Urban intermodal container terminals: The entropy maximizing facility location problem

Seminar on Human Society and Risk: A focus on Transportation and Disaster

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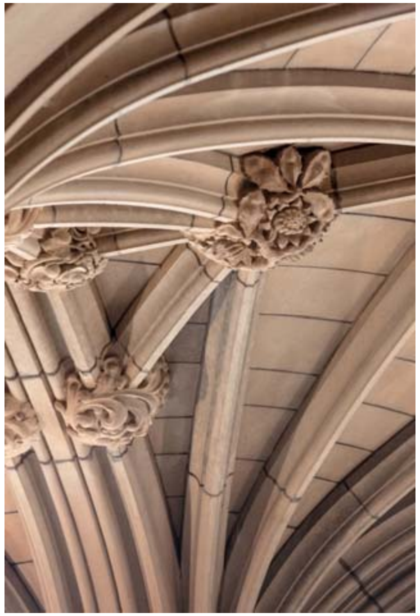


INTRODUCTION : Container Revolution

– The world needs sustainable and reliable supply chains

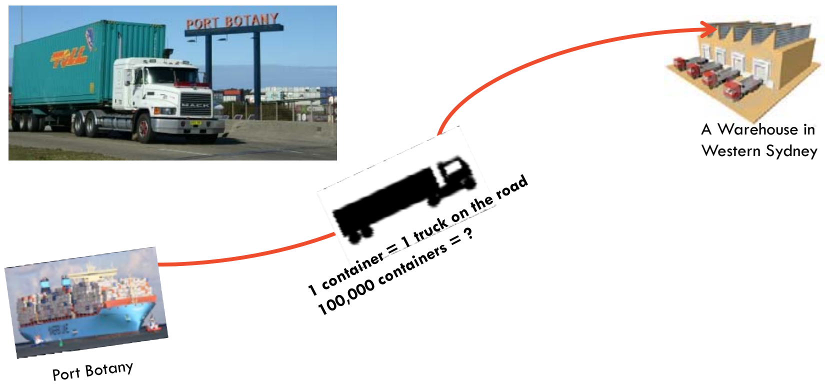
INTRODUCTION

– Ports are part of Sydney's urban fabric

Source: Sydney Ports Corp

INTRODUCTION : Road

– OPTION 1 : Use truck to transport the containers

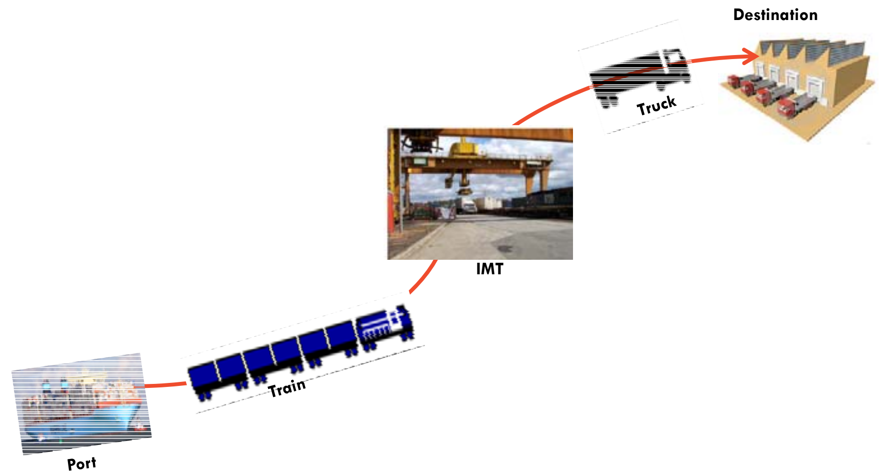


INTRODUCTION : Rail

– OPTION II : Use trains to transport the containers

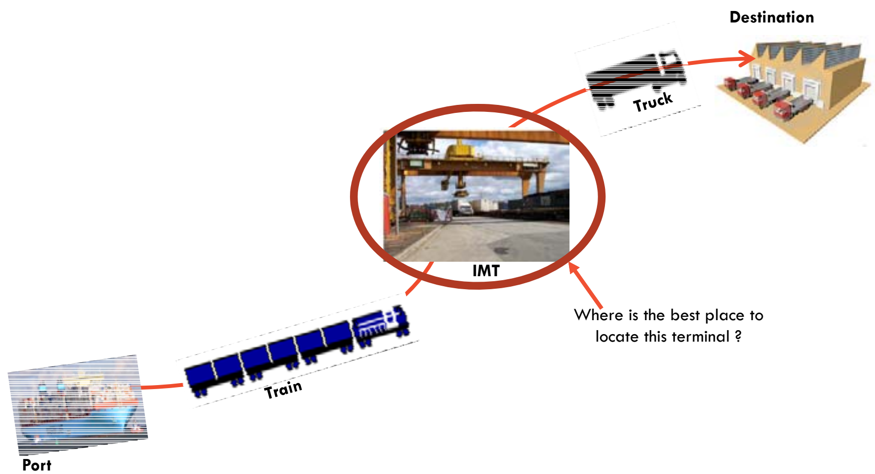
INTRODUCTION : Intermodal Transport

– OPTION III : Use intermodal transport



INTRODUCTION : Key Research Question

– Where are the best places to locate IMTs?



INTRODUCTION : Why is Location Important?

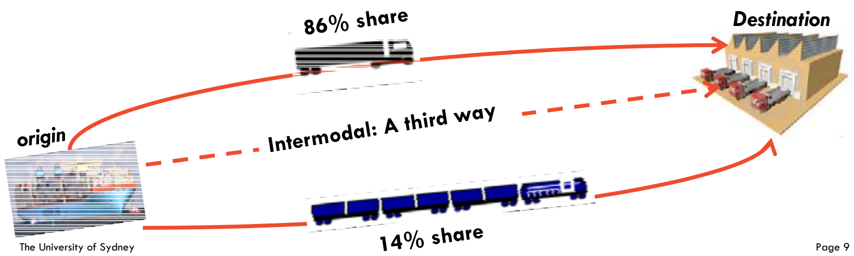
– The location of an IMT determines its **viability**
  - Determines the **volume of cargo** likely to use the IMT
  - Cargo volume is crucial to make an IMT viable

– Influence rail mode share
  - The higher the use of the IMT the higher the share of rail

– Determines the number of **trucks that be taken off** the road
