A Fuzzy Approach for Sustainable Seaport-Dry Port Network Design

Yu-Chung Tsao
Department of Industrial Management
National Taiwan University of Science & Technology (Taiwan Tech), Taipei, Taiwan
Tel: (+886) 2-2737-3624, Email: yctsao@mail.ntust.edu.tw

Vo V. Thanh †
Department of Industrial Management
National Taiwan University of Science & Technology (Taiwan Tech), Taipei, Taiwan
Tel: (+886) 978-351-478, Email: D10401806@mail.ntust.edu.tw

Abstract. The growing in container transport volume generates an almost proportional increase of product flows in the inland transport system as well as the lack of storage space and traffic jam at port terminal for most seaports. Dry port is considered as a method to address these problems. However, establishing and operating dry ports requires more comprehensive consideration relevant objectives (economic, environmental and social objectives). This paper considers a sustainable seaport-dry port network design problem. The objective is to determine the optimal number, location and capacity of dry port, and the number of containers through dry port simultaneously. The proposed multi-objective mathematical model is aimed at minimizing economic costs, environmental and social impacts under uncertain conditions of cargo export demand and some relevant costs. An interactive method based on fuzzy probabilistic multi-objective programming is used to solve the uncertain problem. Finally, numerical analysis demonstrates the effectiveness and efficiency of the proposed model.

Keywords: Sustainable, seaport-dry port network, fuzzy multi-objective optimization, possibilistic programming, economic, environmental and social impact.

1. INTRODUCTION

Dry port is an effective solution to simultaneously reduce congestion in and around the seaport, lower environmental and social impacts, and improve sustainability performance of intermodal transport system (Roso and Lumsden, 2009; Roso, 2013). For this benefits, the dry port has gained more attention from researchers and practitioners in recent years.

The initial dry port concept is mentioned in United Nation text of 1982. Roso et al. (2009) defined dry port as an inland port directly connected to one or several seaports with high capacity transport means. When dry port becomes an essential partner of seaport, the dry port is an extended gateway to offer services that are usually available at seaports (Roso and Rosa, 2012). Seaport-dry port network (SDN) plays an extremely important role in regional economic growth and decreasing harmful effects on environment and society. At the strategic level, SDN design is represented by decisions about the optimal number, location and capacity of dry port. Feng et al. (2013) and Chang et al. (2015) tackled the dry port location problem while minimizing total costs with genetic algorithm. Some researchers are based on clustering methods or multi-criteria decision models to solve the dry port location problem (Li and Jiang, 2014; Nunez et al. 2014).

The sustainable development concept plays an important role in SDNs, when harmful effects of hinterland transport on the environment and society are more and more significantly increase (Bask et al. 2014, Crainic et al. 2015). The concept of sustainable hinterland port was mentioned in Iannone (2012) to indicate an efficient and environmental and social friendly hinterland distribution system supporting the container traffic of seaports. The impact of SDNs on the sustainability should be determined in three main aspects: economic performance, environmental impact, and social responsibility.

Economic performance is considered in dry port planning models under minimum total costs or maximum total profits form (Feng et al. 2013; Chang et al. 2015; Qui et al. 2015). The carbon dioxide (CO_2) emission, pollution and noise cost are the environmental impacts that have been considered in recent studies about SDN (Gu and Lam, 2013; Ambrosion et al. 2016). Social responsibility is associated to accidents and congestion cost in hinterland container logistics system (Iannone, 2012).

Lättilä et al. (2013) considered congestion, pollution, and noise cost to evaluate both social and environmental impacts.

Sustainable seaport-dry port network (SSDN) design is extremely complex since highly uncertain parameters related to social issues must be considered in the model. The complex structure of SSDN and the chaotic business environment have been imposing a high degree of uncertainty in design decisions and overall performance of the network.

Three main approaches that mostly used to overcome this issue: (1) stochastic programing, (2) fuzzy programing and (3) robust optimization. The fuzzy programming approach is one of the most attractive methods since its ability to measure and adjust the satisfaction level of each objective function. It has widely used to solve problems related to supply chain network design under different interactive methods. Saffar et al. (2015) and Pishvaee and Razmi (2012) presented an interactive fuzzy approach based on the ε-constraint for the design of supply chain networks. Talaei et al. (2016) proposed a robust fuzzy optimization model for the closed-loop sustainable supply chain network design to cope with uncertain environment.

To the best of our current knowledge, there has not been recently relevant work that applied interactive fuzzy solution approaches to comprehensively consider three main aspects: economy, environment, and society under uncertain conditions for designing SSDN. This paper considers the SSDN design problem under uncertain environment of demand and costs. A multi-objective mathematical model is proposed to determine the number, location and capacity of dry port, and the number of containers through dry port. This problem is solved by an interactive fuzzy approach combining the expected value of fuzzy numbers and fuzzy multi-objective possibilistic method.

