values from $e=0,1 \ , \ldots, \ \rho_\beta$
$\mathbf{T}$ vector of investments to each extra-capacity strategy $\mathbf{E}, \mathbf{T}=\left(\tau_{\beta\theta_\beta}\right)$
$\xi_{\beta e}$ binary variable which is equal to 1 if an extra-capacity option e is selected for facility β
α_β number of attack types against any facility β
g index of attack type ($g=0, 1, 2, \ldots, \alpha_\beta$)
$Q_{\beta g}$ attack effort to attack facility located at site β using attack action g
$q_{\beta g}$ unit cost to attack facility located at site β using attack action g
$\overline{Q_{\beta g}}$ investment expenditure to attack facility located at site β using attack action g
ω_β value from $g=1,2 \ , \ldots, \ \alpha_\beta$
ω_β^{opt} value from g of the optimal attack strategy
$\mu_{\beta g}$ binary variable which is equal to 1 if a type g attack is used for facility β
$\boldsymbol{\mu}$ matrix, $\boldsymbol{\mu}=\left(\mu_{\beta g}\right)$
$\boldsymbol{\mu}_{\text{opt}}$ matrix, $\boldsymbol{\mu}_{opt}=\left(\mu_{\beta g}\right)$
f_1 the defender production function $f_1\left(\overline{F_{\beta p}}\right)=F_{\beta p}=\left(1/f_{\beta p}\right)\overline{F_{\beta p}}$
f_2 the attacker production function. $f_2\left(\overline{Q_{\beta g}}\right)=Q_{\beta p}=\left(1/q_{\beta p}\right)\overline{Q_{\beta g}}$
D_B defender budget
AT_B attacker budget
$\mathbf{G}$ vector of attack strategy, $\mathbf{G}=\left(\omega_\beta\right)$
$\mathbf{G}_{\text{opt}}$ vector of the optimal attack strategy, $\mathbf{G}_{opt}=\left(\omega_\beta^{opt}\right)$
$\mathbf{Q}_{\text{opt}}$ vector of attack effort of the optimal attack strategy, $\mathbf{Q}_{opt}=\left(Q_{\beta\omega_\beta^{opt}}\right)$
$Q_{\beta\omega_\beta^{opt}}$ element of attack effort vector $\mathbf{Q}_{\text{opt}}$
$\nu_{pg}(\beta)$ destruction probability of a facility β
$\nu_{p\omega_\beta^{opt}}(\beta)$ destruction probability of a facility β for the optimal defence strategy
$\boldsymbol{\nu}(\mathbf{P},\mathbf{G})$ matrix, $\boldsymbol{\nu}(\mathbf{P},\mathbf{G})=(\nu_{pg}(\beta))$
$\boldsymbol{\nu}(\mathbf{P},\mathbf{G}_{\text{opt}})$ matrix, $\boldsymbol{\nu}(\mathbf{P},\mathbf{G}_{\text{opt}})=\left(\nu_{p\omega_\beta^{opt}}(\beta)\right)$
ε_β parameter that expresses the intensity of the contest concerning facility β
R_β the cost required to restore the attacked facility β
$C_R(\mathbf{P},\mathbf{G})$ expected cost required to restore the attacked facilities which depends on $\mathbf{P}$ and $\mathbf{G}$
$C_R(\mathbf{P},\mathbf{G}_{\text{opt}})$ expected cost required to restore the attacked facilities which depends on $\mathbf{P}$ and $\mathbf{G}_{\text{opt}}$
c combinations index, $(c=0 \ , \ldots, \ 2^{n_p+n_w}-1)$
S_c combinations of disabled and functional facilities for the facilities
S set of combinations of disabled and functional facilities, $S=\{S_c\}$
$Ct_c(E)$ cost incurred because of the change in transportation cost when the combination is S_c which depends on the vector $\mathbf{E}$
$\overline{Ac}$ average of the capacity acquisition costs per unit
B_{img} brand image of the company
$YD_c(E)$ annual unmet demand when the combination is S_c