  - Safer for other road users
  - Less road congestion, especially around the port
  - Less **greenhouse gas** emission, better environment, more sustainable

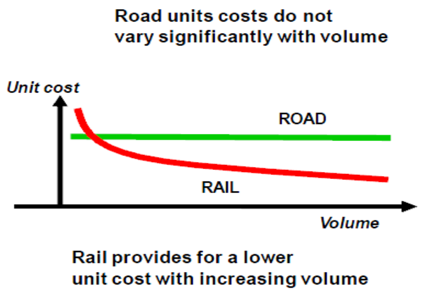
INTRODUCTION : Why the need for Intermodal Terminals?

- In Australia, containerised trade by volume is set to increase from ***6.5 million*** in 2011 to ***11 million TEUs*** (containers) by 2020 (Shipping Australia, 2011)
- Trucks currently accounts for over ***86% of container trips*** to and from the ports (Shipping Australia, 2011)
- Poor Management of empty containers: import, export imbalance
- Congestion around ports with safety & environmental related problems



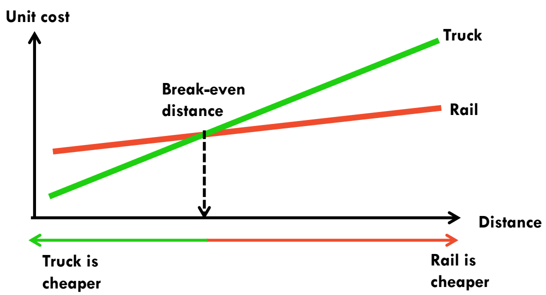
INTRODUCTION : Advantages of IMTs

- **ADVANTAGE I:** Economies of scale of rail
  - Rail has high carrying capacity, and
  - The larger the volume the cheaper to it is to use rail



INTRODUCTION : Advantages of IMTs

- **ADVANTAGE II:** Economies of distance of rail
  - Rail is cheaper for long distance trips
  - Rail is much greener and safer to other road users



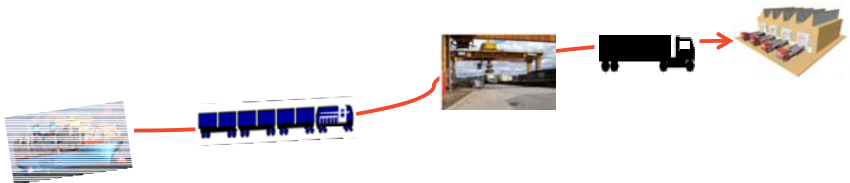
INTRODUCTION : Advantages of IMTs

- **ADVANTAGE III:** Accessibility
  - Less access by rail (can only reach few areas)
  - Flexible and easier access by trucks

