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Container drayage modelling with graph theory-based road connectivity assessment for sustainable freight transportation in new development area

Abstract

Densely populated cities, suffered from land scarcity, are often encountered the need of exploring new development areas. This initiative in developed cities usually includes reconsolidating container depots and proposing multi-storey cargo centre as part of urban development roadmap. Changes on road network and connectivity between ports and container depots affect the efficiency of container drayage operations. A novel container drayage optimization model incorporating the road network and connectivity metrics is developed to minimise the total traveling distance, truck fuel cost, container rental cost and container movements among multiple consignees and shippers. The model is adopted in assessing the container logistics low between the ports and the Hung Shui Kiu New Development Area (HSKNDA) in Hong Kong, one of the most densely populated cities in the world. In assessing the impact of HSKNDA towards container drayage operations in the environment of congested urban area, the road logistics connectivity is evaluated with graph theory-based network metrics using ArcGIS. Road network files are analysed using ArcMap and the road connectivity are evaluated on its completeness, circuitry and complexity using road connectivity metrics and ArcMap. The road connectivity of the circumstances before and after HSKNDA are evaluated and the results revealed that the alpha, beta and gamma indexes changed slightly but the node number, link number and link length are decreased, benefiting container truck movements. The results have been adopted in optimising the container drayage problem in HSKNDA, the operating cost has been reduced in four simulated scenarios when compared to the results obtained by the traditional approach. The proposed approach combines the GIS and optimisation modelling to improve the effectiveness and reduce operating cost in container drayage process. It provides solution in restructuring the physical logistics network, enhancing liner operations efficiency, mitigating carbon emission, and enabling a higher quality of living in the city. It contributes in evaluating the road connectivity on the new development area and develop a novel container drayage model as a smart urban logistics for sustainable freight transportation.

Keywords Road connectivity, logistics, container drayage, transportation, empty repositioning

1. Introduction

Cosmopolitan cities are often encountered with land scarcity problems which result an increasing container movement in central business district (CBD). The land scarcity has pushed the government to explore new urban development area to relief the situation, for example the Hung Shui Kiu New Development Area (HSKNDA) in Hong Kong. The new development area (NDA) could seek to reconsolidate container depots and introduce new multi-storey cargo centres as part of the urban development roadmap. These centres serve as similar role of urban consolidation center (UCC) in the context of city logistics but located within the city centre. Introducing multi-storey cargo centre can increase land use and, at the same time, maintain logistics connectivity and competitiveness with neighbouring cities. Most importantly, the consolidated cargo centre in NDA can reduce the number of freight vehicles affecting the residential areas. The Hung Shui Kiu (HSK) in Hong Kong, an area located in the northwest of the city, is proposed to be one of the potential areas to provide logistics back-up yard services. Since the Planning and Development Study on North West New Territories (NWNT) in 2003, HSK has been identified as a suitable NDA to cater to the long-term multi-purpose development needs in Hong Kong with the goal of sustaining Hong Kong's competitiveness as a global transportation port (HKSARG, 2016b). This strategic initiative is continued to be an important component in the territorial development strategy for "Hong Kong 2030+", a comprehensive strategic study represents the Government's vision, policy and strategy for the territorial development of Hong Kong beyond 2030 (HKSARG, 2016a; 2016b).

HSKNDA is situated in a geographically favorable location in the NWNT (Figure 1a). HSKNDA will be connecting to the neighboring cities in the Pearl River Delta (PRD) region through strategic highways and railways which is served as a "Regional Economic and Civic Hub" with the aim of helping promote economic activities including to provide about 150,000 new employment opportunities, which build upon interaction with the Mainland (Figure 1b) (HKSARG, 2013; 2016b; 2016c). The planning for NDAs in HSK and the North East New Territories (NENT) was announced in the Policy Address by the Chief Executive of Hong Kong. Currently, the land is mainly occupied by open storage / port back-up uses (27%) and village developments (21%), while the total planning area of Logistics and Technology Quarter is about 72 ha (62 ha for Logistics industry and 10 ha for Information Technology & Telecommunication industries) (HKSARG, 2016b; 2016c).

According to HKSARG (2016a; 2016b), there are two main advantages of HSKNDA, namely (1) the potential site is accessible to cross boundary highway network via Shenzhen Bay Bridge and Guangshen Yanjiang Expressway; and (2) the use of existing land could be cost effective compared to potential reclamation sites. By adhering to the Government's sustainable planning principles, the HSKNDA will include six Development Character Areas (DCAs) (Figure 2a). The DCAs aim at increasing housing supply and supporting NWNT economy through providing new residential uses, commercial uses and industrial uses floor areas and by establishing a logistics, enterprise and technology quarter, i.e. DCA 3 (Figure 2b) (HKSARG, 2013; 2016b; 2016c). The latter includes building various modern logistics facilities that involves reconsolidation of existing container depots and establishment of a multi-storey cargo centre. Aiming at complementing the development of Hong Kong as a regional distribution centre and logistics hub, HSKNDA will support Hong Kong-China multimodal transport connectivity and inbound/outbound container trucks movement in depots (HKSARG, 2016c). With the changes on the HSKNDA affecting the development of shipping and logistics trucking operations in the urban area, the impacts towards the road logistics connectivity is evaluated with graph theory-based network metrics using geographic information system (GIS). The circular area with selected depots, terminals and HSKNDA is evaluated with a set of road connectivity index, followed by the development of a container drayage model for the HSKNDA. The proposed smart urban logistics approach combines the GIS technology and operations capabilities in achieving the improvement and cost reduction in container drayage of a liner company (Stölzle et al., 2017; Patterson et al., 2003). It assists ship liners in planning the carried haulage and improves the container utilisation along the along the shipment lifecycle.

