Freight Allocation Problems in the Transportation Industry
交通運輸業中的貨物分配問題

Submitted to
Department of Management Sciences
管理科學系
in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy
哲學博士學位

by

Qin Hu
秦虎

January 2011
二零一一年一月
Freight Allocation Problems in the Transportation Industry

Qin, Hu
Department of Management Sciences
College of Business
City University of Hong Kong

Abstract

This thesis studies freight allocation problems faced by the transportation practitioners at both strategic and operational levels. Shippers and carriers are the key players in the transportation market. The shippers are manufacturers, buying agents, third-party logistics providers (3PL) and any organization that needs to move freight. The carriers are the transportation service providers who can move the freight, such as shipping and trucking companies. The problems investigated in the thesis are all motivated by real projects and related to long-distance ocean shipping.

In the transportation market, carriers often offer price discounts to encourage shippers to purchase more transportation service. Usually, the discount rate offered by each carrier is related to the total freight quantity gained from the shipper across all shipping lanes. The first problem in the thesis aims at helping a shipper allocate forecasted annual demand of each shipping lane to candidate carriers with consideration of discount and minimum quantity commitment while minimizing the total transportation cost. This problem is \( \mathcal{NP} \)-hard in the strong sense, and is therefore unlikely to be solvable optimally in reasonable computation time for large instances. Hence, we propose a heuristic-based algorithm that combines a filter-and-fan search scheme and a tabu search mechanism for the
problem. Experiments on a large number of randomly generated test instances show that as the problem size increases, our algorithm produces superior solutions in less computation time and requires less computer memory, compared to a leading mixed integer programming (MIP) solver.

When conducting freight allocation, the shipper might need to consider some other aspects. Next, we study a freight allocation problem for a shipper who acts as the buying office of a large international retail distributor. The task of the shipper is to plan the distribution of goods from Asia to various sales divisions across Europe. The goods are transported along shipping lanes by carriers, many of which have collaborated to form strategic alliances. Each lane must be serviced by a minimum number of carriers that must belong to a minimum number of alliances and each carrier requires a minimum total freight quantity over all lanes. Moreover, the allocation must not assign an overly high proportion of freight to the more expensive shipping companies servicing any particular lane in order to ensure fairness for different sales divisions, which we call the lane cost balancing constraint. The problem is to allocate projected annual demand of each shipping lane to carriers taking all the above constraints into account, such that the total transportation cost is minimized. We formulate this problem into an MIP model, and show that not only is finding an optimal solution computationally intractable, but so is finding a feasible solution. Therefore, to produce high-quality solutions practically, we devised a meta-heuristic approach for the problem based on tabu search. Our approach has since been developed into an application that is currently employed by the shipper, and it has proved to be a powerful and effective support tool.

The two problems already described both appear at the strategic level. In practice, many shippers need to optimize the distribution of goods at the operational level. The third problem in the thesis produces execution plans for a 3PL
to send a batch of shipments to their retail stores distributed in the United States. Each shipment is firstly shipped to one of distribution hubs in the United States from one warehouse hub in China by container transportation and then sent to its retail store by some parcel express company. Different distribution hubs lead to different parcel delivery costs for each shipment and we assume each distribution hub corresponds to only one shipping route. In addition, one shipment may consists of one or multiple items and for simplifying store operations the items belonging to the same shipment are required to be transported along a unique shipping route. The problem makes decisions on how to allocate shipments to shipping routes and how to load items into containers with various sizes while minimizing the sum of container and parcel delivery costs. We formulate this problem as a variant of the variable size bin-packing problem (VSBPP), which is obviously $\mathcal{NP}$-complete. To solve this problem practically, we propose a genetic algorithm that embeds some local search heuristics and heuristics for the VSBPP. The practical usefulness of the model as well as its solution approach is substantiated by its deployment with a multinational 3PL.
Table of Contents

1 Introduction ........................................... 1
  1.1 Background ........................................ 1
  1.2 Contributions ...................................... 6
  1.3 Thesis Organization .................................. 8

2 The Freight Allocation Problem with All-Units Quantity-Based Discount ........................................... 9
  2.1 Introduction ........................................ 9
  2.2 Literature Review ................................... 10
  2.3 Problem Formulation .................................. 13
  2.4 Solution Procedure .................................. 18
    2.4.1 Problem Transformation ....................... 19
    2.4.2 Filter-and-fan Procedure ..................... 20
    2.4.3 Tabu Conditions ................................ 22
    2.4.4 Algorithm Speed-up .......................... 23
    2.4.5 Candidate Generation Algorithm ............. 25
  2.5 Computational Experiments ........................ 28
    2.5.1 Test Instance Generation ..................... 28
    2.5.2 Results & Analysis ........................... 30
  2.6 Summary ............................................ 31
3 The Freight Allocation Problem with Lane Cost Balancing Constraint

3.1 Introduction .................................... 34
3.2 Related Works .................................. 36
3.3 Problem Formulation ............................ 38
   3.3.1 Problem Description ....................... 38
   3.3.2 Mixed Integer Programming Model .......... 41
3.4 Solution Methodology .......................... 47
   3.4.1 Random Move Tabu Search ................. 48
   3.4.2 Random Move Heuristic ................... 52
   3.4.3 Application Output ...................... 57
3.5 Computational Experiments ..................... 58
   3.5.1 Experiment on Real-World Instance .......... 59
   3.5.2 Generated Test Instances ................. 60
3.6 Summary .................................... 65