Intermodal transport = Combined strengths of rail and truck

Rail = Exploit economies of scale + Economies of distance

Truck = Efficient and flexibility of local pick-up and delivery



INTRODUCTION : Advantages of IMTs

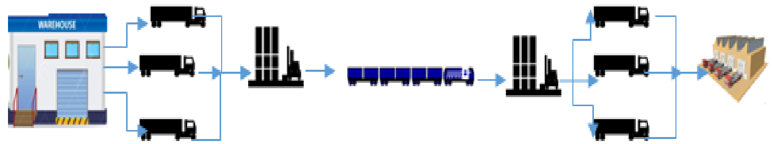
- **ADVANTAGE IV**: Empty containers
  - Empty container storage at IMTs
  - Efficient management of empty containers

- **ADVANTAGE V**: Warehousing & distribution centres
  - Warehousing can be preformed at IMTs
  - Small/medium exporters to consolidate their products for export
  - As a distribution centre for customers/retailers

INTRODUCTION : Three key IMT markets

- **3 Key markets**
  - A : Regional markets (e.g. moving cargo from Sydney to Melbourne)

A. Intermodal transport : Regional market



Source: Russell, L., 2007; Meyrick, 2006

INTRODUCTION : IMTs as Transfer Nodes

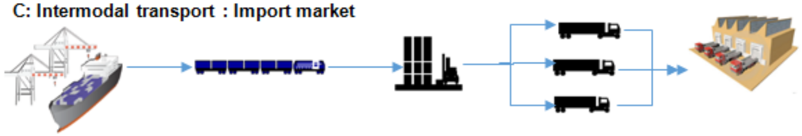
- **3 Key markets**
  - B : Exports
  - C : Imports

  } Metropolitan IMTs for IMEX markets

  - Sydney leads Australia in metropolitan IMTs

B: Intermodal transport : Export market

C: Intermodal transport : Import market



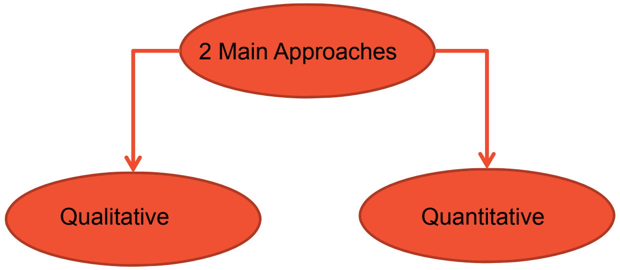
Source: Russell, L., 2007; Meyrick, 2006

MAIN RESEARCH QUESTIONS

1. How many IMTs?
2. Where should they be located?
3. What is the likely demand or usage of the IMTs?
4. What are the likelihoods of the IMTs attracting value adding activities, such as warehousing and empty container storage?

FACILITY LOCATION PROBLEMS

- The problem of finding the best locations of intermodal terminals can be placed in the class of Facility Location Problems (FLP)
- FLP deals with finding the best placement of facilities and the allocation of demands to the facilities to optimise a given objective



LITERATURE REVIEW : Qualitative Methods

Example : Simple Score Method

- List the candidate sites (e.g. Moorebank, Enfield, Eastern Creek)
- List the relevant factors (e.g. Market, Transport, Setup Cost)
- Score each site (e.g. 0-100 scale) on the factors
- Select the site with highest average or maxmin score

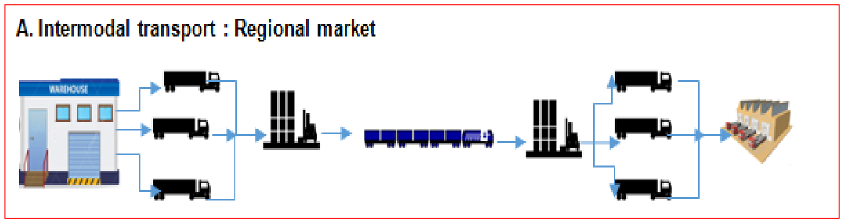
	Market	Transport	Setup cost	Ave Score
Moorebank	70	80	70	73
Enfield	55	75	60	63
Eastern	50	60	90	67