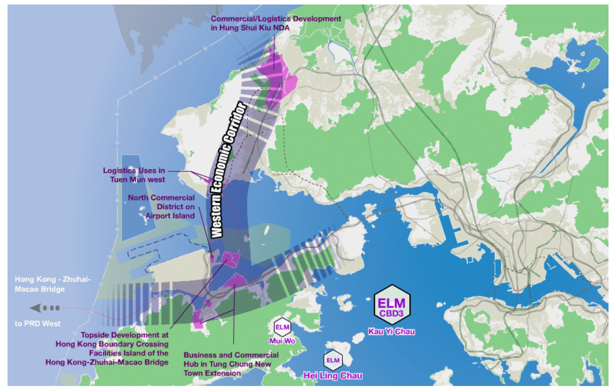

Figure 1a. HSKNDA: Its Strategic Position in The PRD Region

Figure 1b. HSKNDA: Neighboring Towns Integration Via the Proposed Infrastructure

Source: Courtesy of the HKSAR Government (HKSARG, 2013)

Figure 2a: Development Character Areas (DCAs) of HSKNDA

Figure 2b: DCA 3 – Logistics and Technology Quarter

Source: Courtesy of the HKSAR Government (HKSARG, 2013)

In the forthcoming sections, a literature review about the road connectivity, GIS on road connectivity for logistics flow, and container drayage is discussed in Section 2. The development of a container drayage model for urban logistics is presented in Section 3. Section 4 describes the container drayage model with road network and connectivity assessment in urban new development area. The analysis demonstrates the potential of using graph theory-based network metrics and shipper pool strategy to improve transportation network performance and resolve container drayage problems respectively.

Lastly, conclusion and future development is provided from the findings of the analysis in Section 5.

2. Literature Review

Having the road connectivity for container drayage logistics flow being studied, the literature on the road connectivity for logistics flow is reviewed, followed by the critical analysis of the literature about GIS on road connectivity assessment for logistics operations. Latest development of container drayage studies is also reviewed.

As the road connectivity for logistics flow is critical for a city, in particular the cities who play the role of both an international and regional transport hub. For city like Hong Kong, it has an extensive transport network connecting to the world and the region through the container terminals. The development and competitiveness of Hong Kong's port and logistics lied on the advancement and efficiency of their accessibility and connectivity. It is increasingly important for Hong Kong to implement a highly efficient inland transportation system and seaport management (Wang and Slack, 2000). Jiang et al. (2015) and Patarasuk (2015) urged that enhancing the infrastructures and improving transportation system, such as increasing the land cover of road between urban and rural area, can enable policy makers providing better service on the place's connectivity. Connectivity can be perceptibly interpreted as the connection between one place or zone with another, while logistics connection of these places or zones can be mathematically interpreted and measured as the interconnection of nodes in a transportation network (Kansky, 1963). With Graph Theory, a branch of mathematics concerned with networks of points connected by lines, the transportation network performance in a specific area can be measured and analyzed (Kansky, 1963; Morlok, 1967; Tresidder, 2005), The research on logistics connectivity, especially on maritime connectivity has been flourishing in recent years due to the globalization and rapid increase of economic development. Among various maritime logistics research topics, such as shipping scheduling (Agarwal and Ergun, 2008), empty container repositioning (Dong and Song, 2009; Wong et al., 2015) and network design (Zhang and Facanha, 2014; Lam and Yap, 2011), port connectivity is one of the most important research topics particularly the research studies concern the influential factors that affect the efficiency of port and control transport costs (Wang and Slack, 2000; Wilmsmeier et al., 2006; Zarzoso and Hoffmann, 2007).

In view of the rapid development on port connectivity management, methods such as Maximum Transportation Capacity Model (MTCM) and Minimum Transportation Time Model (MTTM) are developed for optimizing maritime trading by measuring how an individual port connect with other ports without transshipment services through enhancing port efficiency and enlarging the coverage of transportation area (Jiang et al., 2015). Previous studies on logistics connectivity not only laid heavy emphasis on marine connectivity but also developed research opportunities in the area of intermodal transportation between sea and land. Finke and Kotzab (2017) carried out an analysis on the container repositioning among ports and depots based on the road connectivity in Germany. Patarasuk (2013) evaluated how road network development contributes to the region in the areas of socioeconomics by measuring the level of road connectivity. Thus, road connectivity for logistics, in particular container drayage and repositioning between ports and depots, has been an important issue as it affects not only shipping line operations but also the global container supply and demand (Bhattacharya et al., 2014).

The measurement of road network connectivity is comparatively complex than the measurement of port connectivity and air network connectivity as the component variables of road network are more complex than those of air network and maritime logistics (Paleari et al., 2010; Lam and Yap, 2011; Tovar et al., 2015; Jiang et al., 2015). For example, more specific road data such as highway, lane, dead-end roads, height, road and speed restriction etc. are required to measure road connectivity, while measuring the connectivity of global shipping network requires less component variables, such as the rating of the number of vessels, container-carrying capacity; maximized vessel size, number of services and number of companies that are used in the Liner Shipping Connectivity Index (LSCI) (Hoffmann, 2005; Patarasuk, 2013). In addition to alpha, beta and gamma indexes (Patarasuk, 2015), Tresidder (2005) suggested other five indexes to determine road connectivity, including Intersection Density (ID), Street Density (SD), Connectivity Node Ration (CNR), Alpha Index (α), Link-Node Ratio (β) and Gamma Index (γ) for measuring circuitry, connectivity, and complexity of a network. With reference to the method of measurement in Tresidder (2005), Sadeghi-Niaraki et al. (2011), Duran-Fernandez and Geogina Santos (2014), and Paratarasuk (2015), this study investigates the potential impact of HSKNDA on the transportation network performance in terms of road connectivity. Based on the six-index approach (Patarasuk, 2005; Tresidder, 2005), the number of links and nodes in a given network are identified in order to access the existing effectiveness and limitation of HSK, which followed by a discussion on the new development of HSK.