4 The Freight Allocation and Consolidation Problem with Container Loading

4.1 Introduction .................................... 66
4.2 Literature Review .............................. 67
4.3 Mathematical Formulation ...................... 70
4.4 Genetic Algorithm ............................. 72
   4.4.1 Chromosome Encoding ..................... 73
   4.4.2 Initial Population ......................... 76
   4.4.3 Fitness Function .......................... 76
   4.4.4 Selection ................................. 82
   4.4.5 Crossover ................................. 83
   4.4.6 Mutation ................................. 84
4.4.7 Local Refinement .......................................................... 85
4.4.8 Termination Criterion ......................................................... 86
4.5 Computational Experiments .................................................... 87
  4.5.1 Test Instances ................................................................. 87
  4.5.2 Experimental Setup .......................................................... 89
  4.5.3 Results and Analysis ......................................................... 91
4.6 Conclusions ........................................................................ 114

5 Conclusions ........................................................................... 116
  5.1 Summary ........................................................................... 116
  5.2 Future Work ....................................................................... 118

Bibliography ................................................................................ 121
List of Figures

1.1 A transportation service procurement process ........... 2
1.2 Transportation network of the 3PL ....................... 5
1.3 Possible routes ........................................ 5

2.1 Example of filter-and-fan algorithm ($\eta_1 = 3, \eta_2 = 2, L = 4$) 22
2.2 Tabu conditions on one tree path ....................... 24

3.1 Allocation plan tradeoff graph .......................... 58

4.1 An example of chromosome encoding scheme ............ 74
4.2 An alternative chromosome encoding scheme ............ 75
4.3 (a) Randomly choose two crossover points. (b) Swap genes. (c) Remove conflicting loading orders. (d) Replace loading orders based on mapping. 84
4.4 (a) Type 1 mutation modifies the shipping route of shipment 2 from 1 to 3. (b) Type 2 mutation exchanges loading orders of items 2 and 6. 85
4.5 An example of consolidation with $\lambda = 2$ .................. 86
4.6 Example FACPCL map .................................. 88
List of Tables

2.1 Example of discount intervals ........................................ 14
2.2 Results of the medium-size instances ................................. 32
2.3 Results of the large-size instances .................................... 33
3.1 Example of unbalanced allocation ...................................... 41
3.2 Example of balanced allocation ....................................... 42
3.3 $I_i = \{1, 2, 3, 4, 5\}, q_i^r = 0.3, b_i = 0$ ............................ 53
3.4 Rules for setting maximum percentage allocation values .......... 60
3.5 Results for the MIP2 model ............................................ 62
3.6 Results for the MIP1 model for instances sizes 50 and 100 ....... 63
3.7 Results for the MIP1 model for instances sizes 300 and 500 ...... 64
4.1 Average CPLEX gaps and computation times for the instance
groups with $|S| = 20$ and small items .................................. 92
4.2 CPLEX results for the instances with $|S| = 20$ and $|R| = 5$ ....... 93
4.3 CPLEX results for the instances with $|S| = 20$ and $|R| = 10$ ....... 94
4.4 CPLEX results for the instances with $|S| = 50$ and $|R| = 5$ ....... 95
4.5 CPLEX results for the instances with $|S| = 50$ and $|R| = 10$ ....... 96
4.6 CPLEX results for the instances with $|S| = 80$ and $|R| = 5$ ....... 97
4.7 CPLEX results for the instances with $|S| = 80$ and $|R| = 10$ ...... 99
4.8 Average CPLEX gaps for all instance groups ....................... 100
4.9 Performance comparison between GA1 and CPLEX ................. 101
4.10 Performance comparison between GA1 and GA2 ........................................ 102
4.11 GA1 results for the instances with $|S| = 20$ and $|R| = 5$ .................................. 103
4.12 GA2 results for the instances with $|S| = 20$ and $|R| = 5$ .................................. 104
4.13 GA1 results for the instances with $|S| = 20$ and $|R| = 10$ ................................. 105
4.14 GA2 results for the instances with $|S| = 20$ and $|R| = 10$ ................................. 106
4.15 GA1 results for the instances with $|S| = 50$ and $|R| = 5$ .................................. 107
4.16 GA2 results for the instances with $|S| = 50$ and $|R| = 5$ .................................. 108
4.17 GA1 results for the instances with $|S| = 50$ and $|R| = 10$ ................................. 109
4.18 GA2 results for the instances with $|S| = 50$ and $|R| = 10$ ................................. 110
4.19 GA1 results for the instances with $|S| = 80$ and $|R| = 5$ .................................. 111
4.20 GA2 results for the instances with $|S| = 80$ and $|R| = 5$ .................................. 112
4.21 GA1 results for the instances with $|S| = 80$ and $|R| = 10$ ................................. 113
4.22 GA2 results for the instances with $|S| = 80$ and $|R| = 10$ ................................. 115

5.1 $I_1 = \{1, 2, 3, 4, 5\}, u_1 = 0.3$ ................................................................. 119