QUALITATIVE METHODS : Limitations

- The preference of one alternative or criterion over the other is very subjective, based on the feelings of the analyst or decision-maker
- Different analysts might provide different weights leading to possibly entirely different site selections.
- No idea how the new IMT competes with existing IMTs or no IMT (road direct)
- No information on the usage of the terminal and transport costs, which are crucial for cost and benefit analysis
- No traffic impacts assessment: A facility like this affects and is affected by road network conditions
- No environmental assessment as usage is unknown

LITERATURE REVIEW : Quantitative Methods

- The usual approach in the facility location literature is Mixed Integer Linear Programming (MILP)
- So far research work on IMTLP are for location of Regional IMTs and based on MILP techniques
- The metropolitan Intermodal Terminal Location Problem (IMTLP) is a new area



LITERATURE REVIEW : Quantitative Methods

- Arnold et al. (2001) provided the first mathematical model for the IMTLP
- Almost all MILP formulations are based on the following assumptions:
  - The origin (where the containers are coming from) and destination (where they are destined) container flows are known and not affected by the IMT locations or changes in transport network conditions
  - The transport costs by all modes are known and also not affected by where the IMTs are located.
  - No treatment of empty containers

LITERATURE REVIEW : Quantitative Methods

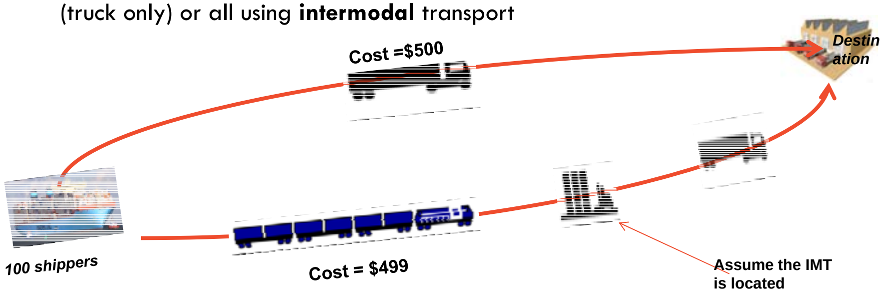
Is the use of MILP models appropriate?

- The general problem composed of two sub-problems:
  - Location problem: Hard to solve
  - Routing problem : Relatively easy to solve
  - Solving both simultaneously : Much harder
- The Location problem deals the best way of selecting *p* from the set of *T* candidate IMTs
- The Routing problem deals with the best way to route the cargo (origin-destination demand) through the IMTs or directly
- The Routing problem a **choice problem**

GAP IN THE LITERATURE

Problems with the Mixed Integer Linear Programming (MILP) Approach:

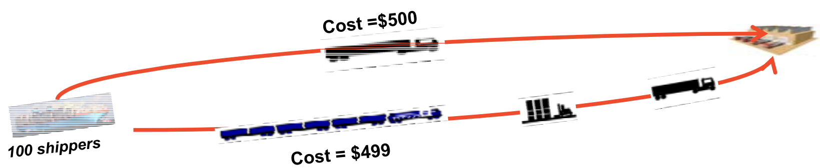
- Solutions are 'All-OR-Nothing (AON) ' in nature
- MILP solution results in shippers making identical decisions in identical circumstances
- Even if the cost are the same, we will have **either** all using **road direct** transport (truck only) or all using **intermodal** transport



GAP IN THE LITERATURE

Problems with Mixed Integer Linear Programming (MILP) Approach:

- We expect some form of split between the 2 modes, say 50 or 60% for intermodal transport, or vice versa
- Also we can't capture all elements of costs or all factors affecting the decision process
- The Routing problem is actually a **choice problem** (intermodal vs road direct)



GAP IN THE LITERATURE

Can we embed a choice within the location model?

- Entropy Maximization : Allows us to embed logit models within location models
  - More flexible and behavioural than MILP models
  - More efficient to solve than MILP models
  - Can approximate MILP models at the extreme

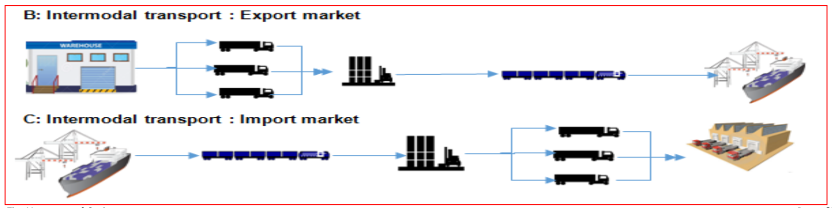
METHODOLOGY : Entropy Maximization

- **A technique first introduce in** statistical mechanics, to relate macroscopic, and measureable properties of physical systems to a description at the molecular or atomic level
- **Main Concept:** To find the **most likely micro state** of an **object** given information about the macro state of the system.
- **Maximum entropy** has been shown to provide the least biased estimate given the information available (Jaynes, 1957a, 1957b).
- **Relation to our problem:**
  - The system of interest : Intermodal terminals (IMTs)
  - The micro states of interest : The **locations** of IMTs and their **usage**

