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The utility maximising ferry network design problem

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Abstract Ferry services are an important mode of public transport in a number of large cities with harbours or rivers, including Brisbane and Sydney. The ferry network design problem (FNDP) focuses on finding a network of ferry services to meet the demand for mobility with a good level of service at a reasonable operating cost. An important feature of the FNDP is that the objective behind the design of the ferry services, namely expected passenger utility, is the same as the objective governing the choice of services made by passengers to complete their trips, resulting in a single level network design problem rather than the more conventional bilevel network design problem. This paper presents an entropy maximising framework that solves the utility maximising service choice and the network design problem jointly.

Keywords: Ferries · Network design · Utility maximisation · Entropy maximisation

1 Introduction

Many studies have formulated the network design problem as a capacity constrained, multi-commodity or multi-mode problem where links between nodes are represented as integer decision variables and commodity flows as continuous variables (Lo and McCord, 1995, 1998; Wang and Lo, 2008, 2010; Wang and Meng, 2012; Wang, 2013; Wang et al., 2013). For the ferry network design problem (FNDP), Lai and Lo (2004)

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developed a ferry fleet management model to optimize simultaneously the fleet size, routing, and service schedule. Wang and Lo (2008) formulated the problem with different service types, considering user preferences for express versus ordinary services. Lo et al. (2013) studied the stochastic ferry service network design problem considering two types of service, regular and ad hoc, to minimize the total operating cost and passenger travel and waiting time.

Most FNDP formulations involve solving a mixed-integer program (MIP), which can be computationally formidable. Moreover, costs are conventionally treated as deterministic. In recent work, Teye et al. (2017a, b, c) formulated a facility location problem for the case of multiple shippers, who decide which if any facility to choose, and where these facilities should be located to maximise expected user utility. Since utility is the basis for both facility choice by shippers and facility location, the combined problem is single level. It is shown in Teye et al. (2017a, b, c) that the combined problem can be formulated as an entropy maximising problem and solved efficiently by a Lagrange relaxation technique.

An entropy maximising approach to the FNDP has many attractions. One result of maximising entropy is the logit discrete choice model. In this case, there are two layers of choice, namely the paths through the ferry network chosen by passengers, and the design of the ferry routes to support those paths. The random utility interpretation of the logit discrete choice model allows us to interpret the logsum term as a measure of expected passenger utility. We can then seek ferry routes that maximise expected passenger utility, subject to passenger path choice and appropriate constraints. As both passenger path choice and network design are governed by expected passenger utility, the combined problem may be formulated as a single entropy maximisation problem. This approach follows that proposed by Teye et al. (2017a,b,c) for locating multi-shipper intermodal terminals, replacing containers by passengers and the depot location problem by the ferry route design problem.

An additional attraction of entropy maximisation is the assertion (Fisk et al., 1985; Jaynes, 1957; Shannon, 1948; Wilson, 1970) that it constructs the least biased probability distribution for a variable of interest consistent with all we know about that variable as expressed by the constraints of the problem. It turns out that the maximised value of a log function on the number of possible ways that a state of the system can occur corresponds to the amount of missing information (or uncertainty or entropy) in the construction of the probability distribution (Boltzmann, 1872; Jaynes, 1957; Shannon, 1948).

In this paper we focus on spanning trees rather than ferry routes per se as we are principally interested in which ferry stations should be connected to each other and where the hubs should be located. Many other factors would need to be considered to design optimum ferry routes, such as crew rostering, bunkering, provisioning and maintenance. If there are n ferry stations then a spanning tree will have $n-1$ links. There are $n!/2$ spanning trees, each connecting any pair of nodes by one path. As we assume that every link is operated in both directions, backtracking on any path is a theoretical possibility, but the presence of the budget constraint discourages this.

