Chapter 1
Analysis of Demand and Operations of Inter-modal Terminals

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Abstract Inter-modal terminals (IMT) reduce road congestion and exploit economies of scale by pooling demand from surrounding areas and using rail to transport containers to and from ports. The alternative to using IMTs is using trucks to transport containers directly to and from the port. Trucks increase road congestion but rail requires additional handling of containers (lift on and lift off). The attractiveness of truck versus rail is dependent on a number of variables such as costs, total travel time, frequency of services, risk, and material resources. To date, the use of open data to analyse and model freight movements has been minimal, primarily because of the shortage of open data focusing on freight movements across cities, regions or countries. In this paper we leverage open government data for the Port Botany rail network and use it to develop flexible and dynamic simulation and optimisation tools that enable various stakeholders including IMT operators, port authorities, and government policy makers to make more informed decisions not only about pricing, but also operation scheduling and internal operations.

1.1 Introduction

Multi-modal transportation is defined as the transportation of goods by at least two different modes of transport (e.g., ships, barges, trains or trucks). In the Greater Sydney freight network, inter-modal terminals (IMT) are

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equipped for the transshipment of containers between rail and road transport modes. In 2014, there were 2.3 million movements of twenty-foot equivalent units (TEU) through Port Botany, of which over 80% correspond to imports. The land transportation of these containers was 2 million carried by truck and 0.3 million carried by rail, corresponding to a 14% share of total transported TEUs, a figure that the NSW State Government is trying to increase in order to reduce congestion and extend the life of valuable road infrastructure [13]. Forecasts indicate that total volume will increase fourfold in the next 25 years, and that there will be an increase in the proportion of containers destined to Sydney's western and south-western suburbs driven by a combination of availability of large parcels of land and lower land prices.

On one hand, these IMTs reduce road congestion and exploit economies of scale by pooling demand from surrounding areas and using rail to transport containers to and from ports, although additional handling of containers is necessary. On the other hand, trucks may transport containers directly to port without the need to transfer containers at IMTs, but this increases road congestion. The attractiveness of truck versus rail is dependent on a number of variables such as costs, demand, total travel time, frequency of services, risk, and material resources, which must be analysed and understood in order to maximise the value of existing infrastructure.

The objective of the present paper is to introduce tools to determine whether the existing network of railway lines and inter-modal terminals is adequate to support future growth of the Port Botany freight system. To that end, we introduce and analyse the results of a simulation and an optimisation model, which leverage on newly available open government data. These models complement each other: the simulation aims at understanding the demand and cost structures of individual, competing IMTs, whereas the optimisation model seeks the greater benefit for all participants in the system. In the remainder of the present paper, we review existing work dedicated to the analysis of operations in IMTs in subsection 1.1.1 and describe the Port Botany bi-modal transportation system in Section 1.2. We then describe the simulation and optimisation models in Sections 1.3 and 1.4, respectively, and present and discuss their results (Section 1.5). We round up the discussion and present ideas for further analysis in Section 1.6.

1.1.1 Previous Work

Literature related to IMTs is mostly concerned with the problem of selecting the optimal location of these facilities. Sörensen et al [14] explained that different transport modes have different environmental footprints, but it is hard for other transport modes to compete with the cost, flexibility and service level of road transport. A consequence is that infrastructure and connectivity at IMTs is still relatively poor. Sörensen et al [14] presented two efficient meta-heuristics for the fast solution of the IMT location problem. In follow-up papers, Lin et al [12] improved on Sörensen et al's model by removing redundant constraints and improving solution times, while also introducing matheuristics to obtain near-optimal solutions quickly. Lin and Lin [11] performed a decomposition of IMT selection and transportation flows for the same problem.

Regarding the optimisation of IMT operations, Alicke [1] presented a constraint satisfaction model to minimise maximum tardiness of operating a single IMT known as *Mega Hub*. The IMT under study had a novel design, and as a consequence, the model was customised for the configuration of the terminal. The resulting model turned out to be very flexible and could be solved quickly. Caris and Janssens [6] optimised the drayage plans at IMTs, that is, created efficient vehicle routes performing all loaded and empty container transports in the service area of one or several container terminals during a single day. A local search heuristic was proposed to address the problem, whereas in a following paper by the same team [4], this is achieved by minimising two objectives: number of vehicles and total distance traveled, using two heuristic algorithms. Gundersen et al [9] presented a Data Envelopment Analysis to compare the performance in terms of security of a set of 18 IMTs, identifying opportunity areas in most of them. Holguín-Veras and Jara-Díaz [10] derive formulae for optimal space allocation and pricing for storage at container terminals, motivated by the increasing service and price differentiation, as the industry is more willing to implement different types of services tailored to customer needs.