The burgeoning importance of modern logistics and supply chain management brings the development and application of GIS to a new level. GIS is commonly applicable for geographical, healthcare and architectural purposes. The technology of GIS has been extended to logistics and transport, for example. vehicle routing problem (Niu et al., 2019; Bruniecki et al., 2016), road networking (Duran-Fernande and Santos, 2014) and land coverage (Patarasuk, 2013). Forster and Berglund (2001) added that GIS technology can reduce transportation accidents that are caused by severe weather conditions. The GIS technology undoubtedly provided valuable information and insights for advanced logistics decision making (Özceylan et al., 2016; Sarkar, 2007; Salim, et al., 2002). It is particularly useful to logistics applications in transportation network and land coverage in larger and more complex geographical areas (Keenan, 2008; Tresidder, 2005; Niemier and Beard, 1993). Table 1 summarized the studies on the application of GIS software in logistics management. Furthermore, combing GIS technology with operations research (OR) methodologies can extend the application of GIS to resolve the measurement issues of logistics connectivity (Keeenan, 2005; Tresidder, 2005; Dill, 2004). Table 2 highlights the studies of adopting GIS technology with OR modeling methods in various logistics applications, which form the theoretical basis of the research on HSKNDA.

Publications	GIS Usage in Logistics	GIS Software Used
Zahari et al. (2018); Akella (2005); Li (2005)	Site selection	MapInfo professional, MapInfo, ArcGIS
Camm (1997)	Product sourcing and distribution	MapBasic, MapInfo
Das et al. (2019); Keenan (2008); Tarantilis and Kiranoudis (2002)	Vehicle routing	ArcView, One JUMP
Jamal et al. (2019); Niemeier (1993)	Land coverage	ArcMap, ArcGIS
Lo and Yeung (2002); McKibben and Davis (2002)	Asset management	ArcView

Table 1. Studies of GIS Usage in Logistics Management

Authors	Topics	Description	Outcome
Berglund (2001)	Test of a GIS model	The author used network data from Sweden and Norway to evaluate a transportation model under a barrier effect.	GIS is made to serve general purpose but not realistic to be a perfect tool for specialized needs, while GIS can export the data that can be used in external programme.
Duran-Fernandez and Santos (2014)	Time-minimization	The authors have developed a GIS model based on the National Road Network in Mexican in order to figure out the shortest path between two locations.	The result shows that the GIS model can identify optimal route with a small bias, which can be fixed by adjusting estimated travel time.
Forster (2000)	The role of GIS in logistics application	The study determined chances for GIS to add comparative advantage for the company on logistics decision.	GIS was limited to support high-level logistics decision-making.
Keenan (2008)	Vehicle routing with GIS	The author argued that traditional techniques are not enough to extend the range of vehicle routing problem.	The study suggested that GIS technology provides a more accurate modeling of real-world vehicle routing problems.
Niemeier and Beard (1993)	Comparison between GIS and Non-GIS transportation planning	The author hypothesized a GIS model that would be beneficial to transportation planning and land-use. The model attempts to analyze the effectiveness of GIS through comparison.	The GIS model produced smaller estimates of the individual growth areas and helped to identify weaknesses in the manual overlay process.
Patarasuk (2013)	Network development	The study is based on the case of Thailand road network and it figures out the relationship between road network, connectivity and land over change.	Owing to the geographical features and governmental planning, the road connectivity does not improve significantly.
Tresidder (2005)	GIS and connectivity	The study introduced the measurement of street network connectivity by using GIS.	The author introduced a step by step approach to measure connectivity, based on the definition of the phrases, e.g. link, node, circuit, etc.

Table 2. Summary of Studies on Use of GIS with OR in Logistics Applications

Plewes (1997) outlined a high-level process of GIS applications from obtaining research data from the GIS measurement component, statistical computation of modeling tools to digitization of pictures or maps and associated operations. As a result, an estimated map can be produced and visualized by GIS, with the advantage of minimizing geometric error by the appropriate geographic scale (Rikalović et al., 2018; Niemeier and Beard, 1993). The application of GIS can go beyond information retrieval and visualization as the modeling tools in GIS can provide the means to apply the spatial data in solving logistics problems. With the HSKNDA being evaluated for road connectivity for container logistics flow in this paper, the ArcMap GIS is used in visualizing and measuring the network connectivity in the designated areas.

Container drayage operation is an important part of maritime supply chain, particularly in intermodal freight transportation, as it often accounts for a significant portion of the overall transportation cost (Zhang and Zhu, 2018; Nishimura et al., 2018; Ng and Talley, 2017). Harrison et al. (2007) have raised the port drayage issues with the increasing container volumes to be picked up from or delivery to a seaport within the urban area. Ship liners and logistics service providers in various countries seek solutions in enhancing the container transportation by integrating different pickup and delivery operations in a single route (Vidović et al., 2012). Before such transportation operations can be optimized by simulation programmes, operations researchers and analysts solve truck scheduling and routing problem in container drayage operation with the use of mathematical modelling and algorithms (Zhang et al., 2010; Cheung et al., 2008).