MAXIMUM ENTROPY FACILITY LOCATION PROBLEM

Our Model : MIMTLP (Metropolitan IMT Location Problem)

- Our model captures the impacts of empty container parks (ECP) in the location problem
- Efficient management of empty containers (storage, use and re-positioning) is generally considered one of the key driving force behind the development MIMTs (Meyrick, 2006; Russell, L., 2007; AHRCR, 2007)
- MIMTLP deals with the use of exactly one IMT in the intermodal transport chain



METHODOLOGY : Basic Entropy Maximization Model (BEM)

- **Objective function** : Finding the most likely intermodal and road direct flows

$$\max\left\{-\sum_{i\in I}\sum_{t\in T}\sum_{j\in J}\left(X_{itj}InX_{itj}-X_{itj}\right)-\sum_{i\in I}\sum_{k\in K}\sum_{j\in J}\left(W_{ikj}InW_{ikj}-W_{ikj}\right)\right\}$$

All states of intermodal flows

All states of road direct flows

- We are interested in the most likely state for each mode

- X_{itj} The cargo flow transported from origin *i* *through IMT t to destination j*
- W_{ikj} The cargo flow transported by road direct from origin *i* to destination *j* using ECP *k*

METHODOLOGY : Entropy Maximization

Basic Entropy Maximization Model (BEM)

$$L = \max\left\{-\sum_{i\in I}\sum_{t\in T}\sum_{j\in J}\left(X_{itj}\ln X_{itj} - X_{itj}\right) - \sum_{i\in I}\sum_{k\in K}\sum_{j\in J}\left(W_{ikj}\ln W_{ikj} - W_{ikj}\right)\right\}$$ **Objective function**

Subject to:

1. $X_{itj} \le q_{ij} Y_t \quad \forall i\in I, j\in J, t\in T$
2. $W_{ikj} \le q_{ij} Y_k \quad \forall i\in I, j\in J, k\in T$
3. $\sum_{t\in T} Y_t = p$
4. $\sum_{k\in K} W_{ikj} + \sum_{t\in T} X_{itj} = q_{ij} \quad \forall i\in I, j\in J$
5. $\sum_{i\in I}\sum_{j\in J} X_{itj} + B_t = b_t \quad \forall t\in T$
6. $\sum_{i\in I}\sum_{j\in J} W_{ikj} + H_k = h_k \quad \forall k\in K$
7. $\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} \omega_{ikj} W_{ikj} + \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} c_{itj} X_{itj} = C$
8. $\sum_{t\in T} f_t Y_t = F$
9. $Y_t \in \{0,1\} \quad \forall t\in T$
10. $X_{itj} \ge 0; W_{ikj} \ge 0 \quad \forall i\in I, j\in J, k\in K, t\in T$

METHODOLOGY : Solving the BEM

- Hard to solve
- There is no available software for solving BEM
- What actually makes the problem hard to solve are the location variables Y_t
- All constraints associated with Y_t are hard constraints
- If we can find a way of removing the hard constraints, the problem can be much easier to solve or least provide some insight
- We use the **Lagrangian relaxation** technique to do this

METHODOLOGY : Solving the BEM

Lagrangian relaxation (Relax constraints 1, 2 & 8)

$$L(X,W) = \max\left\{-\sum_{i\in I}\sum_{t\in T}\sum_{j\in J}\left(X_{itj}\ln X_{itj} - X_{itj}\right) - \sum_{i\in I}\sum_{k\in K}\sum_{j\in J}\left(W_{ikj}\ln W_{ikj} - W_{ikj}\right)\right\}$$

Subject to:

