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研究課題名（和文）Exact Optimization of Multiple Allocation Hub Location Routing Problem

研究課題名（英文）Exact Optimization of Multiple Allocation Hub Location Routing Problem

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研究成果の概要（和文）：大都市圏における郵便配達サービスに対する需要の高まりは、環境負荷や配送費用の上昇などの社会問題を引き起こしている。ハブアンドスポーク型の配送ネットワークを整備することが考えられる。ハブアンドスポークネットワークの最適化は、ハブ配置配送計画問題（HLRP）に相当するが、HLRPに関する研究は充分に蓄積されていない。本論文は、社会問題の抑制・解消、ならびに、HLRP（容量制約付き単一割り当てハブ配置配送計画問題と容量制約付きマルチ割り当てハブ配置配送計画問題）に関連する知見を充実させることに着目して、モデル化と解法アルゴリズムの開発を通じて、都市内郵便配達システムの最適化を試みたものである。

研究成果の学術的意義や社会的意義
本研究では、都市内郵便配達システムに関連する拠点配置と配送計画の効率化研究の発展に貢献するものである。CSAHLRPやCMAHLRPのモデル化、および、解法アルゴリズムの提案を行い、都市内郵便配達システムの設計への応用について検討したものであり、理論的な側面だけでなく、実用的な計画策定にも有効な知見を与えるものである。開発したCMAHLRPモデルや、その解法アルゴリズムを、実際的な問題例に適用した。その結果、本論文が開発した手法により、配送費用とCO2排出量が効率的に削減されることを確認した。

研究成果の概要（英文）：In recent years, the increasing demand for postal delivery services in metropolitan areas has given rise to social problems such as environmental impact and rising delivery costs. One possible solution to these problems is to develop a hub-and-spoke delivery network. Optimizing a hub-and-spoke network corresponds to the hub location routing problem (HLRP), but there has not been a sufficient amount of research on HLRP. In light of the above background, this paper attempts to optimize an urban postal delivery system through modeling and the development of a solution algorithm, with a focus on preventing and resolving these social problems as well as enhancing knowledge related to HLRP. We also developed an application of the CMAHLRP in solving warehouse matching platform system (WMPS). A realistic instance was created using the data provided by a company. The results indicate that applying CMAHLRP can efficiently reduce the operating costs and the CO2 emissions.

研究分野：交通計画

キーワード：Multiple allocation　Hub location and Routing　Mathematical Modelling

１．研究開始当初の背景

Urban freight movement (such as parcel delivery, shops and office inventory replenishment, etc.) is a major economic activities in cities. However, this also contributes its share in environmental and other traffic related problems. Therefore, optimization of urban freight movement has both economic as well social benefits. Traditionally, operations of a large urban freight carrier are modelled using Hub Location and Routing Problem (HRLP). Given a network of branch offices/ customers, two steps are used in the HLRP. In first step, depots (hubs) are located and each branch office/customer is assigned to a "single" hub forming a cluster. In second step, optimal routing is sought for each cluster. Because each customer is assigned to only one hub, the problem is referred as "single allocation" (as shown in Figure 1). If the demand of freight movement arises between customers i and j belonging to two different hubs (n and m, respectively); it must be routed via inter-hub movement. This operation causes a large detour and would generate extra costs and emissions. This problem can be managed by allocating a customer to multiple hubs (called Multiple Allocation HLRP) (as shown in Figure 2).

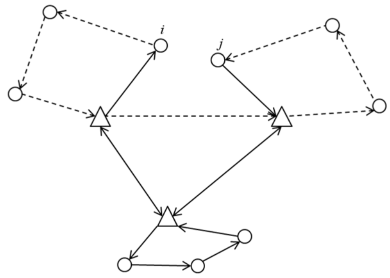


Figure 1 Detour in case of single allocation

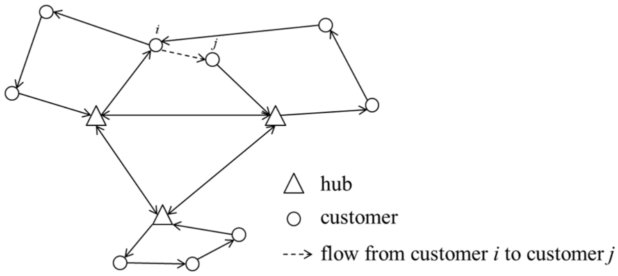


Figure 2 Cost reduction in case of multi allocation

２．研究の目的

The main objective of this research is to create an exact optimization technique for Multiple allocation HLRP. In order to appreciate the economic (i.e. delivery cost) advantages of the proposed MAHLRP, it will be compared with the standard single allocation version. For this purposes, a novel capacitated version of the SAHLRP problem will be modelled and an exact solution algorithm will also be developed for it. The exact optimization are usually feasible for small instances of this type of problems. But, it provides benchmark solutions, which are essential to evaluate the performance of heuristics approaches, which are usually faster and can solve real-life (large sized) problems. We will also propose a heuristics solution algorithms for both capacitated SAHLRP and MAHLRP. A realistic case study applying the developed models and algorithms will also be presented, highlighting the applicability of the approach and emphasizing its economic and social benefits.