Recent studies on container drayage has been continuously increasing and incorporated various problem dimensions (Zhang and Zhang, 2017; Vidović et al., 2017; Zhang and Wang, 2014; Mittal et al., 2013; Cheung et al., 2008). The problem ranges from traditional pick-up and delivery problems (Vidović et al., 2011; Parragh et al., 2008; Bontekoning et al., 2004) to other additional considerations, for example, real-time re-assignment (Escudero et al., 2013), flexible orders (Zhang et al., 2014), constrained with limited resources (Zhang et al., 2011). Zhang et al. (2011) developed a reactive tabu search (RTS) in solving the container drayage problem in which the problem is described as a multiple travelling salesman problem with time windows (m-TSPTW). Zhang et al. (2014) later then further formulated the container drayage problem as a mixed-integer nonlinear programming model based on a determined-activities-on-vertex (DAOV) graph. Song et al. (2017) also based on DAOV to solve container drayage problem under a separation mode in which a container can be separated from the truck during loading and unloading operations. This paper considered container drayage problem with shipper pool and changes on multiple ports in a new development area. The model developed for the container drayage has incorporated the road connectivity index and assessment into the optimisation function and constraints. The model is then applied into the HSKNDA to enhance the logistics flow.

3. Container drayage model with road connectivity index

The government urban logistics initiative on HSKNDA will include the consideration of introducing multi-storey cargo consolidation centre and rearranging the container depots in the hinterland of Hong Kong. The cargo consolidation centre serves similar role of urban consolidation centre (UCC) in city logistics but located within the city of Hong Kong supporting as an automated storage and retrieval system (ASRS) for both empty and laden containers. The movement of full and empty containers among a number of terminals, depots, customers and the cargo consolidation centre exhibits the container drayage problem (Song et al., 2017; Nishimra et al., 2017; Zhang et al., 2015). Container drayage is the transport of various types of containers over a short distance in the shipping and logistics industry, often refer to the movement among multiple facilities, such as terminals, depots, warehouses, and customer premises. The objective in solving container drayage problems is mainly minimizing the total cost of all the operations carried out by a company in the hinterland of a terminal (Escudero et al., 2013). With Hong Kong handling 19,813 thousand twenty-footer equivalent units (TEUs) in 2016 (Lloyd's List, 2017), thousands of containers are moving from terminals to warehouses, depots and customer premises each day. Ship liners needs to tackle not only laden pickup and empty return of consignees from multiple terminals and depots as well as empty pickup and laden return from multiple depots to terminals each day. Changes in logistics and transport infrastructure in HSKNDA will change the road connectivity and thus affect the logistics flow of containers. Upon reviewing the road connectivity through the evaluation from graph theory-based network metrics, the container drayage problem and the use of shipper pool strategy is evaluated in this paper.

With ship liners handles the operations on the laden pickup and empty return of consignee as well as the empty pickup and laden return of shippers in multiple terminals and depots every day, whether the time and costs require to move the empty containers could be reduced by delivering the empty container from the consignee to the nearby shippers in the right time and the same type of container size type, which is regarded as shippers' container pool. The model, together with the change from multiple depots to single multi-storey container consolidation centre, is set up to reduce the total time and cost involved, including total travelling distance, total travelling time, truck fuel cost, and container rental cost. Figure 3 shows the container drayage problem with shipper pool and changes on multiple depots in HSKNDA in different container size type. Traditionally, consignee receives an arrival notice from carrier for laden container pickup at a terminal. After cargo unstuffing in consignee's warehouse, the empty container is delivered to designated depot advised by liner for storage if it is a carrier haulage. Shipper, upon the advised from ship liner, will pick up the container in the depot for another outbound shipment. After stuffing the cargo, shipper will truck the container to the terminal before the container yard cut-off time for cargo loaded onboard to a planned vessel. The terminals in Hong Kong are mainly in Kwai Tsing area and most of the depots are located in Yuen Long and Tuen Mun, the northwest region in New Territories. The longer the distance between terminals and depots, unnecessary time and cost might be incurred to shippers and carriers.

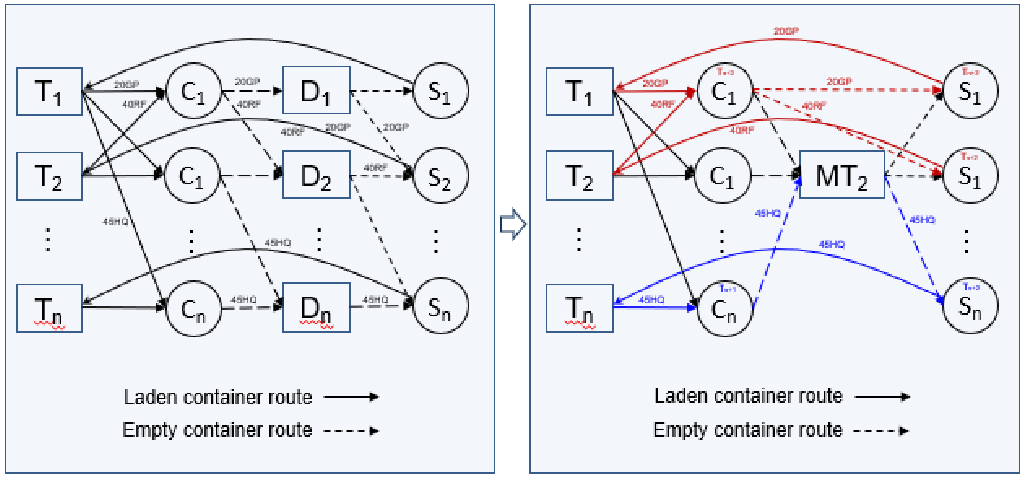

Figure 3. Container drayage problem with shipper pool and changes on multiple depots

3.1 Assumptions and notations

The fundamental assumptions used in this literature is that all containers are measured in Twenty-footer Equivalent Unit (TEU), with one 20’ container as 1 TEU while 1 40GP container as two TEUs. A high-cube container will be considered as having an additional 0.3 TEU.

