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論文題目	Hub Location Routing Problem for the Design of Intra-City Express Systems (都市内郵便配達システムの最適設計を想定したハブ配置配送計画問題に関する研究)		

（論 文 内 容 の 要 旨）

Increasing demand for the intra-city express services has recently led to various social problems, such as, high delivery cost, low delivery efficiency, road congestion, air pollution, and so on. The Hub location routing problem (HLRP) is usually employed to optimise networks of intra-city express systems to relieve these problems. Previous studies concerning the HLRP mainly focus on the uncapacitated versions of single-allocation hub location routing problem (SAHLRP). Moreover, only a few studies are related to the un-capacitated version of the multi-allocation hub location routing problem (MAHLRP), which is an extension of the SAHLRP that reduces the inefficiencies resulting from one-to-one assignment of non-hub nodes to hubs. In recent times, parcel delivery is getting greater share in urban deliveries, and therefore, hub and vehicle capacity must be considered when designing intra-city express systems.

With these considerations, this dissertation tries to provide mathematical models for the capacitated single-allocation hub location routing problem (CSAHLRP) and capacitated multi-allocation hub location routing problem (CMAHLRP). Exact and heuristics solutions are developed, and extensive numerical experiments on newly generated benchmark instances are conducted to show the efficacy of the developed exact and heuristics solutions. Finally, a realistic application of the CMAHLRP is undertaken to investigate its economical and social improvements.

The thesis is organised as follows.

Chapter 1 Introduction

Chapter 1 describes the background of this study. It introduces the network topology of intra-city express systems and the role of the HLRP in the design of the systems. Definitions and applications of various HLRP variants and their shortcomings are also presented, which serve as the motivation for this thesis. Finally, Chapter 1 ends with the objectives and outline of this thesis.

Chapter 2 Literature Review

Chapter 2 reviews the literature available for the HLRP and its related problems, including the hub location problem, the vehicle routing problem, and the location routing problem, focusing on their features, classifications, and solutions methods. The literature review found that only the uncapacitated version of the SAHLRP has been optimally solved, and the MAHLRP has never been exactly solved before. Moreover, only a few studies are available for the MAHLRP, where some studies did not consider vehicle capacity or hub capacity, whereas others separated the pickup and delivery.

Chapter 3 Capacitated Single-Allocation Hub Location Routing Problem

Chapter 3 introduces a new formulation for the CSAHLRP first, which can be used to solve its small-sized instances via commercial solvers. To solve larger instances, an exact solution algorithm is proposed for the first time, based on the branch-and-price-and-cut framework, which decomposes the problem into a master problem (MP) and a pricing subproblem. The MP is strengthened by several valid inequalities, and the pricing subproblem is solved by a bidirectional labelling algorithm. Moreover, Chapter 3 presents a meta-heuristic algorithm, named adaptive large neighbourhood decomposition search (ALNDS), to solve the CSAHLRP on large-sized instances. The ALNDS algorithm generates an initial solution first and tries to improve it iteratively in the form of subproblems. In each iteration, one of the subproblems is selected, and the selected subproblem of the existing solution is destroyed by a destroy operator and repaired by a repair operator to get a new solution. The exact approach and the heuristic approach are tested on the newly generated instances based on the benchmark data set widely used so far. Numerical results indicate that the exact algorithm outperforms the CPLEX in both solution quality and computational time as well as that the heuristic algorithm can find high-quality solutions in reasonable times.

Chapter 4 Capacitated Multi-Allocation Hub Location Routing Problem

Chapter 4 concentrates on the CMAHLRP, where each non-hub node can be served by multiple hubs, and both the hubs and the vehicles are assumed to be capacitated. Furthermore, route length constraints are imposed to ensure the service level. The problem is formulated as a MIP and then optimally solved for the first time by an exact solution algorithm based on the branch-and-price-and-cut framework. In the exact solution, the vehicle capacity constraints are considered in the MP rather than in the pricing subproblem. The ALNDS algorithm developed for the CSAHLRP is also extended to solve the CMAHLRP on large-sized instances based on the following schemes: i) An approximation algorithm is used to approximate the objective function value of the solutions. ii) Non-hub nodes were divided into subnodes to enable multi-allocation option. Correspondingly, the destroy and repair operators do not remove/insert complete non-hub nodes, while only subnodes are considered in these operators. A series of numerical experiments are undertaken on the instances generated from the benchmark data set to test the proposed model and algorithms. 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.

Chapter 5 Case Studies

Chapter 5 introduces the generated case studies based on the realistic supply chain network of a freight company in Tokyo, which consists of factories, warehouses, and customers. In the target network, freight flows are transported from factories to customers via hubs, sharing many common features with intra-city express systems. Three case studies are generated, and the proposed CMAHLRP model and algorithms are applied to these case studies, and the results were compared with the existing approaches. The results indicate that applying the proposed models and algorithms to these realistic cases can efficiently reduce the operating costs and the CO_2 emissions. Therefore, the CMAHLRP can be used to achieve both economical and social improvements in the existing system.

Chapter 6 Conclusions and Future Works

Chapter 6 summarises the research motivation, objectives, methodological frameworks, experiment results, applications, and corresponding findings. This chapter also focuses on identifying future research directions for this research, e.g., proposing more efficient valid inequalities, addressing variants of the HLRP such as with time windows or stochastics factors, and so on.

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（論文審査の結果の要旨）

近年、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。その解消方法として、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（hub location routing problem: 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、以上のような背景を踏まえて、社会問題の抑制・解消、ならびに、HLRP 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。本研究で得られた主な成果は次の通りである。

1. 提案されたモデルやアルゴリズムを検証するために、広く使用されているハブ配置問題のベンチマーク問題に基づいて、容量制約付き単一割り当てハブ配置配送計画問題（capacitated single-allocation hub location routing problem: CSAHLRP）と容量制約付きマルチ割り当てハブ配置配送計画問題（capacitated multi-allocation hub location routing problem: CMAHLRP）の問題例を生成した。生成した問題例は、容量制約付き HLRP に類する問題のベンチマーク問題の作成に利用可能である。
2. CSAHLRP を混合整数計画問題として新たに定式化を行った。提案されたモデルは、比較的厳しい境界条件を有するので、市販のソルバーを用いて小規模問題を解くことができる。さらに、CSAHLRP の厳密解を求めるために、分枝価格カット法に基づく厳密解法を開発した。開発された厳密解法の結果の精度や計算時間は、市販のソルバー（CPLEX）よりも優れていることを確認した。
3. 大規模な CSAHLRP 問題を解くために、適応型大規模近傍分解探索（adaptive large neighborhood decomposition search: ALNDS）と称する近似解法を開発した。導入されたアルゴリズムは、妥当な時間内に高精度の近似解を算出できることから、CSAHLRP の実際規模の問題を求解することも可能である。
4. 集荷と配送を同時に扱い、ハブ容量と車両容量の両方を考慮した CMAHLRP を、混合整数計画問題の枠組みで新たに定式化した。CMAHLRP の厳密解法を開発するとともに、マルチ割り当てスキームを考慮して、近似解法である ALNDS アルゴリズムも開発した。数値解析の結果、提案した厳密解法が市販のソルバー（CPLEX）よりも優れており、マルチ割り当てスキームを適用することにより配送費用を削減できることを明らかにした。
5. 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 CO_2 排出量が効率的に削減されることを確認した。

以上の通り、本論文は、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ことから、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和 4 年 8 月 12 日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。

なお、本論文は、京都大学学位規程第１４条第２項に該当するものと判断し、公表に際しては、当該論文の全文に代えてその内容を要約したものとすることを認める。