The rest of this paper is organized as follows: Section 2 describes the detailed problem and model formulation. Section 3 shows the interactive fuzzy approach. Section 4 presents a numerical analysis. Section 5 concludes this research.

2. MULTI-OBJECTIVE MODEL FOR SSDN

An export-oriented SSDN is considered including two crucial elements: nodes and links. Nodes represent single seaport, multi-potential locations for dry port and shippers. Links connect the shipper to seaports, either directly by road or through dry ports by road first, then to the seaport by rail.

2.1 Model assumptions

For SSDN with a single type of freight, the government will determine the number, location and capacity of dry ports. The shippers choose route freight to seaport, either directly or through dry port. In addition, the following assumptions are made.

- The location of the seaport, multi-candidate location of dry ports and shippers are predetermined.
- The set-up and operate cost and the number created job of each dry port are depend on the given various capacity levels.
- The freight volume of each shipper is known and it must be exported through seaport.
- The established dry ports will attract immigration.
- The transported freight have a certain damage level.

2.2 Model formulation

The SSDN design problem is formulated as a multi-objective possibilistic mixed integer linear programming (MOPMILP) model. The indices: P, D, M are used to indicate a set of shippers, candidate location and capacity levels of dry ports, respectively.

The parameters and decision variables are illustrated in the following.

Parameters:

cf_d^m	facility cost of opening constructing each dry port d with capacity level m
c^{rd}	transportation cost for per container per distance by road
c^{rl}	transportation cost for per container per distance by rail
c_d^{str}	storage cost of candidate dry port d with capacity level m per day
c^{cdm}	damaged cost for unit cargo
c^{hr}	unit time cost of human resources
f^{ds}	distance transport between facitilites in seaport-dry port network
f^{trc}	parameter that depends on traffic congestion of each area
f^{im}	parameter that depends on immigrant rate of each area
f^{dm}	parameter that depends on damaged cargo speed
n^{uep}	number of the unemployed before candidate dry port d is opened
n^{ep}	number of the created employment when dry port d with capacity level m is built
o^{rd}	unit carbon dioxide emission for per container per distance by road
o^{rl}	unit carbon dioxide emission for per container per distance by rail
e^{cb}	unit cost of carbon dioxide emission handling with the outside market

q_{ds}^{m}	volume of containers transported from dry port d with capacity m to seaport s
s^{uep}	social cost for the per unemployed
s^{im}	social cost for per immigrant
r_i	total export demand of inland city $i \in P$
T_d	operational time of candidate dry port d
t_d	storage time of candidate dry port d
t^{dl}	average congestion time of each area
φ_d^m	capacity with level m for candidate location of dry port d

Decision variables:

$$x_d^m = \begin{cases} 1 & \text{if dry port } d \text{ with capacity level } m \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$$

q_{id}^{m}	volume of containers transported from shippers $i \in P$ to candidate dry ports $d \in D$ with capacity m
q_{is}	volume of containers transported directly from shippers $i \in P$ to seaport $s \in S$

The model is as follows:

$$\text{Min } W_1 = \sum_{d\in D}\sum_{m\in M}\tilde{c}f_d^m x_d^m + \sum_{i\in P}\sum_{d\in D}\sum_{m\in M}\tilde{c}^{rd} f^{ds}\tilde{f}^{trc} q_{id}^m + \sum_{d\in D}\sum_{m\in M}\sum_{i\in P}\tilde{c}_d^{str} t_d q_{id}^m + \sum_{d\in D}\sum_{m\in M}\tilde{c}^{rl} f^{ds} q_{ds}^m + \sum_{i\in P}\tilde{c}^{rd} f^{ds}\tilde{f}^{trc} q_{is} \tag{1}$$

$$\text{Min } W_2 = \sum_{i\in P}\sum_{d\in D}\sum_{m\in M}\tilde{o}^{rd} f^{ds}\tilde{f}^{trc} q_{id}^m \tilde{e}^{cb} + \sum_{d\in D}\sum_{m\in M}\tilde{o}^{rl} f^{ds} q_{ds}^m \tilde{e}^{cb} + \sum_{i\in P}\tilde{o}^{rd} f^{ds}\tilde{f}^{trc} q_{is}\tilde{e}^{cb} \tag{2}$$

$$\text{Min } W_3 = \sum_{d\in D}\sum_{m\in M}(n^{uep} - \tilde{n}^{ep}) s^{uep} x_d^m + \sum_{d\in D}\sum_{m\in M} s^{im}\tilde{f}^{im}\tilde{n}^{ep} x_d^m + \sum_{i\in P}\sum_{d\in D}\sum_{m\in M}(\tilde{c}^{hr} + \tilde{c}^{cdm}\tilde{f}^{dm} q_{id}^m)\tilde{t}^{dl} + \sum_{i\in P}(\tilde{c}^{hr} + \tilde{c}^{cdm}\tilde{f}^{dm} q_{is})\tilde{t}^{dl} \tag{3}$$