Assumption 1. The empty container returned to the depot or shipper could be reused instead of damaged and need to be repaired or disposed. If cleaning is needed for the container, the time is assumed minimal. Garmentainer is not involved, thus there is no bars set up time required.

Assumption 2. No structural changes on the road network. The truckers operate with regular schedule, the trucks travel at economic speed, and it is assumed that no sudden breakdown of the vehicles during operations.

Assumption 3. Shippers picking up empty containers at depots are executed as planned. Depots have sufficient supply of containers. There is no requirement of container moving between depots, that is, assume no depot-to-depot container movements.

Assumption 4. There is no service disruption, for example, terminal congestion, port strike, truck collision, etc. The developed model assists the truck haulage planning on meeting various shippers demand. Contingency and recovery plan is required beyond the optimisation container drayage plan, for example, phase-in schedule of new containers, cancel booking order, further leasing in containers, etc.

Notations:

To describe the system, the following notations are introduced.

Container movement input data

Exp	set of shippers with export containers (demand)
Imp	set of consignees with import containers (supply)
D	the number of depots which is placed empty containers (d $\in D$)

Cost input data

C^f	the fuel cost of trucking a container per mile
C^r	the rental cost per container
C_d^I	the inventory holding cost per container at depot *d*
F^l	the distance factor which determines the focus of customer on either time or distance
F^t	the time factor which determines the focus of customer on either time or distance
L	the traveling distance of container movement
T	the traveling time of container movement

Container quantity variables

x_{id}	the number of carrier haulage empty containers returned from consignee *i* to depot *d*
x_{dj}	the number of carrier haulage empty containers trucked from depot *d t*o shipper *j*
x_{ij}	the number of carrier haulage empty containers trucked from consignee *i* to shipper *j*
x_r	the number of empty containers required to be leased from container leasing companies

Travelling distance and time variables

l_{ij}	the traveling distance from consignee (import) i to shipper (export) *j* ($i \in Imp, j \in Exp = 1 ... N$)
l_{id}	the traveling distance from consignee *Imp* to depot *d* ($i \in Imp, d = 1 ... D$)
l_{dj}	the traveling distance from depot *d* to shipper *j* ($j \in Exp,\ d = 1 ... D$)
l^{short}	the shortest traveling path of consignee-shipper matching set *k*
t_{ij}	the traveling time from consignee *i* to shipper *j* ($i \in Imp, j \in Exp = 1 ... N$)
t_{id}	the traveling time from consignee *i* to depot *d* ($t \in T, i \in Imp,\ d = 1 ... D$)
t_{dj}	the traveling time from depot *d* to export side *j* ($j \in Exp,\ d = 1 ... D$)
t^{short}	the shortest traveling time of consignee-shipper matching set *k*

Empty container inventory variables (at depots)

K_d	the storage of empty container at the depot *d*
V_d	the number of empty containers with extra storage charges at depot *d*
H_d	net stock of empty container of depot at the beginning
N_d	net stock of empty container of depot at the end
S_j	the supply of carrier's empty container from consignee *i*
D_i	the demand of carrier's empty container form shipper *j*
Z	the objective function value

3.2 Objective function and constraints

The container drayage decision support model is evaluated. The objective of the model is to minimise the weighted sum of travelling distance, travelling time truck fuel cost, container rental cost, and opportunity cost.

Objective function:

$$Z(x_{id}, x_{dj}, x_{ij}, x_r) = \sum_{d} \sum_{i \in Imp} \sum_{j \in Exp} \left[(x_{id} + x_{ij} + x_{dj}) \times L\right] F^{l} + \sum_{d} \sum_{i \in Imp} \sum_{j \in Exp} \left[(x_{id} + x_{ij} + x_{dj}) \times T\right] F^{t} + \sum_{d} \sum_{i \in Imp} \sum_{j \in Exp} \left[(x_{id} \times l_{id} + x_{ij} \times l_{dj} + x_{dj} \times l_{ij})\right] C^{f} + x_r\, C^{r} + C_d^{I} V_d \tag{1}$$

Constraints:

(1) Depot balancing and leasing constraint. Incoming empty containers from consignees can be supplied by the container supply to shippers and lease-in containers. Total number of leasing containers can supply empty container demands when the total demand exceeds the total number of onhand inventory, with a rental cost C^r for each of the lease-in container. Here shortage is not allowed.

$$\sum_{d} \left(\sum_{i} x_{id} + K_d \right) + \mathrm{x}_r \geq \sum_{d} \left(\sum_{j} x_{dj} \right) \tag{2}$$

(2) Supply constraint. Sum of container leasing, depot inventory, and depot empty return containers is equal to the container supply. For each of the consignee, the supply of empty containers consists of depot empty return containers and the containers to shippers.

$$S_{imp} = \sum_{i} S_i$$

$$S_i = \sum_{d} x_{id} + \sum_{j} x_{ij} \tag{3}$$

(3) Demand constraint. Container demand is equal to the demand of empty container pickup from shippers. For each of the shippers, the demand of empty containers is satisfied by the empty containers from depots and from consignees directly.

$$D_{exp} = \sum_{j} D_j$$

$$D_j = \sum_{d} x_{dj} + \sum_{i} x_{ij} \tag{4}$$

(4) Depot storage constraint. Inventory storage cost of empty containers at depot *d* depends on the number of containers at depot *d*, which is the numbers of empty containers from consignees plus the shortage of empty containers at the depot minus the number of empty containers supplied to shippers.