３．研究の方法

The main approach for this research was to develop mathematical models for the CSAHLRP and CMAHLRP along with their exact and heuristics solutions. Extensive numerical experiments on newly generated benchmark instances were conducted to show the efficacy of the developed exact and heuristics solutions.

(1) Exact Solution of the CSAHLRP and the CMAHLRP:
New mixed-integer programming (MIP) formulations for the CSAHLRP and MAHLRP were proposed. These formulations can be used to solve their small-sized instances via commercial solvers (such as CPLEX). To solve larger instances, exact solution algorithms were proposed for the first time, based on the branch-and-price-and-cut (BPC) framework. The BPC approach decomposes the problem at hand into a master problem (MP) and a pricing subproblem. The algorithm begins with a restriction of the MP, which only considers a small subset of the variables, called as restricted master problem

(RMP). The variables found by the pricing subproblem are gradually added to the RMP. The process terminates when no variable is found, and then the linear relaxation of the MP is solved optimally. To obtain an integer solution, column generation is often embedded in a branch-and-bound framework, resulting in a branch-and-price algorithm (as shown in the Figure). For the CSAHLRP the pricing subproblem was a capacitated shortest path problem, to be solved to get feasible routes from each open hub. For the CMAHLRP the capacity constraints were kept in the master problem due to multi-allocation, and instead a route length resource was used in the shortest path pricing subproblem. The MP is strengthened by several valid inequalities, and the pricing subproblem is solved by a bidirectional labelling algorithm.

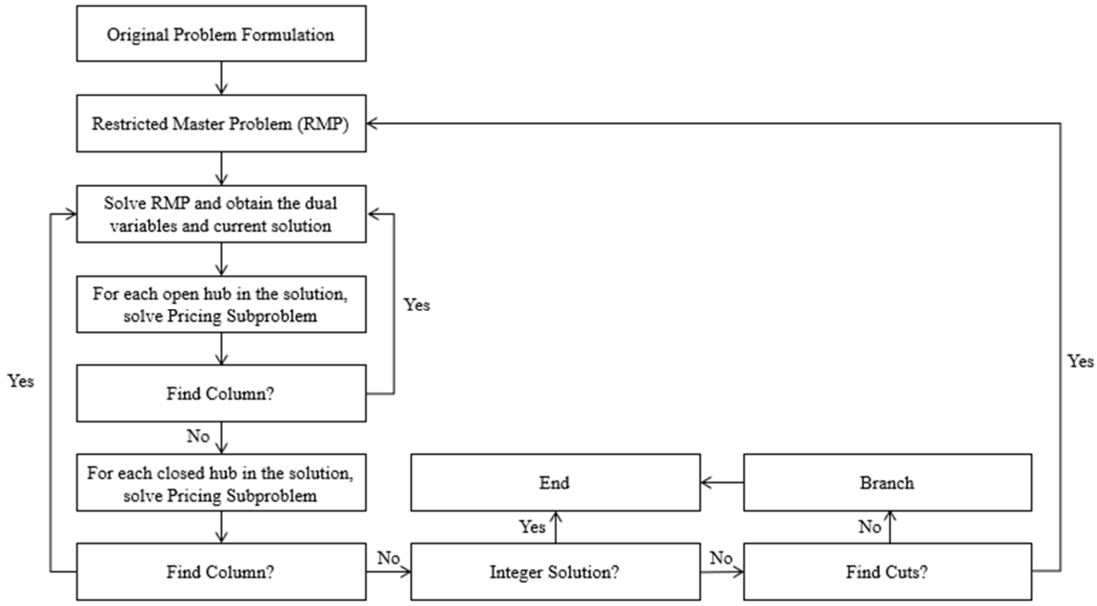


Figure: Outline of branch-and-price-and-cut algorithm (for each branch node)