1. $X_{itj} \le q_{ij} Y_t \quad \forall i\in I, j\in J, t\in T$
2. $W_{ikj} \le q_{ij} Y_k \quad \forall i\in I, j\in J, k\in T$
3. $\sum_{t\in T} Y_t = p$
4. $\sum_{k\in K} W_{ikj} + \sum_{t\in T} X_{itj} = q_{ij} \quad \forall i\in I, j\in J$
5. $\sum_{i\in I}\sum_{j\in J} X_{itj} + B_t = b_t \quad \forall t\in T$
6. $\sum_{i\in I}\sum_{j\in J} W_{ikj} + H_k = h_k \quad \forall k\in K$
7. $\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} \omega_{ikj} W_{ikj} + \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} c_{itj} X_{itj} = C$
8. $\sum_{t\in T} f_t Y_t = F$
9. $Y_t \in \{0,1\} \quad \forall t\in T$
10. $X_{itj} \ge 0; W_{ikj} \ge 0 \quad \forall i\in I, j\in J, k\in K, t\in T$

METHODOLOGY : Solving the BEM

Lagrangian relaxation : Divide & Conquer

$$L(X,W,\lambda,\mu) = \sum_{i\in I}\sum_{t\in T}\sum_{j\in J} X_{itj}\left(1 - \ln X_{itj} - \lambda_{itj}\right) + \sum_{i\in I}\sum_{k\in K}\sum_{j\in J} W_{ikj}\left(1 - \ln W_{ikj} - \mu_{ikj}\right) + \sum_{i\in I}\sum_{t\in T}\sum_{j\in J}\left(\lambda_{itj} + \mu_{ikj}\right) q_{ij} Y_t + \alpha\left\{F - \sum_{t\in T} f_t Y_t\right\}$$

Subject to:

4. $\sum_{k\in K} W_{ikj} + \sum_{t\in T} X_{itj} = q_{ij} \quad \forall i\in I, j\in J$
5. $\sum_{i\in I}\sum_{j\in J} X_{itj} + B_t = b_t \quad \forall t\in T$
6. $\sum_{i\in I}\sum_{j\in J} W_{ikj} + H_k = h_k \quad \forall k\in K$
7. $\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} \omega_{ikj} W_{ikj} + \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} c_{itj} X_{itj} = C$
10. $X_{itj} \ge 0; W_{ikj} \ge 0 \quad \forall i\in I, j\in J, k\in K, t\in T$

Subject to:

3. $\sum_{t\in T} Y_t = p$
9. $Y_t \in \{0,1\} \quad \forall t\in T$

METHODOLOGY : Solving the BEM

Two models : Routing model (RM) + Location model (LM)

$$RM = \sum_{i\in I}\sum_{t\in T}\sum_{j\in J} X_{itj}\left(1 - InX_{itj} - \lambda_{itj}\right) + \sum_{i\in I}\sum_{k\in K}\sum_{j\in J} W_{ikj}\left(1 - InW_{ikj} - \mu_{ikj}\right)$$

Subject to:

4 $$\sum_{k\in K} W_{ikj} + \sum_{t\in T} X_{itj} = q_{ij} \quad \forall i \in I, j \in J$$

5 $$\sum_{i\in I}\sum_{j\in J} X_{itj} + B_t = b_t \quad \forall t \in T$$

6 $$\sum_{i\in I}\sum_{j\in J} W_{ikj} + H_k = h_k \quad \forall k \in K$$

7 $$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} \omega_{ikj} W_{ikj} + \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} c_{itj} X_{itj} = C$$

10 $$X_{itj} \geq 0; W_{ikj} \geq 0 \quad \forall i \in I, j \in J, k \in K, t \in T$$

$$LM = \sum_{i\in I}\sum_{t\in T}\sum_{j\in J}\left(\lambda_{itj} + \mu_{ikj}\right) q_{ij} Y_t + \alpha\left\{F - \sum_{t\in T} f_t Y_t\right\}$$

Subject to:

3 $$\sum_{t\in T} Y_t = p$$

9 $$Y_t \in \{0,1\} \quad \forall t \in T$$

METHODOLOGY : Solving the BEM

With some algebraic manipulation, it can be shown that:

— The **intermodal flows** can be expressed as:

$$X_{itj} = q_{ij}\frac{\xi_t\left(b_t - B_t\right)\exp\left\{-\beta\left(c_{itj} + \lambda_{itj}\right)\right\}}{\sum_{t\in T}\xi_t\left(b_t - B_t\right)\exp\left\{-\beta\left(c_{itj} + \lambda_{itj}\right)\right\} + \sum_{k\in K} G_k\left(h_k - H_k\right)\exp\left\{-\beta\left(\omega_{ikj} + \mu_{ikj}\right)\right\}}$$

— and the **road direct** flows as:

$$W_{ikj} = q_{ij}\frac{G_k\left(h_k - H_k\right)\exp\left\{-\beta\left(\omega_{ikj} + \mu_{ikj}\right)\right\}}{\sum_{t\in T}\xi_t\left(b_t - B_t\right)\exp\left\{-\beta\left(c_{itj} + \lambda_{itj}\right)\right\} + \sum_{k\in K} G_k\left(h_k - H_k\right)\exp\left\{-\beta\left(\omega_{ikj} + \mu_{ikj}\right)\right\}}$$

— where ξ_t and G_k are constants to be estimated

METHODOLOGY : Why the interest in Logit Models?