$$V_d = \left(\sum_i x_{id} + K_d\right) - \sum_j x_{dj} \tag{5}$$

(5) Distance constraint. The distance determines the shortest path of container movement on whether the consignee should deliver the empty container directly to next assigned shipper or return to the nearest depot.

$$l_{ij}^{short} = min\{l_{ij} , l_{id} + l_{dj}\} \tag{6}$$

(6) Total distance constraint. The constraint determines the total distance as the total shortest path of the movement of all the containers travelling from consignee to shipper.

$$L = \sum_i \sum_{\mathrm{j}} l_{ij}^{short} \tag{7}$$

(7) Empty return time constraint. The time required to return the empty container. The constraint determines the shortest travelling time of container movement on whether the consignee should return the empty container to the assigned shipper or return the empty container to the nearest depot.

$$t_{ij}^{short} = min\{t_{ij} , t_{id} + t_{dj}\} \tag{8}$$

(8) Total container movement time. The constraint determines the total time of container movement directly from consignee to assigned shipper with a shipper pool approach. The time affected incorporate the correction factors related to the road connectivity condition using the alpha index (α), link-node ratio (β), and gamma index (γ).

$$T = \sum_i \sum_j t_{ij}^{short} \times \mathrm{U}(\alpha, \beta, \gamma) \tag{9}$$

(9) Non-negativity constraints.

$$F^l + F^t \leq 1 \tag{10}$$

$$x_{id} \geq 0 \tag{11}$$

$$x_{dj} \geq 0 \tag{12}$$

$$x_{ij} \geq 0 \tag{13}$$
$$x_r \geq 0$$

4. Container drayage model with Graph Theory-based road connectivity on HSKNDA

The total container movement time in the city is affected by the road network and connectivity. With this, road network data collected from the Transport Department of Hong Kong was used and imported into ArcMap GIS with the analysed area shown in Figure 4. The data is then applied to indexes equations in characterizing road performance of circular between the major ports and depots in Hong Kong. The mathematical model is formulated by road connectivity problems and inland container movement with defined terminals. In the following section, the method of using a graph theory-based approach to measure the level of connectivity for comparing the before and after the development of HSKNDA is presented, followed by the results and analysis. Six road network files were included: Centerline, Turn, Intersection, Nonstop Restriction (NSR), Run-in & Run-out and Road route (See Table 3). Applying road network data into indexes equations based on Graph Theory, road performance of circular between major ports and depots can be characterized with the measurement focusing on completeness, circuitry and complexity. Below are the six different connectivity measures with network indexes employed in this study (Tovar et al., 2015; Tresidder, 2005; Patarasuk 2013):

- Intersection Density (*ID*)
- Street Density (*SD*)
- Connected Node Ratio (*CNR*)
- Alpha Index (α)
- Link-Node Ratio (β)
- Gamma Index (γ)

Such that the network indexes are calculated as follows:

$$ID = R/A \tag{14}$$
$$SD = l/A \tag{15}$$
$$CNR = R/N \tag{16}$$
$$\alpha = (L - N + 1) / 2\,(N - 5) \tag{17}$$
$$\beta = L/N \tag{18}$$
$$\gamma = L/\,3(N\text{-}2) \tag{19}$$

where A = the total study area; l = the length of links; L = the number of edges / actual distance (Links); N = the number of nodes (Vertexes); and R = the number of real nodes.

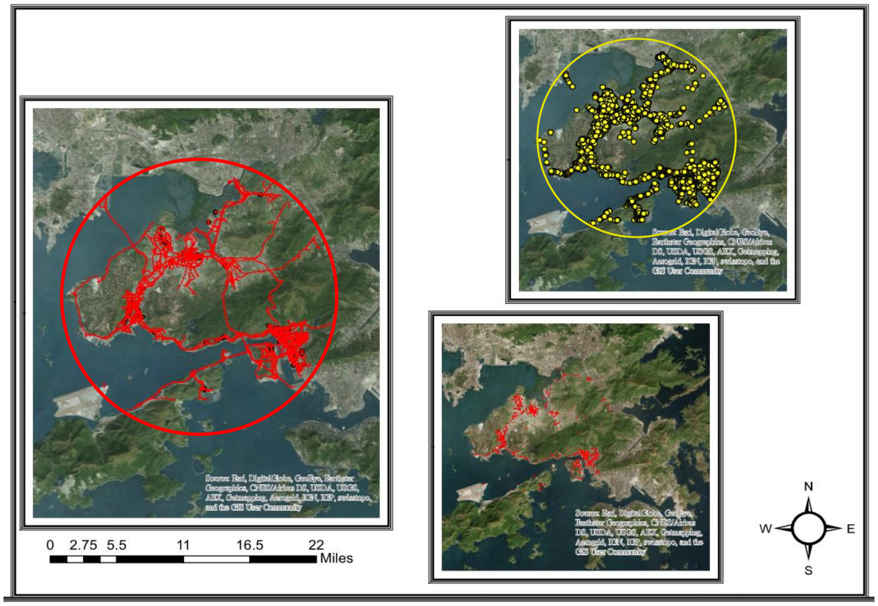

Figure 4. The evaluated area on the road connectivity of HSKNDA

Item Name	Description
Centerline	Line feature of road centerline
Turn	Turn feature representing restricted turn movement among road center lines
Intersection	Point feature on intersection of two centerlines
Run-in and Run-out	Run-in and Run-out point feature of run-in, run-out, or run-in/run-out of off-street parking sites
No stopping restriction (NSR)	Line feature representing extent of no stopping restriction along roads
Road Route	Line feature as underlying layer for storing linear referencing events
Speed Limit	Linear referencing line event representing extent of road with specified speed limit
Vehicle restriction	Linear referencing point event representing location of directional sign or traffic sign indicating road access with permit or authorization