Regarding the combined use of simulation and optimisation, Gambardella and Rizzoli [8] provided a short review of the main classes of problems at IMTs whose instances can be found in the operations of container terminals, and advocated for the combined use of simulation and optimisation. Vidović et al [15] addressed the problem of optimally locating inter-modal freight terminals in Serbia by combining optimisation for locating facilities, and simulation for validating the solution.

1.2 The Port Botany Bi-modal System

In Sydney's Port Botany freight system, containers can be transported directly between the premises of the freight owners and the port with trucks via the road network. Alternatively, they can be transported via an intermediate inter-modal rail terminal. The system comprises the Greater Sydney metropolitan region that extends out 50 km from the port. For this study, it must be determined whether the existing network of railway lines and inter-modal terminals is adequate to support future growth. The system comprises the following components:

1. **Production/consumption Areas**. These areas contain producers that send containers with goods for export and also contain the end customers for imports. The areas aggregate the total supply of containers for export as well as demand of containers imported, to the suburb level. Customers within each suburb area determine their transport choice by selecting the service provider that best satisfies their price and service time requirements. The simulation part of the study considered 233 postcode locations as origin of exports and destination of imports. By contrast, the optimisation study aggregates these into ten production areas.
2. **Inter-modal Terminals**. An IMT is a transfer facility with road and rail access, and on-site warehousing. In the model presented here, each IMTs run its own rail assets (wagons/locomotives) and container handling assets (forklifts or cranes); in the real world, trains are operated by train companies that may or not own an IMT. For example, some logistics companies own trains and an IMT, but Cooks River IMT does not own any trains. Import containers change from trains to trucks at the IMT facilities on their way to the production areas, and export containers are placed into train consists from trucks on their way to the port terminals for shipping. The rate at which containers can be processed by a facility is determined by the number of handling assets, while the rate at which containers can be transported to and from the port is determined by the rail assets. Five IMTs are considered. Additional information on the features of the set of IMTs servicing the Port Botany freight system can be found in Chi Thai [7].
3. **Port terminals**. Terminals are export-shipping points and entry points for imports, and also have warehousing facilities available. Two terminals are included in the case study.

A schematic of the system is depicted in Figure 1.1. Producers have the option to send containers for export and receive imports directly from terminals by truck, or to use IMTs. If this is the case, containers are transferred from trains to trucks and vice versa in the IMTs for imports and exports, respectively. Storage facilities exist at terminals and IMTs, which require container transfer equipment (cranes and forklifts). Currently, Port Botany is serviced by trains from existing IMTs located in Cooks River, McArthur and Yennora and the recently opened terminals at Chullora and Enfield [13]. A proposed facility in Moorebank will be able to service the increasing demand in Sydney's southwest. Figure 1.2 indicates the location of these sites and shows the spatial distribution of the destination of deliveries of imported containers into the Greater Sydney area.

The importance of understanding this system resides in the fact that, on one hand, IMTs reduce road congestion and exploit economies of scale by pooling demand from surrounding areas and using rail to transport containers to and from ports. Additionally, it may be in the interest of local government authorities to encourage rail transport in order to reduce congestion and extend the life of valuable road infrastructure. On the other hand, rail requires

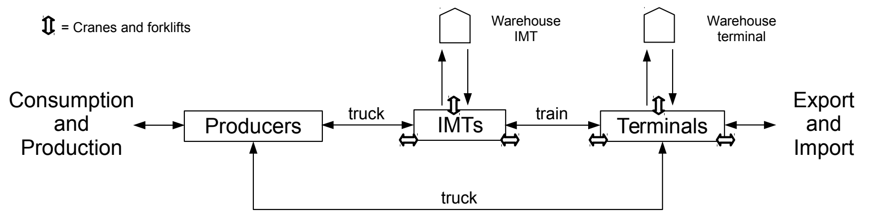

Fig. 1.1 Schematic of Port Botany freight system. Containers are transported by truck between producers and IMTs and between producers and terminals. Transport by rail occurs only between IMTs and terminals. IMTs and terminals count with warehousing space to store containers. Cranes of forklifts are necessary to load and unload containers to and from trucks and train consists

additional handling of containers (lift on and lift off), while direct transport from and to ports by truck may be more convenient and save the need for extra-handling in IMTs. In other words, there is a trade-off to be analysed in the attractiveness of truck versus rail that depends on a number of variables such as cost, total travel time, frequency of services, risk etc.

In the remainder of this paper, we describe and present initial results from the simulation and optimisation models, the former focused on understanding the demand and cost structures of individual, competing IMT's, and the latter aimed at obtaining the greater benefit for all participants in the system. In this sense, the optimisation and simulation models described complement each other.

1.3 Simulation of Rail Demand

We simulated computationally the operations of IMTs and their resulting container throughput, and generated an underlying demand for container imports and exports in the Greater Sydney region based on real data provided by the Australian Bureau of Statistics [2]. The goal of this simulator, of which a more detailed description can be found in Banerjee et al [3], is to improve the efficiency and profitability of IMTs. In order to achieve this objective, we built a model of internal operation of IMTs within a value-driven modelling framework. The model of internal operations can be used to predict profit based on different asset mixes like number of trains and wagons, number of forklifts, etc. and different pricing structures.