2 Methodology

We treat passenger utility randomly thus recognising passenger heterogeneity. To achieve this, we formulate an entropy maximising problem with respect to passenger flows x and maximise entropy with respect to a given passenger demand matrix, passenger flow conservation constraints, a total travel distance budget, and binary network design variables y. The set of feasible networks is restricted to spanning trees for the reasons outlined previously. Entropy maximisation is equivalent to utility maximisation as entropy maximisation delivers the logit discrete choice model, which is known to be consistent with utility maximisation when utility is random with a Gumbel distribution.

The FNDP supply-side decision variable is $y_{ij} \in \{0,1\}$, which indicates whether there is a connection between ferry station i and ferry station j with no intermediate ferry stations. As attention is limited to spanning trees, a ferry network of $n = |F|$ ferry stations can have only $n-1$ direct connections (links) between ferry stations (nodes):

$$\sum\nolimits_{i,j \in F} y_{ij} \leq n-1 \tag{1}$$

To ensure there are no cycles in the network, we added the following subtour constraints:

$$\sum\nolimits_{i,j \in V} y_{ij} \leq |V| - 1; \forall\, V \in F, V \neq F, V \neq \emptyset \tag{2}$$

The number of subsets V of ferry stations is potential very large, making these constraints difficult to implement.

The demand-side decision variable is x_{ij}^{m}, which is the flow of passengers from ferry station i to ferry station j destined for ferry station m. We assume a fixed origin-destination (OD) matrix of passenger trips for the ferry network, hence the demand flow conservation constraint is:

$$\sum\nolimits_{j \in F \setminus \{i\}} \left(x_{ij}^{m} - x_{ji}^{m}\right) = \begin{cases} -\sum\nolimits_{j \in S} D_{jm} \text{ if } i = m \\ D_{im} \text{ otherwise} \end{cases}, \forall i \in F, m \in F \tag{3}$$

implying that an excess of passengers leaving ferry station i destined for ferry station m must be equal to the origin-destination flow of passengers D_{im} from ferry station i to ferry station m, unless $i = m$.

The following passenger flow constraint is added to ensure that only ferry links included in the spanning tree are available to passengers:

$$\sum_{m \in F \setminus \{i\}} x_{ij}^{m} \leq M y_{ij}, \forall i \in F, j \in F \setminus \{i\} \tag{4}$$

where M is a large number ('big M').

Let T_{ij} be the sailing time between ferry station i and ferry station j. We assume that passengers are sensitive to sailing times and account for this by setting a notional travel time budget T:

$$\sum_{i \in F; j, m \in F \setminus \{i\}} T_{ij} x_{ij}^{m} \leq T \tag{5}$$

The link flows are determined by the path flows via the link flow conservation constraint:

$$x_{ij}^{m} = \sum_{k \in P(rm); r \in F/\{m\}} \delta_{ijkrm} h_{krm}, \forall i \in F/\{m\}, j \in F \setminus \{i\} \tag{6}$$

where h_{krm} is the flow of passengers on path $k \in P(rm)$ from ferry station $r \in F$ to ferry station $m \in F$ and δ_{ijkrm} is equal to 1 if link (ij) lies on path $k \in P(rm)$ from ferry station $r \in F$ to ferry station $m \in F$, and 0 otherwise. $P(rm)$ is the set of paths from ferry station $r \in F$ to ferry station $m \in F$.

The path entropy function is:

$$E = -\sum_{r \in F; m \in F \setminus \{i\}} h_{rm} (\ln(h_{rm}) - 1)$$

Maximisation of path entropy subject to constraints (1) to (6) delivers the utility maximising passenger flows.

The presence of spanning the spanning tree constraints make this problem difficult to solve, so we have developed a greedy heuristic for approximately solving the problem. The heuristic starts with the minimal spanning tree calculated by Kruskal's algorithm. Links are then swapped, inserting the link which increases path entropy (passenger utility) most and deleting the link that reduces path entropy (passenger utility) least. A local optimum is reached fairly quickly, whereby the link just inserted is immediately deleted. To escape the local optimum, we taboo a link if it is removed just after insertion, and continue swapping until there are no more links to taboo.