Table 3 Summary of IRNP RdNet Entities from Transport Department

Intersection Density (ID) captures the intersection density of an area, measured by a ratio involving the number of intersections in the street/road network, i.e. it is the number of intersections per unit of area. A higher number of ID would indicate more intersections, and presumably, higher connectivity. *Street Density (SD)* is measured by street intersections and urban blocks per unit area of urban land, which is the number of linear miles of street per square mile of land. A higher number of SD would indicate more streets, and presumably, higher connectivity. *Connected Node Ratio (CNR)* is the number of street intersections divided by the number of intersections plus cul-de-sacs. The maximum value of CNR is 1.0. Higher numbers indicate that there are relatively few cul-de sacs and dead ends, and presumably a higher level of connectivity. *Alpha Index (α)* is the ratio of the number of actual circuits to the maximum number of circuits. This measure comes from geography, where the value ranges from 0 to 1. *Link-Node Ratio, i.e. Beta Index (β)* is the number of links divided by the number of nodes within a study area. Theoretically, a perfect grid has a ratio of 2.5. However, this measurement does not reflect the length of the link in any way. Lastly, *Gamma Index (γ)* is the ratio of the number of links in the network to the maximum possible number of links between nodes. Like Alpha Index, this measure comes from geography where its values range from 0 to 1.

The result of road connectivity analysis based on network indexes in the aspects of complexity, completeness and road coverage are analysed by comparing before and after the development of HSKNDA. It is based on a recommended plan of road network to enhance logistics transportation and 40ft container truck-road coverage between HSK, Kwai Chung and River Trade Terminal. The preference of container movement in the study area using optimal simulation model is evaluated and compared. The findings help management and decision-makers realize the feasibility of the HSKNDA project and whether the project can address the major concern of the Hong Kong logistics industry. Table 4a presents four types of road network data that reports the number of nodes, links and length of road. These include the data obtained before and after the development of New Territories West (NTW) Area (column 1 and column 2) and the data obtained before and after the development of HSKNDA (column 3 and column 4). We then access the performance of these road connections between Hong Kong's major ports and depots. Table 4b shows the results of the six network indexes, i.e. Intersection Density (*ID*), Street Density (*SD*), Connected Node Ratio (*CNR*), Alpha Index (α), Beta Index (β) and Gamma Index (γ). Based on the results, the road connectivity in NTW area had appropriately 16% circuitry (α from 0.1596 to 0.1569), medium complexity (β from 1.3188 to 1.3134) and 44% connectivity (γ from 0.4398 to 0.4380). As shown in Table 4b, the change of these indexes on assessing before and after the development of HSKNDA is insignificant even link number, link length and total nodes have declined slightly. Though the slight changes are interpreted as limited impact of HSKNDA towards the road network performance in Hong Kong, the decrease of node number, link number and link length actually benefits container truck movements.

Road Network Data	New Territories West Area		HSK New Development Area	
	Measurements before HSKNDA	Measurements after HSKNDA	Measurements before HSKNDA	Measurements after HSKNDA
Real Nodes (*R*)	5,240	5,219	69	48
Dangle Nodes (*D*)	741	754	29	42
Total Nodes (*N*)	5,981	5,973	98	90
Link Number (*L*)	7,888	7,845	138	95
Link Length (*l*) (km)	1,053	1,061	13.3968	20.9162

Table 4a Summary of Road Network Data

Connectivity Indexes	New Territories West Area			HSK New Development Area		
	Values before HSKNDA	Values after HSKNDA	Impact on HSKNA Change	Values before HSKNDA	Values after HSKNDA	Impact on HSKNA change
Intersection Density	8.6450	8.6104	-0.40%	9.6639	6.7227	-30.4%
Street Density	1.7378	1.7502	-0.71%	1.8763	2.9294	+56.1%
Connected Node Ratio	0.8761	0.8738	-0.26%	0.7041	0.5333	-24.2%
Beta (Link-Node) Ratio	1.3188	1.3134	-0.41%	1.4082	1.0556	-25.0%
Gamma Index	0.4398	0.4380	-0.41%	0.4946	0.3598	-27.3%
Alpha Index	0.1596	0.1569	-1.69%	0.2147	0.0343	-84.0%

Table 4b Result of Connectivity Analysis Using 6 Indexes

Table 4. Road network data and the connectivity analysis results on HSKNDA

The results on analysing the road connectivity in the HSKNDA indicating that there is a decline on *ID* (from *ID* = 8.6450 to 8.6104) as real node and intersection are decreased in the same area (See Table 4b). Also, roads are less connected due to decrease of connection between links. Furthermore, the *SD* increased significantly by 56.1% implies the improvement on connectivity in the same area due to more options for truck driver to reach the destination. For the measure of *CNR*, the adverse change (-24.2%) indicates that a lower connectivity occurs after the development of HSKNDA. According to the Government, as a large proportion of HSKNDA is planned for constructing logistics infrastructure as well as residential and commercial buildings, the extension of road link and length of the study area could be affected the increase of street block. Hence, the road coverage may be reduced after the HSKNDA effects. Overall, the results show that there is an improvement on the street density index regardless of the decrease of network connectivity as shown in other indicators. The changes of connectivity are due to the incompleteness of current HSK area where new development will take place afterward. According to Patarasuk (2013), the connectivity could improve significantly when new roads are built over the current road infrastructure.