(2) Heuristic Solution of the CSAHLRP and the CMAHLRP:
Meta-heuristic algorithms, named adaptive large neighbourhood decomposition search (ALNDS), were developed for both CSAHLRP and MAHLRP to solve the large-sized instances. The ALNDS algorithm generates an initial solution first and tries to improve it iteratively in the form of subproblems (i.e. hub location, node allocation, and routing). In each iteration, one of the subproblems is selected, and the selected subproblem of the existing solution is destroyed by a destroy operator (e.g. random hub removal, worst allocation removal, and worst cost non-hub node removal from routes, etc.) and repaired by a repair operator (greedy insertion, and regret insertion) to get a new solution. For each subproblem, a series of destroy and repair operators is employed. Each subproblem, destroy operator, and repair operator is associated with a weight and selected by a roulette mechanism according to their weights. The weights are adjusted adaptively based on the past iterations. If the new solution is better than the current solution, it is accepted and used as the input for the next iteration. Otherwise, a SA mechanism is applied to determine whether it is accepted. The process terminates when the stopping condition is met. Algorithm 1 shows a pseudocode overview of our solution method.

Algorithm 1: ALNDS
Generate initial solution S_0
Set current solution $S' = S_0$
Set current best solution $S_{best} = S_0$
While terminal condition unsatisfied:
    Select a subproblem
    Select destroy method and destroy the solution of the subproblem
    Select repair method and repair the solution of the subproblem
    Obtain the new solution S''
If S'' better than S_{best}
        $S_{best} = S''$

$S' = S''$
Else
If S'' better than S'
$S' = S''$
Else
Accept solution with SA mechanism
Endif
Endif
Update scores of corresponding subproblem and operators
Update weights of subproblems, destroy methods and repair methods if needed
End While
Output S_{best}

The ALNDS algorithm developed was extended to solve the CMAHLRP on large-sized instances based on the following schemes: i) An approximation algorithm was used to approximate the objective function value of the solutions. ii) Non-hub nodes were divided into subnodes to enable multi-allocation option (as shown in the figure). Correspondingly, the destroy and repair operators do not remove/insert complete non-hub nodes, while only subnodes are considered in these operators.

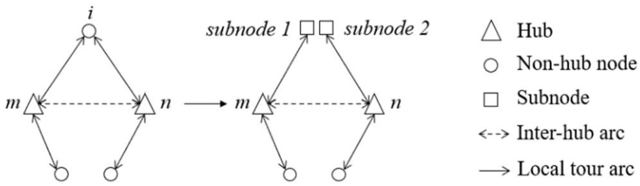


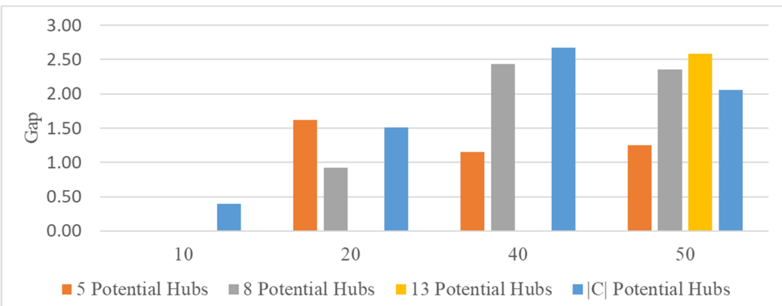
Figure: Split of non-hub nodes

４．研究成果

A series of numerical experiments are undertaken on the instances generated from the benchmark data set to test (the Australia Post or AP data set) the proposed model and algorithms. In general, the results prove that the proposed algorithms outperform the CPLEX in solving the CMAHLRP as well as that applying the multi-allocation scheme can efficiently reduce the operating cost as compared to the CSAHLRP.

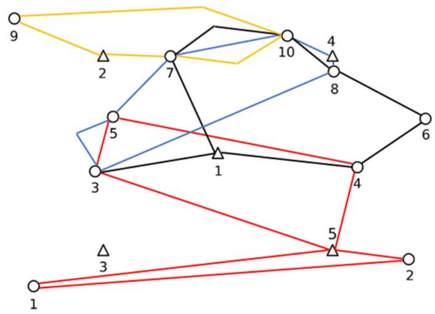
(1) Comparison of Exact Solution Algorithm of CSAHLRP with CPLEX:
In total 28 instances from 5 to 40 non-hub nodes were tested. CPLEX (a commercially available solver) could only found optimal solutions for the eight smallest instances with 10 and 15 non-hub nodes. The proposed algorithm was able to find optimal solutions for most of the instances (22 of 28). For the instances solved optimally by both the CPLEX solver and the proposed algorithm, the average computational time for these instances decreased from 137.43s (CPLEX) to just 10.95s (proposed algorithm). The average CPU times for solving the instances with 20 and 25 non-hub nodes (only solved by the proposed algorithm) were 610.00s and 2780.72s, respectively. These results prove that the proposed algorithm outperforms CPLEX in the solution quality and can provide optimal solutions or high-quality solutions for this variant of problem.