The value-driven model framework incorporates: (1) a detailed operational model of IMTs including costs, capacities and service times for different asset mixes within an IMT; (2) a model of spatial demand for containers; (3) competition from direct truck transport or other IMTs. The components of the

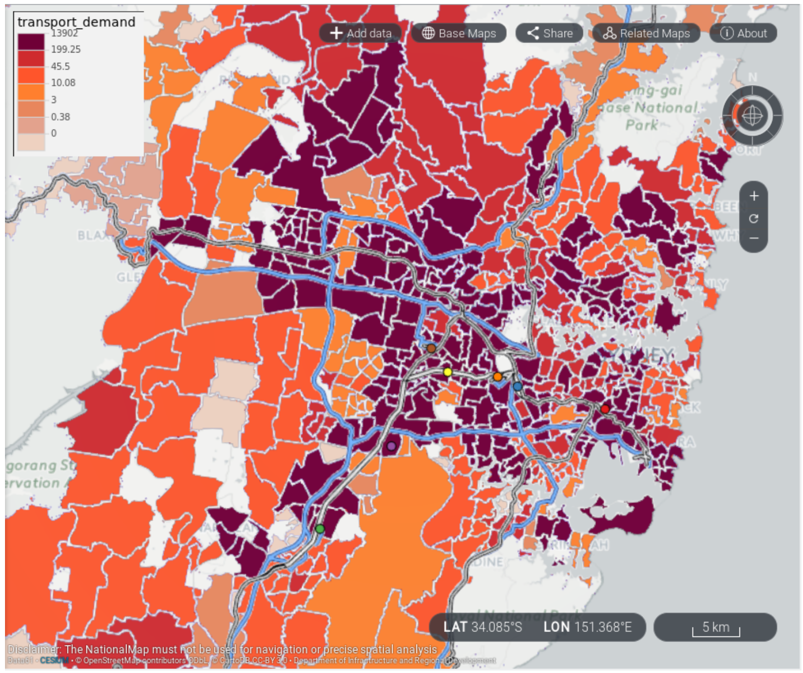

Fig. 1.2 IMTs and spatial distribution of the delivery destination of imported containers into the Sydney metropolitan region. The IMTs shown are McArthur (green), Yennora (brown), Villawood (yellow), Chullora (orange), Enfield (blue), Cooks River (red) and Moorebank (purple). The gray lines in this map represent rail and the blue lines represent the main roads.

model are calibrated based on internal operational data and publicly available data, and the decision to use an IMT is based on price, transportation time and the frequency of delays [5]. The model allows analysts to perform what-if analyses, predict the outcome of different investment and operational decisions, and compare individual IMTs. On one hand, the simulation model takes into account the travel times and demand for containers at level of suburbs. On the other hand, it only considers imports, which account for the majority of container movements in the Sydney region.

1.4 Optimisation of Operations

The aim of the linear optimisation model is to maximise the net economic benefit, defined as the sales of all containers minus the total costs of operating the entire supply chain. These costs comprise transportation costs, the costs of violating the soft inventory limits at warehouses, the costs of moving containers to and from warehouses, and the costs of hiring extra trains and container-handling equipment if the available resources are not sufficient. The full formulation can be found in the Appendix.

Profit as described above is expressed in Equation (1.1). A summary of the constraints follows:

1. The *soft inventory capacity constraints* (1.2) impose a penalty for exceeding the desirable limits to the amount of containers that may be stored in the IMT and terminal warehouses.
2. The *hard inventory capacity constraints* (1.3) state the maximum number of containers that can be stored at sites with warehousing capability.
3. The *crane capacity constraints for IMTs* (1.4) impose a limit on how many containers the cranes (or forklifts) can move at any time period, and a penalty when the available container moving resources are not sufficient. For IMTs, containers must be moved in and out of the warehouses, as well as to trucks or trains if they are going to be brought into and sent out of the facility at the current planning period.
4. The *crane capacity constraints for terminals* (1.5) are similar to the constraints for IMTs described above, but in addition to all the containers moved into and out of the warehouses and the train and truck loading and unloading operations, we need to consider that the containers for export must be loaded into the ships, and containers for import must be unloaded from the ships.
5. The amount of containers that can be imported or exported is constrained by expressions (1.6) and (1.7).
6. The *conservation constraints at IMTs* (1.8) define the flow of containers at IMTs and their warehouses. We consider that the initial inventory level at all warehouses is zero.
7. The *conservation constraints at terminals* (1.10) define the flow of containers at terminals and their warehouses.
8. The *conservation constraints at producers* (1.12) assume that the producers do not hold inventory and that all containers produced must enter the supply chain.
9. The *constraints for consist assembly* (1.14) and (1.16) state that the space for containers in the trains is limited. Wagons have room for three TEUs (slots). Containers can be 40 foot and occupy two TEUs, or 20-foot and occupy one TEU. The current version of the optimisation model distinguishes four commodities, `20ft-EXP`, `40ft-EXP`, `20ft-IMP` and `40ft-IMP`. Knapsack-like constraints so that the number of containers transported by rail in a road segment is not more than the capacity of all the trains travelling in that road segment at any given period. The model assumes that every truck can only carry one container.
10. *Road capacity constraints.* We assume that roads have a fixed capacity.