With the assessment of impact of the development of HSKNDA towards the road logistics connectivity, the evaluation of impact of HSKNDA towards the container drayage operations is carried out and an optimisation simulation is conducted to enhance the effectiveness of container drayage operations in a ship liner company. The operations covered 15 depots located in New Territories ($d_1 - d_{15}$) and two container terminals, namely Kwai Chung Terminal, River Trade Terminal, and the proposed multi-storey container consolidation centre in HSK ($d_{16} - d_{18}$). The fuel cost of HKD7 per km is used. Container storage rental and storage cost on each of the depots are collected, e.g. Hop Lik Container Service has published the container storage cost at HKD180 per day. Container rental cost is set at HKD140 per day. The average crane charge is HKD100 per move. The maximum container storage capacity of the depot in each of the two terminals and HSK consolidation centre is assumed to be 3,000 units on average while the maximum container storage capacity in each of the depot in the New Territories is assumed to be 600 units. The initial inventories in each of the two terminals and UCC in HSK are assumed to be 100 units and initial inventories in each of the depot are 20 units.

With reference to the road connectivity assessed and locations of depots and terminals, the developed container drayage model is simulated in a solver analytics programme to enhance the current consignee empty return and shipper laden pickup container drayage operations. Four scenarios analysis are carried out, namely (1) Scenarios 1: balance situation, i.e. a balance of empty container demand and supply with both 4,800 TEU; (2) Scenario 2: deficit situation, i.e. demand exceed supply (6,400 TEU vs 4,800 TEU). Lease-in containers from leasing companies will be part of the supply sources to cover the gap; (3) Scenario 3: surplus situation, i.e. supply exceed demand (7,000 TEU vs 6,400 TEU). The exceeded containers will be stored in the depots and terminals, and (4) Scenario 4: UCC situation, i.e. a balance situation of empty container demand and supply of 4,200 TEU with UCC developed at HSK. The simulated results are shown in Table 5. The improvements in fuel cost, distance travelled, and time used in the four scenarios are tabled. Upon the shipper pool approach with containers matching between multiple consignees and shippers in consideration of the empty container return and pickup schedule and container size type, the fuel costs, travelled time, and container storage costs in the depots will be reduced. The changes in the road connectivity with the UCC development in HSK is simulated in Scenario 4. The model illustrates a more effective improvement in the scenario of deficit situation compared to other scenarios. The model also assists a better container drayage arrangement with UCC in HSK, with fuel consumption reduced. This, in return, facilitates a lower carbon emitted in the new development area, enabling a smarter and higher quality of living in the city.

Scenario	**Cost, distance and time**	**Original**	**Optimised**	**Percentage Improvement**
Scenario 1	Fuel Cost (HKD/km)	1,007,300	515,620	48.81
	Distance (km)	143,900	73,660	48.81
	Time (min)	151,750	70,785	53.35
Scenario 2	Fuel Cost (HKD/km)	839,160	353,609	57.86
	Distance (km)	119,880	50,515	57.86
	Time (min)	132,860	48,369	63.59
Scenario 3	Fuel Cost (HKD/km)	1,273,944	712,160	44.10
	Distance (km)	181,992	101,737	44.10
	Time (min)	196,700	97,848	50.26
Scenario 4	Fuel Cost (HKD/km)	675,174	443,461	34.32
	Distance (km)	96,453	63,351	34.32
	Time (min)	107,315	60,684	43.45

Table 5. Container drayage simulated results

5. Conclusion

The reconsolidation of the container depots and consideration of developing multi-storey cargo centre in the HSKNDA will change the urban logistics development in a city, like Hong Kong. Instead of multiple depots scattered in the New Territories, a UCC-like ASRS systems is replacing the depots and affects the road network and logistics flow of the empty container return and pickup operations. Any improvement in this operation will certainly assist ship liners in reducing the processing the consignee empty container return and shipper empty pickup operations and increase the container utilisation. In assessing the potential of HSKNDA for logistics use and its impact towards the environment of congested urban area in Hong Kong, the road logistics connectivity is evaluated with graph theory-based network metrics. The road network data is obtained from the Transport Department and the road connectivity is visualised and evaluated with ArcGIS.

Comparing the road connectivity of the circumstances before and after HSKNDA, the results showed that the alpha, beta and gamma indexes changed slightly but the node number, link number and link length are decreased, benefiting container truck movements. The container drayage model aims to minimise the total travelling distance and time, truck fuel costs, container rental costs and inventory costs, covering the inbound laden pickup, inbound empty return, outbound empty pickup, outbound laden return container movements, and emission impact to nearby residents. A novel shipper pool model is proposed for the drayage problem to minimize travelling opportunity costs and system operating costs. The proposed approach has been applied to four scenarios and compared with the traditional drayage approach. The results showed that the operating cost obtained by shipper pool approach have been reduced significantly for the four simulated scenarios compared to the results obtained by the traditional approach. The proposed smart urban logistics approach combines the GIS technology and operations capabilities in achieving the improvement and cost reduction in container drayage of a liner company. It assists ship liners in planning the carried haulage and improves the container utilisation along the lifecycle of shipments and containers in the company. The model also reduced the road congestion and vehicle emission in residential areas, facilitating a smarter and higher quality of living in the city. The research work contributes in evaluating the road connectivity in the new HSKNDA and develop a novel container drayage model to enhance the future urban logistics operation efficiency and environmental condition in the new development area. The current simulations covered 15 depots, which is about half of the total number of depots in the New Territories, further studies could be extended to cover all the depots. A correlation study on the analysed road connectivity index, e.g. alpha index, beta index and gamma index, against the road distance could be carried out and the results could be incorporated into the objective functions to refine the container drayage model.

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