(2) Comparison of Exact Solution Algorithm of CSAHLRP with Heuristics (ALNDS):
The performance of the developed heuristics was evaluated in variety of ways. For example, it was compared with CPLEX, and with our proposed exact solution of the CSAHLRP. For the small-sized instances solved optimally by the CPLEX, the computational times were significantly reduced in the ALNDS (from 33.64 seconds on average to 2.40 seconds on average). Similarly, for the instances solved optimally by both the branch-and-price-cut algorithm and the ALNDS, the computational times were significantly reduced in the ALNDS (from 1320.02 seconds on



average to 17.68 seconds on average). Another evaluation shows that the ALNDS remained robust (with smaller percentage gap between its best and average output of 10 runs), even when the number of hubs and non-hub nodes increased.

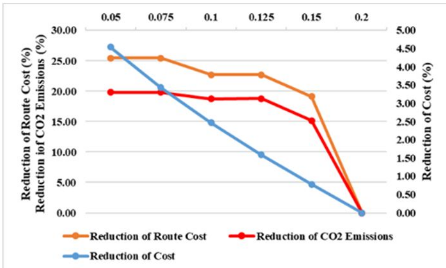
(3) Comparison of Exact Solution Algorithm of CMAHLRP with CPLEX:
Solving the CMAHLRP is much more difficult than solving the CSAHLRP due to the multi-allocation (as shown in the figure), therefore, only 20 instances from 5 to 25 non-hub nodes were tested. CPLEX (a commercially available solver) could only found optimal solutions for the ten smallest instances with 10 and 15 non-hub nodes, and even couldn’t provide a feasible integer solution for one of the 25 non-hub nodes instance. The proposed algorithm was able to find optimal solutions for 18 instances. For the instances that have not been solved exactly, the optimality gaps (the difference between upper and lower bound) were relatively small (0.33% and 0.19%), whereas for the CPLEX the corresponding average was 25.53% on average. For the instances solved optimally by both the CPLEX solver and the proposed algorithm, the average computational time for these instances decreased from 1496.52s (CPLEX) to just 137.51s (proposed algorithm). These results prove that the proposed algorithm outperforms CPLEX in the solution quality and can provide optimal solutions or high-quality solutions for this variant of problem.



(4) Comparison of Exact Solution Algorithm of CMAHLRP with Heuristics (ALNDS):
In case of CMAHLRP also the proposed ALNDS performed satisfactorily. For example, out of the 18 exact solutions, ALNDS was able to find exact solutions for 15 instances at significantly low computation time (65.11 seconds on average as compared to 752.05 seconds (average of exact solution algorithm)). The ALNDS also outperformed CPLEX both in terms of solution quality and solution time.

(5) Comparison between CMAHLRP and CSAHLRP using Heuristics (ALNDS):
The application of multi-allocation reduced operating cost in all of the instances with an average reduction of 11.09%, as compared to the single-allocation cases. The CMAHLRP was able to reduce total operating cost more efficiently in the instances with small size and tight hub capacity. The main reason is that the inter-hub transportation cost makes a larger part in these instances and the application of multi-allocation mainly reduces the inter-hub transportation cost with the cost of higher local tour cost. The number of multi-allocated non-hub nodes is smaller in the instances with loose hub capacity than in the instances with tight hub capacity because of the same reason. Therefore, it can be concluded that the CMAHLRP is more suitable in urban logistics cases which typically have tight hub capacities.

(6) Application of CMAHLRP:
We also developed an application of the MAHLRP in solving warehouse matching platform system (WMPS). As a CMAHLRP application the WMPS can be setup where the factories and their final customers represent the non-hub nodes and the rental warehouses as hubs. A realistic instance (case study) was created using the data provided by company operating a basic version of the WMPS in Japan. The results indicate that applying the proposed models and algorithms to these realistic cases can efficiently reduce the operating costs and the CO2 emissions, by as much as 4.55% and 19.82%, respectively. Therefore, the CMAHLRP can be used to achieve both economic and social improvements in the existing system.



５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Wu Yuehui、Qureshi Ali Gul、Yamada Tadashi、Yu Shanchuan	４．巻 75
２．論文標題 Branch-and-price-and-cut algorithm for the capacitated single allocation hub location routeing problem	５．発行年 2023年
３．雑誌名 Journal of the Operational Research Society	６．最初と最後の頁 410～422
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/01605682.2023.2197933	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Wu Yuehui、Qureshi Ali Gul、Yamada Tadashi	４．巻 302
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３．雑誌名 European Journal of Operational Research	６．最初と最後の頁 1113～1127
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ejor.2022.02.002	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

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２．発表標題 A Multi-Allocation Hub Location Routing Problem
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４．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関