In contrast to the simulation model, the optimisation model is a strategic planning tool and does not take into account travel times. Demand for containers is modelled at an aggregate level, at least in the current stage of development. However, the optimisation model does calculate the optimal flows for import and export containers that maximise the net economic benefit to the region.

1.5 Results and Discussion

The simulation was coded in Python[1] version 3.5.2, and we obtained the results of subsection 1.5.1 in a desktop computer using an Intel® i7-4712HQ CPU at 2.27 GHz. We implemented the optimisation problem in version 1.5 of the Clojure[2] language with an Excel interface. We obtained all the results in subsection 1.5.2 using version 12.4 of the CPLEX[3] optimiser in a 64-bit Intel Xeon CPU with two processors of eight cores (2.27 GHz) each and 48 GB of RAM. The problem has 32220 integer variables and 55352 constraints. A typical run takes around ten minutes to complete.

As mentioned above, the simulation considered 233 postcode locations as origin of exports and destination of imports. By contrast, the optimisation study aggregated these locations into ten production/consumption areas, as shown in Figure 1.3. A fleet of ten trains was considered.

1.5.1 Operations

The results from the simulation model indicate that the median transportation time is almost the same for both transport modes, at 2.30 days for trucks and 2.31 days for rail, even when there is a delay in changing modes at IMTs. Rail has an advantage in the most distant regions of the area under study, with the fastest 5% of containers travelling by rail taking 3.5 hours less time to move through the system than the fastest 5% travelling by rail.

The base scenario was configured using data corresponding to the transport system as it was configured in 2014. During this year 2.3 million TEUs were transported in the system, and five IMTs were in operation: McArthur, Chullora, Minto, Yennora and Cooks River. The configured simulation model can reproduce the observed characteristics of the system, in particular the existing 14% market share of rail transport. The market equilibrium determined by the model is shown in Table 1.1 and the model outputs for this base scenario are displayed in Table 1.2.

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[1] https://www.python.org/downloads/release/python-352/, accessed on the 28 of July 2016.

[2] http://clojure.org/, accessed on the 8 of April 2016.

[3] http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/index.html, accessed on the 16 of May 2016.

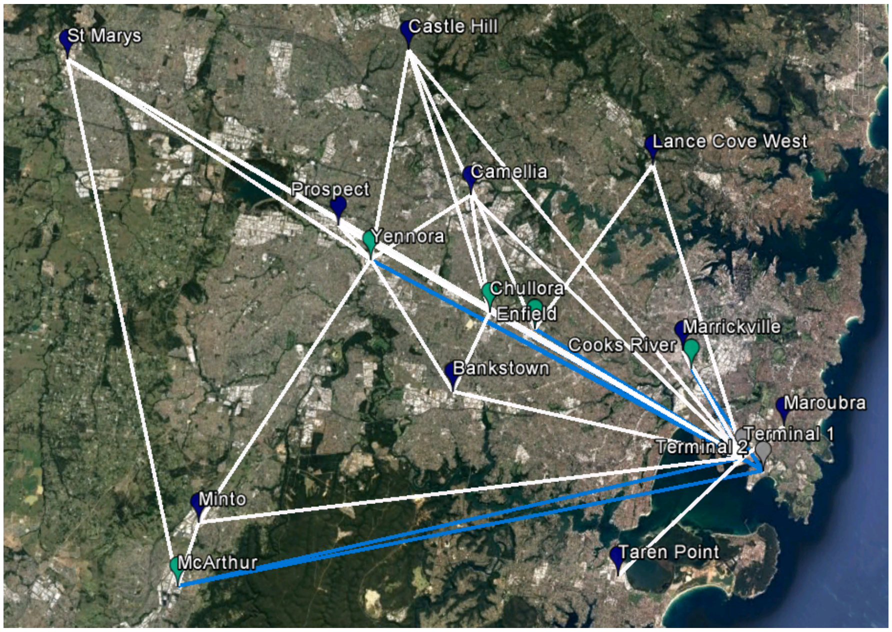

Fig. 1.3 Location of all sites that form the optimisation case study. Producers are marked in blue, IMTs in green and terminals in gray. The model considers that all producers are connected to all terminals and to all IMTs by road (white lines), and that all IMTs are connected to all terminals by rail (blue lines). Only the road segments used at some point of the time horizon are shown.