3 Case study

The network design model was implemented for the ferry network in Sydney to demonstrate the applicability of the ferry connection problem. The current ferry network is shown in Fig. 1.

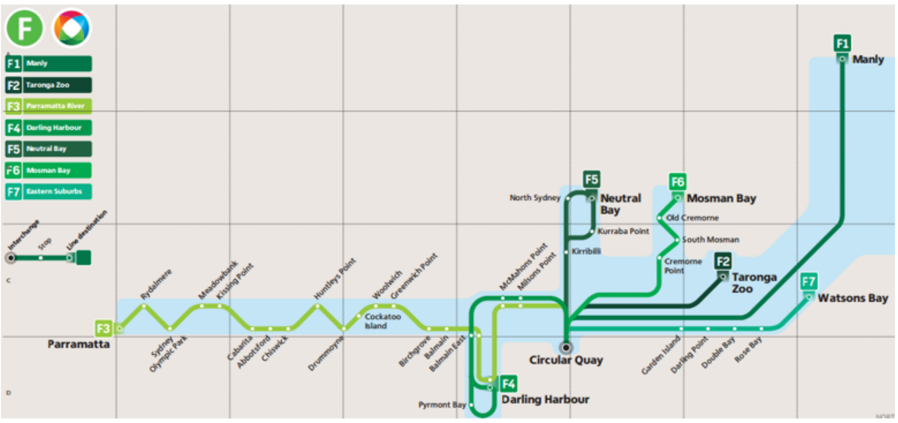

Fig. 1: Sydney ferry network (Source: https://transportnsw.info/getting-around/ferry)

The current Sydney ferry network contains 36 ferry stations. The minimal spanning tree based on Euclidean distances is shown in Fig. 2. The swap heuristic was implemented in the Scilab environment, leading to the optimal set of ferry connections illustrated in Fig. 3. Interestingly the results confirm the dominant role of Circular Quay as a hub for the central and eastern harbour, while Darling Harbour is the hub for the western harbour.

