Optimal competitive freight network design as hierarchical variational inequalities programming problems

Loukas Dimitriou *

Department of Civil and Environmental Engineering, University of Cyprus, 75 Kallipoleos Str., P.O. Box 20537, 1678 Nicosia, Cyprus

A B S T R A C T

Freight networks are a case of systems that multiple participants are composing interrelations along the complete supply chain. Their interrelations correspond to alternative behavior, namely, cooperation, non-cooperation and competition, while they are large-scale spatially distributed systems combining multiple means of transportation and the infrastructure and equipment typically utilized for servicing demand, results to a complex system integration. In this paper, the case of the optimal design of freight networks is investigated, aiming to highlight the particularities emerging in this case of transportation facilities strategic and/or operational planning and the multiple game-theoretic and equilibrium problems that are structured in cascade and in hierarchies. The application that is investigated here focuses in the design of a significant 'player' of the freight supply chain, namely container terminals, while the proposed framework will aim on analyzing investment strategies built on integrated demand–supply models and the optimal network design format. The approach will build on the multilevel Mathematical Programming with Equilibrium Constraints (MPECs) formulation, but is further extended to cope with the properties introduced by the 'designers' (infrastructure authorities), shippers and carriers competition in all levels of MPECs. Since container terminals are typically competing each other, the nomenclature used here for formulating appropriate MPECs problems are based on hierarchies of Variational Inequalities (VI) problems, able to capture the alternative relationships emerging in realistic freight supply chains. The proposed formulations of the competitive network design case is addressed by a novel approach of co-evolutionary agents, which can be regarded as new in equilibrium estimation. Finally, the results are compared with alternative network design cases, namely the centralized cooperative and exchanging design. Under this analysis it is able to highlight the differences among alternative design cases, but moreover an estimation of the 'price of anarchy' in transportation systems design is offered, an element of both theoretical as well as practical relevance.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Freight networks rapid integration has been the key element in the last decades development of global economy. The structure and the characteristics of the freight systems involves a large number of distributed stakeholders, operators, methods/technologies and 'users', while it is subject to particularities of the economics of infrastructure in each part of the system. Though, one thing is evident on such large-scale systems; it is a system operating simultaneously under the concepts of

Nomenclature

A	the set of all links
$a \in L \subseteq A$	subset L of the truck links
$a \in T \subseteq A$	subset T of the railways links
$a \in N \subseteq A$	subset N of the nautical links
$a \in M \subseteq A$	subset M of the terminal links
CC_i	handling fees on terminal i
CpK	cost per kilometer
D^n	total demand on destination n
E_0	elitist set
F_{max}	maximum performance
G	directed graph
K_m	the set of alternatives in hierarchical branch m
$P(m)$	marginal probability for selecting hierarchical branch/nest m
$P(k|m)$	conditional probability for selecting alternative k subject to hierarchical branch m
P_{mk}^{rs}	selection probability of path k of the hierarchical branch m connecting origin r and destination s
P_0	initial population
Y_a	terminals' capacity in TEUs/year
Y_a^0	existing performance of terminal α in TEUs/year
V_k	deterministic utility
TC_a	total cost of link α
Z	network's entropy term
a_{mk}^{rs}	inclusion coefficient of alternative route k in hierarchical branch/nest m for servicing origin–destination pair r–s
b_a	unit cost for increasing capacity at link a
c_a	use cost of link a
$d^{(k)}(x)$	distance of solution x from elitist set at iteration k
d^n	vector of decent direction at n iteration
l_a	length of link a
f_{mk}^{rs}	flow at path k of the hierarchical branch m connecting origin r destination s
m	hierarchical branch
q^{rs}	demand between origin r and destination s
x^n	decision variables vector at iteration n
x_i	link's i flow at i in TEUs/year
w_a	capacity addition in terminal α, in TEUs/year
θ	dispersion coefficient
λ	lagrange multiplier
λ_a	coefficient for transforming capacity additions to monetary units for link a
μ_m	nesting coefficient (distinguished for each nest m)
ω	terminal congestion curve coefficient

optimal capital utilization and economic efficiency and that are economic systems of scope. These characteristics – among others – distinguish freight transportation from other forms (e.g. urban systems, transit systems, etc.) and one element that signifies the difference is the sharp competition throughout the supply system.

In the current paper the case of a freight system design of unitized cargo under these circumstances is analyzed. In particular, the case of the optimal design of containerized freight system (or a significant part of it) by means of optimal investments planning under competition is aimed and how this assumption alters the problem of optimal design both conceptually as well as methodologically. For analyzing optimal investment strategies in a service system that is highly adaptive in operating changes, a unified demand–supply model is developed for capturing the 'market' reactions to investment plans. Market's reaction to operational services is modeled here by means of a multimodal and multi-activity network equilibrium model, able to handle spatial, modal and technological particularities. In order the paradigm of optimal design to be more lucrative, the application here is focusing on optimal strategic capacity investments design of competing container terminals. Container terminals are important parts of the integrated containerized market, while bottleneck effects are emerging, effecting on the competitiveness of their hinterland, the transport operators servicing the terminals and the regional freight service routes. At the same time, container terminals importance is highlighted by the competition that is typically developed among them either for prioritized service, pricing and other contracting-related issues.