Table 1.1 Modelled market equilibrium for services offered by the inter-modal terminals.

	Railing price ($/TEU)	trains per day
McArthur inter-modal shipping terminal	230	3
Sydney freight terminal	225	3
Yennora IMT	240	3
Cooks River IMT	220	3

Table 1.2 Outputs of simulation for one year for the base 2014 scenario.

	TEUs handled	Market share	Average delivery price	Average road distance travelled
Direct truck service	945028	85.8	646	30.0
McArthur inter-modal shipping terminal	28614	2.6	628	10.8
Sydney freight terminal	47750	4.3	660	21.9
Yennora IMT	75000	6.8	654	14.8
Cooks River IMT	4800	0.4	669	26.5

1.5.2 Rail Demand

The optimisation model serves as a complement to the simulation model, so instead of calculating the equilibrium prices for individual IMTs, in this case we considered a time horizon of 60 days and that the cost of railing was a fixed parameter with value $200.00. Other data used was as close to the data used on the simulation as possible, although in some cases it had to be aggregated, as in the case of the producers, or estimated, as in the case of the train fleet size. Fleet size was estimated to get as close to the rail transportation share of 14%; in the optimisation model the share of total rail transport is 14.73%. The fraction of exports transported by rail is 16.88%, and for imports, this is 14.19%.

Tables 1.3 and 1.4 show the optimal flows of exports and imports, respectively. The model indicates that, given the current production and consumption data, all producing and consuming areas (except Castle Hill and St. Mary) import and export around 10% of their needs directly by road to terminal 1. Castle Hill and St. Mary have a lower share of road transport at around 3-5%. Yennora and McArthur are the IMTs with the highest share of rail transport, a result that is compatible with the simulation results in Table 1.2. The model also indicates that most containers should be handled at terminal one: 92.6% of exports and 98.8% of imports should pass through this terminal. This is probably an aspect of the model that could be improved, but at present, we do not have information regarding the actual handling capacities or operating rules of these terminals.

Table 1.3 Total number of export containers and percentage received at terminals from IMTs or directly from producers for base case.

	Terminal 1	Terminal 2	% Terminal 1	% Terminal 2
Mcarthur	1107	287	1.56	5.05
Yennora	5501	5014	7.75	88.21
Chullora	471	329	0.66	5.79
Enfield	170	0	0.24	0.00
Cooks River	0	54	0.00	0.95
Lance Cove West	7724	0	10.89	0.00
Marrickville	7546	0	10.64	0.00
Maroubra	6884	0	9.70	0.00
Taren Point	6890	0	9.71	0.00
Minto	6675	0	9.41	0.00
Bankstown	7752	0	10.93	0.00
Camellia	7785	0	10.97	0.00
Prospect	2588	0	3.65	0.00
St Marys	3386	0	4.77	0.00
Castle Hill	6472	0	9.12	0.00
TOTAL:	70951	5684	100.00	100.00

Table 1.4 Total number of import containers and percentage sent from terminals to IMTs or directly to producers for base case

	Terminal 1	Terminal 2	% Terminal 1	% Terminal 2
Mcarthur	3922	1450	1.30	38.00
Yennora	35494	2270	11.72	59.49
Chullora	288	96	0.10	2.52
Enfield	0	0	0.00	0.00
Cooks River	6	0	0.00	0.00
Lance Cove West	33175	0	10.95	0.00
Marrickville	31268	0	10.32	0.00
Maroubra	25585	0	8.45	0.00
Taren Point	30251	0	9.99	0.00
Minto	25714	0	8.49	0.00
Bankstown	28492	0	9.41	0.00
Camellia	31593	0	10.43	0.00
Prospect	10124	0	3.34	0.00
St Marys	16321	0	5.39	0.00
Castle Hill	30617	0	10.11	0.00
TOTAL:	302850	3816	100.00	100.00

1.6 Concluding Remarks

Inter-modal terminals reduce road congestion and exploit economies of scale by pooling demand from surrounding areas and using rail to transport containers to and from ports. In the Port Botany freight system, trains and trucks supply the Greater Sydney metropolitan area with 2.3 million containers per year, with forecasts indicating that total volume will increase fourfold in the next 25 years. In the present paper, we introduce and analyse the results of a simulation and an optimisation model, which leverage on newly available open government data [2] in order to to determine whether the existing network of railway lines and inter-modal terminals is adequate to support future growth of the Port Botany freight system.