The first objective function (1) is an attempt to minimize the total cost, including set-up and operate cost, storage cost, and transportation cost between shippers and seaport through dry ports. The second objective function (2) minimizes the CO_2 emission handling cost caused by road and rail transport. The social responsibility is dealt in the third objective function (3), wherein the first and second terms relate to the unemployment and immigration cost for per employee. Two remained terms are traffic congestion cost, including two components: (1) the fixed time cost of resources involving human and vehicle, (2) the variable cost, which depends on the volume of transported containers.

The constraints about the storage time of each containers, established capacity of dry ports, container flows between facilities, and ensuring the export demand of each shipper are presented as follows.

S.t

$$t_d = \frac{T_d}{\tilde{\varphi}_d^m} \tag{4}$$

$$\sum_{d\in D}\sum_{m\in M} q_{id} + q_{is} = r_{i\in P}, \ \forall i \in P \tag{5}$$

$$\sum_{i\in P} q_{id} = q_{ds}, \ \forall d \in D \tag{6}$$

$$\sum_{i\in P} q_{id} \le \tilde{\varphi}_d^m x_d^m, \ \forall d \in D, \forall m \in M \tag{7}$$

$$\sum_{m\in M} x_d^m \le 1, \ \forall d \in D \tag{8}$$

$$x_d^m \in \{0;1\}, \ \forall d \in D, \forall m \in M \tag{9}$$

$$q_{id} \ge 0, \forall i \in P, \ \forall d \in D \tag{10}$$

$$q_{is} \ge 0, \forall i \in P, \ \forall s \in S \tag{11}$$

The symbol ~ is used to assign uncertain parameters in the objective functions and constraints under the triangular fuzzy numbers form.

3. SOLUTION METHOD

The proposed MOPMILP model in this research can be effectively transformed into an equivalent model by applying the method of Pishvaee and Torabi (2010). The method is superior approach to preserve the linearity of the original possibilistic model and it can be easily applied to various types of fuzzy numbers for uncertain parameters. The method is summarized as follows.

The general form of MOPMILP model to design SSDN can be sated as equation (12).

$$\begin{aligned}
&\text{Min } W_1 = \tilde{f}x_d^m + \tilde{c}(q_{id} + q_{is}) \\
&\text{Min } W_2 = \tilde{o}(q_{id} + q_{is}) \\
&\text{Min } W_3 = \tilde{s}x_d^m + \tilde{k}(q_{id} + q_{is}) \\
&\text{S.t} \\
&t_d = \frac{T_d}{\tilde{\varphi}_d^m}, \\
&Aq_{id} + Bq_{is} = \tilde{r}_i, \\
&Cq_{id} = 0, \\
&Sq_{id} \le \tilde{\varphi}_d^m x_d^m, \\
&Px_d^m \le 1, \\
&x_d^m \in \{0,1\}, \ q_{id}, q_{is} \ge 0.
\end{aligned} \tag{12}$$

Given the triangular fuzzy number $\tilde{f} = (f^{(1)}, f^{(2)}, f^{(3)})$, its expected interval and expected value in Jimenez (1996) are applied to deal with a lack of precision in objective functions. For uncertain parameters in constraints, the ranking method of Jimenez et al. (2007) and the definition of fuzzy equations in Parra et al. (2005) is used to overcome.

Consequently, the equivalent crisp α-cut level model of the model (12) can be written as follows.

$$\text{Min } W_1 = (\frac{f^{(1)} + f^{(2)} + f^{(3)}}{3})x_d^m + (\frac{c^{(1)} + c^{(2)} + c^{(3)}}{3})(q_{id} + q_{is})$$

$$\text{Min } W_2 = (\frac{o^{(1)} + o^{(2)} + o^{(3)}}{3})(q_{id} + q_{is})$$

$$\text{Min } W_3 = (\frac{s^{(1)} + s^{(2)} + s^{(3)}}{3})x_d^m + (\frac{k^{(1)} + k^{(2)} + k^{(3)}}{3})(q_{id} + q_{is})$$