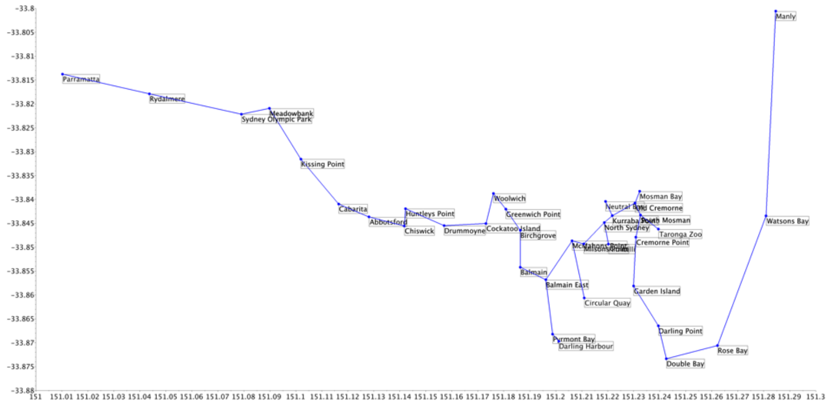

Fig. 2: Minimal spanning tree based on Euclidean distances

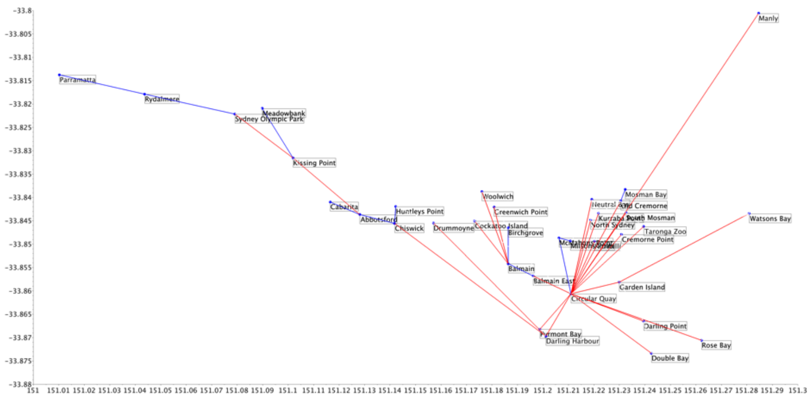

Fig. 3: Maximum entropy (passenger utility) spanning tree

3 Conclusions

The principle contribution of this paper is the presentation of a utility maximising FNDP achieved by entropy maximisation. This combines network design with passenger path choice in a single optimisation problem. We have restricted the networks considered to spanning trees, as these indicate which pairs of ferry stations should be connected to each other and where the hubs should be located. The optimisation of ferry routes per se would require consideration of many other factors, like crew rostering, provisioning and bunkering. The path choice model implicit in entropy maximisation with a budget constraint allows for passenger heterogeneity.

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References

Boltzmann, L., 1872. In: Brush, S.G. (Ed.), Lectures on Gas Theory. *University of California Press, Berkeley*.

Fisk, C., Smith, T. E., Weibull, J. W., Erlander, S., Roy, J. R., Batten, D. F., Norcliffe, A., 1985. Entropy and information theory: are we missing something?. *Environment and Planning A*, *17*(5), 679-710.

Jaynes, E. T., 1957. Information theory and statistical mechanics. *Physical review*, *106*(4), 620-630.

Lai, M.F., Lo, H.K., 2004. Ferry service network design: optimal fleet size, routing, and scheduling. *Transportation Research Part A, 38*(4), 305–328.

Lo, H.K., An, K., Lin, W.H., 2013. Ferry service network design under demand uncertainty. *Transportation Research Part E, 59*, 48–70.

Lo, H.K., McCord, M.R., 1995. Routing through dynamic ocean currents: general heuristics and empirical results in the gulf stream region. *Transportation Research Part B, 29(2)*, 109–124.

Lo, H.K., McCord, M.R., 1998. Adaptive ship routing through stochastic ocean currents: general formulations and empirical results. *Transportation Research Part A, 32(7)*, 547–561.

Shannon, C.E., 1948. A mathematical theory of communication. *Bell System Technical Journal 27*, 379–423 and 623–656.

Teye, C., Bell, M.G., Bliemer, M.C., 2017a. Urban intermodal terminals: The entropy maximising facility location problem. *Transportation Research Part B: Methodological*, 100, 64-81.

Teye, C., Bell, M.G., Bliemer, M.C., 2017b. Entropy maximising facility location model for port city intermodal terminals. *Transportation Research Part E: Logistics and Transportation Review*, 100, 1-16.

Teye, C., Bell, M.G., Bliemer, M.C., 2017c. Locating urban and regional container terminals in a competitive environment: An entropy maximising approach. *Transportation Research Procedia,* 23, 208-227.

Wang, D.Z.W., Lo, H.K., 2008. Multi-fleet ferry service network design with passenger preferences for differential services. *Transportation Research Part B, 42(9)*, 798–822.

Wang, D.Z.W., Lo, H.K., 2010. Global optimum of the linearized network design problem with equilibrium flows. *Transportation Research Part B, 44*, 482–492.

Wang, S., 2013. Essential elements in tactical planning models for container liner shipping. *Transportation Research Part B, 54*, 84–99.

Wang, S., Meng, Q., 2012. Liner ship route schedule design with sea contingency time and port time uncertainty. *Transportation Research Part B, 46(5)*, 615–633.

Wang, S., Meng, Q., Yang, H., 2013. Global optimization methods for the discrete network design problem. *Transportation Research Part B, 50*, 42–60.

Wilson, A.G., 1970. Entropy in Urban and Regional Modelling. *Pion, London*.