These two complementary models offer a holistic approach that moves away from simple capacity considerations and assesses the effect of changes on the behaviour of key market players. Both models capture the logistic processes from port to final delivery destination, with the simulation model also taking into account a more detailed set of production/consumption areas, transportation time and the frequency of delays. The optimisation model is not as detailed, but provides insights on the greater benefit and more efficient use of resources for all participants in the system. Our simulation results indicate that the median transportation time is almost the same for both transport modes, at 2.30 days for trucks and 2.31 days for rail, even when there is a delay in changing modes at IMTs. The optimisation results indicate that terminal 2 is underutilised and that, indeed, McArthur and Yennora should be the IMTs with the largest inter-modal transfers. We have introduced the models and presented preliminary results, but many improvements are possible as more data becomes available. Some of these include adding imports to the simulation model, considering commodity level characteristics (e.g., perishables), refinement of delivery time and reliability, refining the transport decision model in the simulation, and attempting a more detailed description of individual producer/consumer areas for optimisation.

Appendix

Let us define the decision variables x^E_{ijkt} and y^E_{ijkt} as the containers for export that travel between sites i and j carrying commodity k at period t by truck and by rail, respectively; x^I_{ijkt} and y^I_{ijkt} as the containers for import that travel between sites i and j carrying commodity k at period t by truck and by rail, respectively; z^E_{ikt} and z^I_{jkt} the containers that go to export and that come as import at terminal i, respectively; u^+_{ikt} and u^-_{ikt} the containers that are moved into and out of the IMTs' warehouses, respectively; v^+_{ikt} and v^-_{ikt} the containers that are moved into and out of the terminals' warehouses, respectively; w_{ikt} and w_{ikt} the containers that are stored in the IMT and terminal warehouses, respectively; $\alpha^{\uparrow}_{ikt}$ and $\alpha^{\downarrow}_{ikt}$ the amount by which the minimum and maximum desired inventory levels at sites with warehouses (i.e., IMTs and terminals) are violated, respectively; γ_t the number of additional trains needed at time t and δ_{it} the number of additional container-handling equipment at IMT i at time t. Also, let N be the number of wagons in a consist (normally 32), n_{ijt} the number of trains that travel between sites i and j, and γ_t the number of additional trains needed in excess of the total available, $MAXNT$. We can now define the objective function as

$$
\begin{aligned}
\text{Maximise}\quad & \sum_{i\in\mathscr{P}}\sum_{k\in\mathscr{K}^I}\sum_{t\in\mathscr{T}} SP_{kt} z^I_{ikt} + \sum_{i\in\mathscr{P}}\sum_{k\in\mathscr{K}^E}\sum_{t\in\mathscr{T}} SP_{kt} z^E_{ikt} \\
& - \sum_{(i,j)\in\mathscr{L}^E_R}\sum_{k\in\mathscr{K}^E}\sum_{t\in\mathscr{T}} RTC_{ijkt}\ x^E_{ijkt} - \sum_{(i,j)\in\mathscr{L}^I_R}\sum_{k\in\mathscr{K}^I}\sum_{t\in\mathscr{T}} RTC_{ijkt}\ x^I_{ijkt} \\
& - \sum_{(i,j)\in\mathscr{L}^E_P}\sum_{t\in\mathscr{T}} PTC_{ijt}\ n_{ijt} - \sum_{i\in\mathscr{R}\cup\mathscr{P}}\sum_{t\in\mathscr{T}} SVC_{it}\sum_{k\in\mathscr{K}}(\alpha^{\uparrow}_{ikt} - \alpha^{\downarrow}_{ikt}) \\
& - \sum_{i\in\mathscr{R}}\sum_{k\in\mathscr{K}}\sum_{t\in\mathscr{T}} CM_{ikt}\left[u^+_{ikt} + u^-_{ikt} + \sum_{j\in\mathscr{S}}(x^E_{jikt} + x^I_{ijkt}) + \sum_{j\in\mathscr{P}}(y^E_{ijkt} + y^I_{jikt})\right] \\
& - \sum_{i\in\mathscr{P}}\sum_{k\in\mathscr{K}}\sum_{t\in\mathscr{T}} CM_{ikt}\left[v^+_{ikt} + v^-_{ikt} + \sum_{j\in\mathscr{S}}(x^E_{jikt} + x^I_{ijkt}) + \sum_{j\in\mathscr{R}}(y^E_{jikt} + y^I_{ijkt}) + z^E_{ikt} + z^I_{ikt}\right] \\
& - \sum_{t\in\mathscr{T}} FC_t\gamma_t - \sum_{i\in\mathscr{R}} CC_i\sum_t \delta_{it}\ .
\end{aligned}
\tag{1.1}
$$

where SP_{kt} is the sales price of commodity k at period t, RTC_{ijkt} and PTC_{ijkt} are the transportation costs per km from i to j by road and rail, respectively, SVC_{it} is the cost of violationg soft inventory limits at site i, CM_{ikt} is the cost of moving containers within a site i, FC_t is the cost of setting up additional trains at period t, and CC_i is the cost of additional container movements.