S.t

$$t_d = \frac{T_d}{\alpha(\frac{\varphi_d^{m(1)} + \varphi_d^{m(2)}}{2}) + (1-\alpha)(\frac{\varphi_d^{m(2)} + \varphi_d^{m(3)}}{2})}, \quad (13)$$

$$Aq_{id} + Bq_{is} = \alpha(\frac{r_i^{(1)} + r^{(2)}}{2}) + (1-\alpha)(\frac{r^{(2)} + r^{(3)}}{2}),$$

$$Cq_{id} = 0,$$

$$Sq_{id} \le [\alpha(\frac{\varphi_d^{m(1)} + \varphi_d^{m(2)}}{2}) + (1-\alpha)(\frac{\varphi_d^{m(2)} + \varphi_d^{m(3)}}{2})]x_d^m,$$

$$Px_d^m \le 1,$$

$$x_d^m \in \{0,1\},\ q_{id}, q_{is} \ge 0.$$

SSDN design is a multi-objective programming problem. The fuzzy programming is one of the most attractive methods because of their capacity in measuring the satisfaction level of each objective function directly. Torabi and Hassini (2008) proposed a new approach for solving multi-objective problems, called TH method. The TH method yields efficient solutions because it provides balanced and unbalanced solution with compromise of the objective functions for decision-maker. In this paper, to solve the proposed SSDN design model, we also applied TH method with the steps of the solution approach can be summarized, as follows.

Step 1: Determine the appropriate triangular possibility distribution for uncertain parameters and formulate the SSDN design problem under MOPMILP model.

Step 2: Convert MOPMILP model into the equivalent crisp one by using equation (13) with the pre-determined α-cut level by decision maker.

Step 3: Determine the α-positive idea solution (α-PIS) by solving each objective function separately. The α-negative idea solution (α-NIS) for each objective function can be estimated as follows:

$$W_1^{\alpha-NIS} = W_1(x_d^m, q_{id}, q_{is})_2^{\alpha-PIS},$$

$$W_2^{\alpha-NIS} = W_2(x_d^m, q_{id}, q_{is})_1^{\alpha-PIS},$$

$$W_3^{\alpha-NIS} = W_3(x_d^m, q_{id}, q_{is})_1^{\alpha-PIS}.$$

Step 4: Determine a linear membership function for each objective function as follows:

$$\mu_{W_i}(\mathrm{u}) = \begin{cases} 1 & W_i < W_i^{\alpha-PIS} \\ \frac{W_i^{\alpha-NIS} - W_i}{W_i^{\alpha-NIS} - W_i^{\alpha-PIS}} & W_i^{\alpha-PIS} \le W_i \le W_i^{\alpha-NIS}, \quad i = 1,2,3 \\ 0 & W_i > W_i^{\alpha-NIS} \end{cases}$$

$\mu_{W_i}(\mathrm{u})$ denotes the satisfaction degree of W_i objective function.

Step 5: Transform the crisp model into a single- objective model by using TH method.

$$\text{Max } \omega(x) = \xi\omega_o + (1-\xi)\sum_{i=1,2,3} h_{w_i}\mu_{w_i}(\upsilon)$$

$$\text{S.t} \quad \omega_o \le \mu_{w_i}(\upsilon), i = 1,2,3$$

$$x \in F(x),\ \xi \text{ and } \omega_o \in [0,1]$$

Where: $\omega_0 = \min_{w_i}\{\mu_{w_i}(x)\}$: the minimum satisfaction degree of objective functions.

h_{w_i} : the importance of the w_i objective function, i =1,2,3.

ξ : the coefficient of compensation.

Step 6: Specify the weight of the fuzzy goals (h_{wi}), the value coefficient of compensation (ξ) and solve the respective single-objective mixed integer-linear programming model. If the decision-maker is satisfied with the current solution, stop, otherwise provide another compromise solution by changing the value of ξ and α and go to step 3.

4. NUMERICAL EXAMPLE

This section provides a numerical example to illustrate the validity of the proposed model. The size of the test problem and other some relevant data are given in Table 1-3.

Table 1. Size of test problem

P	D	M	S
33	9	3	1

The unit CO2 emission is estimated by vehicle speed and fuel consumption. The congestion cost is identified by the unit time cost, damaged cargo percent, and average congestion time.

Table 2: Parameters related to CO_2 emission

Unit CO_2 emission per distance	Fuzzy value
By road *(o^{rd})* (kg/teu-km)	(0.034, 0.044, 0.054)
By rail *(o^{rl})* (kg/teu-km)	(0.006, 0.007, 0.008)
Unit cost for handling *(e^{cb})* ($/kg)	(0.03, 0.04, 0.05)

Table 3: Parameters related to congestion traffic.