— **The Logit models** : Known for its strength in policy testing

  — Fit a logit model on the output from BEM to capture the behavioural mechanism in the choice and use of intermodal terminals

  — The logit model will provide the means to test the relative weights or importance of the drivers of intermodal terminals use

  — We can also test various policies such a pricing, subsidies, and so on to promote the use of the located terminals

Two Major Extensions

— **Inelastic demand:** The models in the literature and that presented here assume that the flow of cargo between each origin-destination pair is:

  — Not influenced by where the IMTs are located: Cargo destined for a warehouse can be re-directed to an IMT (change of destination)

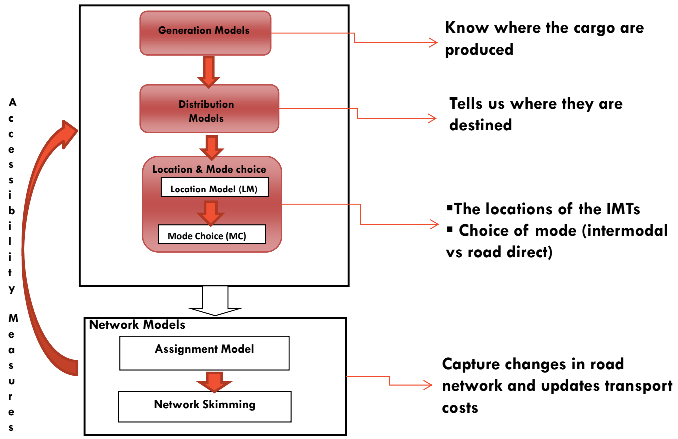
  — Not affected by changes in policy variables: We expect land use policy (e.g. re-zoning, rent or labour) and accessibility to influence the destination of cargo

— **Known and unchanged transport costs :** No changes in road network conditions

  — Expect to influence and be influenced by where the IMTs are located

  — Traffic impact analysis is very important, at least to ascertain if the road network around the located IMTs have enough capacity to cope with any additional truck traffic without causing local congestion

Where we want to get to



Numerical Example: MILP problems and EM potential

▪We use numeric example to ascertain the superiority of the EM over the MILP model in terms of location decision and policy testing

▪ The data used in the example were randomly generated but constrained by minimum and maximum values from reports and the literature.

▪The input data are:

1. Number of origin zones = 1 (e.g. the container port)
2. Number of destination zones = 10 zones
3. Number and location of plausible IMT sites = 5
4. Number of IMTs to locate = 1

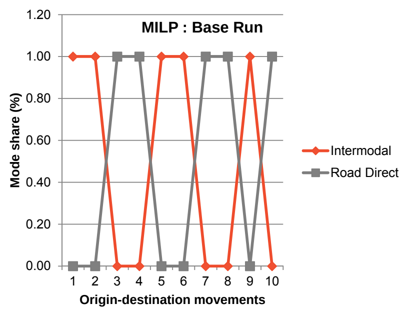
Results : Choice of location - MILP

▪The MILP Resulted in **IMT 1** as the best site for locating any new IMT with a 50% of the market

▪Can be observed that all flows from the origin to destinations 1,2,5,6, and 9 went through IMT 1

▪A Clear demonstration of corner point solution of the MILP

Destination	Cargo (TEUs)	IMT 1	Road Direct
1	476	476	-
2	193	193	-
3	777	-	777
4	156	-	156
5	109	109	-
6	1019	1,019	-
7	376	-	376
8	373	-	373
9	688	688	-
10	791	-	791
Total	4,957	2,484	2,473
Mode Share		50%	50%



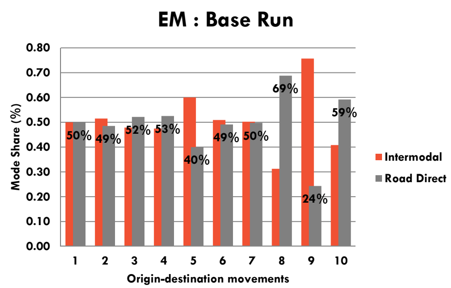
Results : Choice of location – Entropy model

▪The MILP Resulted in **IMT 2** as the best site for locating any new IMT with a 51% share

▪The Entropy model do not suffer from 'corner' solutions.