Subject to:

$$WDES_i^{\mathtt{min}} - \sum_{k\in\mathscr{K}} \alpha_{ikt}^{\downarrow} \le \sum_{k\in\mathscr{K}} w_{ikt} \le WDES_i^{\mathtt{max}} + \sum_{k\in\mathscr{K}} \alpha_{ikt}^{\uparrow} \qquad \forall i \in \mathscr{R}\cup\mathscr{P}, \quad \forall t\in\mathscr{T}\,. \tag{1.2}$$

$$WDES_i^{\mathtt{max}} + \sum_{k\in\mathscr{K}} \alpha_{ikt}^{\uparrow} \le WLIM_i \qquad \forall i \in \mathscr{R}\cup\mathscr{P}, \quad \forall t\in\mathscr{T}\,. \tag{1.3}$$

$$\sum_{k\in\mathscr{K}} (u_{ikt}^{+} + u_{ikt}^{-} + \sum_{j\in\mathscr{S}} x_{jikt}^{E} + \sum_{j\in\mathscr{S}} x_{ijkt}^{I} + \sum_{j\in\mathscr{P}} y_{ijkt}^{E} + \sum_{j\in\mathscr{P}} y_{jikt}^{I}) - \delta_{it} \le W_i^{\mathtt{max}} \qquad \forall i\in\mathscr{R},\ \forall t\in\mathscr{T}\,. \tag{1.4}$$

$$\sum_{k\in\mathscr{K}} (v_{ikt}^{+} + v_{ikt}^{-} + \sum_{j\in\mathscr{S}} x_{jikt}^{E} + \sum_{j\in\mathscr{S}} x_{ijkt}^{I} + \sum_{j\in\mathscr{R}} y_{jikt}^{E} + \sum_{j\in\mathscr{R}} y_{ijkt}^{I} + z_{ikt}^{E} + z_{ikt}^{I}) - \delta_{it} \le W_i^{\mathtt{max}} \qquad \forall i\in\mathscr{P},\ \forall t\in\mathscr{T}\,, \tag{1.5}$$

where δ_{it} is the number of additional container-handling operations needed at site i at time t and

$$z_{ikt}^{E} \le EXP_{ikt} \qquad \forall i\in\mathscr{P},\ \forall k\in\mathscr{K}^{E},\ \forall t\in\mathscr{T}\,, \tag{1.6}$$

$$z_{ikt}^{I} \le IMP_{ikt} \qquad \forall i\in\mathscr{P},\ \forall k\in\mathscr{K}^{I},\ \forall t\in\mathscr{T}\,. \tag{1.7}$$

$$\sum_{j\in\mathscr{S}} x_{jikt}^{E} + \sum_{j\in\mathscr{P}} y_{jikt}^{I} + u_{ikt}^{-} = \sum_{j'\in\mathscr{S}} x_{ij'kt}^{I} + \sum_{j'\in\mathscr{P}} y_{ij'kt}^{E} + u_{ikt}^{+} \qquad \forall i\in\mathscr{R},\ \forall k\in\mathscr{K},\ \forall t\in\mathscr{T}, \tag{1.8}$$

$$w_{ik,t+1} = w_{ikt} + u_{ikt}^{+} - u_{ikt}^{-} \qquad \forall i\in\mathscr{R},\ \forall k\in\mathscr{K},\ \forall t\in\mathscr{T}\,. \tag{1.9}$$

$$\sum_{j\in\mathscr{S}} x_{jikt}^{E} + \sum_{j\in\mathscr{R}} y_{jikt}^{E} + v_{ikt}^{-} + z_{ikt}^{I} = \sum_{j'\in\mathscr{S}} x_{ij'kt}^{I} + \sum_{j'\in\mathscr{R}} y_{ij'kt}^{I} + v_{ikt}^{+} + z_{ikt}^{E} \qquad \forall i\in\mathscr{P},\ \forall k\in\mathscr{K},\ \forall t\in\mathscr{T}, \tag{1.10}$$

$$w_{ik,t+1} = w_{ikt} + v_{ikt}^{+} - v_{ikt}^{-} \qquad \forall i\in\mathscr{P},\ \forall k\in\mathscr{K},\ \forall t\in\mathscr{T}\,. \tag{1.11}$$

$$\sum_{j\in\mathscr{R}\cup\mathscr{P}} x_{jikt}^{I} = CONS_{ikt} \qquad \forall i\in\mathscr{S},\ \forall k\in\mathscr{K}^{I},\ \forall t\in\mathscr{T}\,, \tag{1.12}$$

$$\sum_{j\in\mathscr{R}\cup\mathscr{P}} x_{ijkt}^{E} = PROD_{ikt} \qquad \forall i\in\mathscr{S},\ \forall k\in\mathscr{K}^{E},\ \forall t\in\mathscr{T}\,, \tag{1.13}$$

where $PROD_{ikt}$ and $CONS_{ikt}$ are the amounts of produced and consumed containers of export and import commodities, respectively, in producer i.