Parameters	Fuzzy value
Unit time cost for resource *(c^{hr})* ($/h)	(7, 8, 9)
Average congestion time *(t^{dl})* (h)	(0.4, 0.5, 0.6)
Damaged cargo percent *($c^{cdm}.f^{dm}$)* (%)	(24, 25, 26)

The export demand in hinterland (TEU), capacity levels (TEU) and installation costs (USD) of dry ports, were obtained from a similar paper (Chang et al., 2015). The deterministic parameters will be modified into triangular fuzzy numbers based on the expert's opinion.

The objectives value are evaluated for each discrete value of α-level in set $T = \{0.6, 0.7, 0.8, 0.9, 1\}$. We set the objective weight vector as: $h_{wi} = (0.4, 0.3, 0.3)$ and the coefficient of compensation ξ = 0.6. Test was coded in LINGO 10.0 optimization software and run on a 3.40 GHz computer with 8.0 GB RAM. The results are presented in Table 4. According to the Table 4, the solution of model with α = 0.7 has highest balance degree of objective functions. The values of decision variable of this solution are shown in Table 5. There are not the volume of container that directly delivered to seaport and all opened dry port establish the capacity at the maximum level.

Table 4: α-level optimal solutions

α-level	W_1 (10^8)	W_2 (10^8)	W_3 (10^8)	ω_o
0.6	8.9734	0.1621	0.8333	0.4493
0.7	**8.6506**	**0.1575**	**0.9109**	**0.7450**
0.8	8.6580	0.1576	0.9109	0.6912
0.9	8.6654	0.1578	0.9109	0.6845
1	8.6729	0.1579	0.9109	0.5694

Table 5: Values of decision variable at α =0.7

Shippers	$\mathbf{X}^{(1,3)}$	$\mathbf{X}^{(2,3)}$	$\mathbf{X}^{(3,3)}$	$\mathbf{X}^{(4,3)}$
Q(1,1,3)	8060.5			
Q(3,1,3)	332			
Q(3,3,3)			2278.5	
Q(4,2,3)		7589.5		
Q(6,3,3)			94865.5	
Q(7,2,3)		13965		
Q(7,4,3)				49281
Q(11,2,3)		17331.5		
Q(13,1,3)	10638.5			
Q(14,4,3)				76561.5
Q(16,1,3)	2613.5			
Q(17,2,3)		1908.5		
Q(20,2,3)		3342.5		
Q(22,1,3)	72156.5			
Q(25,1,3)	3802.5			
Q(26,2,3)		3463		
Q(26,3,3)			34580.5	
Q(27,4,3)				18457.5
Q(28,2,3)		4227.5		
Q(31,1,3)	16696.5			
Q(31,3,3)			117116	
Q(32,2,3)		82472.5		
Q(33,3,3)			2575.5	

Shippers	$\mathbf{X}^{(5,3)}$	$\mathbf{X}^{(7,3)}$	$\mathbf{X}^{(8,3)}$	$\mathbf{X}^{(9,3)}$
Q(2,7,3)		253.5		
Q(5,5,3)	22211.5			
Q(6,5,3)	64939.5			2449.5
Q(7,7,3)		4252.5		
Q(8,7,3)		20782.5		
Q(9,9,3)				65291.5
Q(10,9,3)				5279.5
Q(12,7,3)		18002.5		
Q(15,9,3)				19419.5
Q(18,9,3)				6006.5
Q(19,8,3)			6930.5	
Q(21,5,3)	3495.5			
Q(23,8,3)			16653.5	
Q(23,9,3)				2728
Q(24,5,3)	23653.5			
Q(29,7,3)		101262.5		
Q(30,9,3)				3125.5

$\mathbf{X}^{(a,b)}$: a: dry port location, b: capacity of dry port

5. CONCLUSIONS

This paper proposes a multi-objective possibilistic mixed integer-linear programming model to solve SSDND problem. The strategic decisions related to the number, location and capacity of dry ports, and the volume of containers transported between hinterlands, dry ports and seaport are reasonably considered by using the effective transformation approach of Pishvaee and Torabi (2010). This approach provides both balanced and unbalanced efficient solutions for decision makers with the compromise of the objective functions in order to minimize the total cost of the entire system, including economic, social, and environmental cost under the effects of uncertainty and incompleteness of data. Further studies on the stability of possibilistic programming are necessary in order to provide decision makers better insights. In addition, several possible future research directions may be considered to extend our model. For example, including multi-freight and multi-seaport in the proposed model or considering the vehicle routing problem may make the model more comprehensive and closer to reality.

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