▪E.g. 50% splits of destination 1 demand. MILP would have assigned100% of the demand to either the road direct or IMT 2 mode

Destination	Cargo (TEUs)	IMT 2	Road Direct
1	476	238	238
2	193	99	93
3	777	372	405
4	156	74	82
5	109	65	44
6	1019	519	500
7	376	189	187
8	373	116	256
9	688	521	167
10	791	323	468
Total	4,957		2,442
Mode Share	51%		49%



Results : Choice of location – Entropy model

▪It determines the demand for each mode probabilistically:

▪Accounting for the fact that not all factors affecting the choice of mode are captured in the modelling process

Destination	Cargo (TEUs)	IMT 2	Road Direct
1	476	238	238
2	193	99	93
3	777	372	405
4	156	74	82
5	109	65	44
6	1019	519	500
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9	688	521	167
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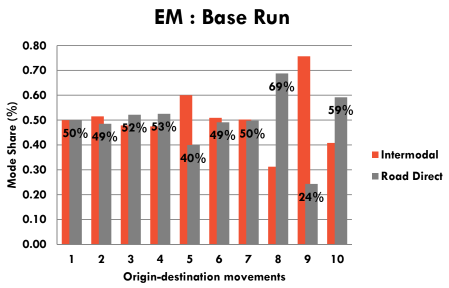
Mode Share	51%		49%



Results : Policy Testing

▪Assume we want to testing for policies that can promote more use of the located IMT.

▪A plausible policy may be road pricing or subsidy for intermodal transport users

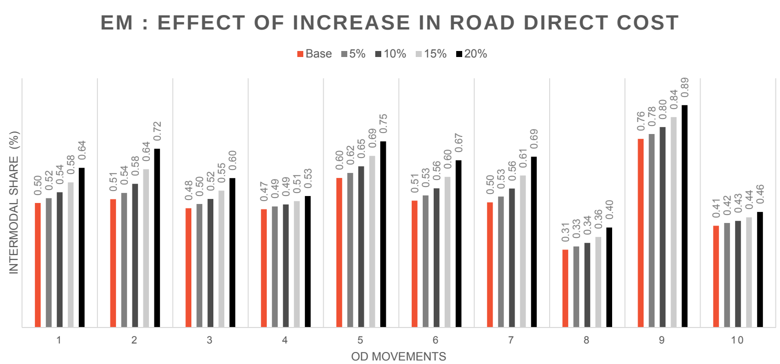
▪Implemented by increasing the overall cost of road direct by 5%, 10%, 15% and 20%

▪ Keeping the cost of the located IMT unchanged

Results : Policy Testing – Entropy model

▪As we would expect, the intermodal transport share increases marginally as the cost of road direct transport increases.

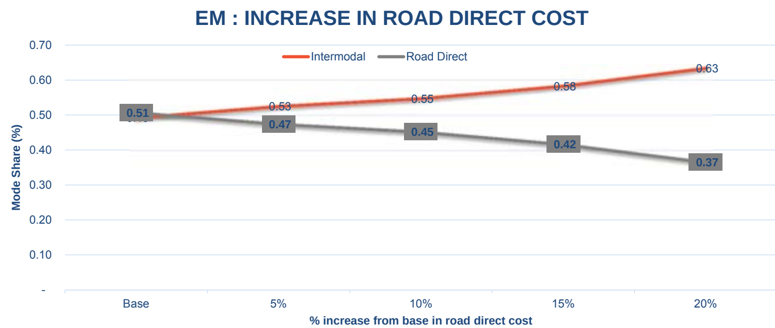
▪For the share of flows to destination 1 increased from 50% (base) to 64%



Results : Policy Testing – Entropy model

▪Overall mode share over all origin-destination pairs

▪Also demonstrate marginal distribution of intermodal share with increasing road direct cost.



CONCLUSIONS

– IMTs have the potential to improve the efficiency, sustainability and reliability of intermodal (containerised) cargo flows

– In a context of many shippers exercising choice, the mixed integer linear program (MILP) model is inappropriate due to corner solutions

– Entropy maximisation (EM) model provides integrated choice models and is relatively easy to solve