$$\sum_{k\in\mathscr{K}^I} NS_k\ y^I_{ijkt} - 3\ N\ n_{ijt} \leq 0 \qquad \forall (i,j) \in \mathscr{L}^I_P,\ \forall t \in \mathscr{T}\ ,\ and \tag{1.14}$$

$$\sum_{k\in\mathscr{K}^E} NS_k\ y^E_{ijkt} - 3\ N\ n_{ijt} \leq 0 \qquad \forall (i,j) \in \mathscr{L}^E_P,\ \forall t \in \mathscr{T}\ , \tag{1.15}$$

where NS_k is the number of slots a container of type k takes.

$$\sum_{(i,j)\in\mathscr{L}_P} n_{ijt} - \gamma_t \leq MAXNT \qquad \forall t \in \mathscr{T}\ . \tag{1.16}$$

$$\sum_{k\in\mathscr{K}} x^E_{ijkt} \leq Q_{ij} \qquad \forall (i,j) \in \mathscr{L}^E_R,\ \forall t \in \mathscr{T}\ , \tag{1.17}$$

$$\sum_{k\in\mathscr{K}} x^I_{ijkt} \leq Q_{ij} \qquad \forall (i,j) \in \mathscr{L}^I_R,\ \forall t \in \mathscr{T}\ , \tag{1.18}$$

where Q_{ij} is the capacity of the road segment (i, j).

References

[1] Alicke K (2002) Modeling and optimization of the intermodal terminal Mega Hub. OR Spectrum 24:1–17

[2] Australian Government (2016) Experimental statistics on international shipping container movements. Tech. Rep. 5368.0.55.018, Australian Bureau of Statistics, ABS House 45 Benjamin Way, Belconnen ACT 2617, http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/5368.0.55.018Main+Features12009-10?OpenDocument

[3] Banerjee S, Mathews G, Aracena C, Thorne B, Tyshetskiy Y, Vitsounis T (2016) Computationally simulating intermodal terminal attractiveness and demand. In: Proceedings of the 23 Intelligent Transport Systems World Congress, Melbourne, Australia, accepted

[4] Braekers K, Caris A, Janssens G (2014) Bi-objective optimization of drayage operations in the service area of intermodal terminals. Transportation Research Part E 65:50–69

[5] Brooks M, Puckett S, Hensher D, Sammons A (2012) Understanding mode choice decisions: A study of Australian freight shippers. Maritime Economics and Logistics 14(3):274–299

[6] Caris A, Janssens G (2009) A local search heuristic for the pre- and end-haulage of intermodal container terminals. Computers and Operations Research 36:2763–2772

[7] Chi Thai (2011) Metropolitan Intermodal Terminal Study 2011. Tech. rep., Shipping Australia Limited, URL http://www.transport.nsw.gov.au/sites/default/files/b2b/freight/rail-access-review-shipping-aust-mits-attachment.pdf
[8] Gambardella L, Rizzoli A (2000) The role of simulation and optimisation in intermodal container terminals. In: Moller D (ed) Proceedings of the 12th European Simulation Symposium (ESS 2000), Society for Computer Simulation, PO BOX 17900, San Diego, CA 92177 USA, Hamburg, Germany, pp 422–426
[9] Gundersen E, Kaisar E, Scarlatos P (2009) Assessing container terminal safety and security using Data Envelopment Analysis. In: Mastorakis N, Jha M (eds) Proceedings of the Second WSEAS International Conference on Urban Planning and Transportation, WSEAS, World Scientific and Engineering Academic Society, Ag Loannou Theologou 17-23, 15773 Zographou, Athens, Greece, Mathematics and Computers in Science and Engineering, pp 125–130
[10] Holguín-Veras J, Jara-Díaz S (2006) Preliminary insights into optimal pricing and space allocation at intermodal terminals with elastic arrivals and capacity constraint. Networks and Spatial Economics 6(1):25–38
[11] Lin C, Lin S (2016) Two-stage approach to the intermodal terminal location problem. Computers and Operations Research 67:113–119
[12] Lin C, Chang Y, Lin S (2014) Efficient model and heuristic for the intermodal terminal location problem. Computers and Operations Research 51:41–51
[13] New South Wales Government (2015) Navigating the future: NSW Ports' 30 year master plan. Tech. rep., NSW Ports, http://www.nswports.com.au/assets/Publications/NSW-Ports-Master-Plan-2015.pdf
[14] Sörensen K, Vanovermeire C, Busschaert S (2012) Efficient metaheuristics to solve the intermodal terminal location problem. Computers and Operations Research 39:2079–2090
[15] Vidović M, Sečević S, Kilibarda M, Vlajić J, Bjelić, Tadić S (2011) The p-hub model with hub-catchment areas, existing hubs, and simulation: A case study of serbian intermodal terminals. Networks and Spatial Economics 11:295–314