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論文題目	MULTI-OBJECTIVE ANT COLONY SYSTEMS FOR OPTIMIZING HAZARDOUS MATERIAL TRANSPORTATION（危険物輸送の最適化のための多目的アントコロニーシステムに関する研究）		

（論文内容の要旨）

This study presents a new meta-heuristics algorithm based on Multi-Objective Ant Colony System (MOACS) for optimization of Vehicle Routing and scheduling Problem with Time Windows (VRPTW) in hazardous material transportation. Methods and results of the study have been summarized under 7 chapters.

Chapter 1 is an introduction. Starting from the background on Hazardous Material (HazMat) transportation and its significance in urban freight transportation, the chapter emphasizes requirement on developing a route optimization tool such as VRPTW in the field. VRPTWs in HazMat transportation are multi-objective and Pareto optimization over scalar optimization is the appropriate approach to deal it. Path choice and routing are two important processes in solving VRPTW. Shortest paths between all customers including depot are determined during path choice. The obtained paths are then used in routing to determine the optimal routes of the fleet of vehicles. Path choice in classical VRPTW is single objective and allows the two processes to be carried out separately in two steps. In Hazardous material Vehicle Routing and scheduling Problem with Time Windows (HVRPTW), both path choice and routing are multi-objective, and with Pareto optimization, both these processes result in non-dominated solutions. Emphasising the fact, the chapter introduces necessity of single step optimization in HVRPTW.

Chapter 2 provides a review of related literatures. Two streams of literatures; those relating to Multi-objective Optimization Problem (MOP) and to the HazMat transportation have been discussed. Revision of solution algorithms to MOPs signifies that Multi-objective Ant Colony Optimization (MOACO) with its better performance observed in previous multi-objective studies is more suitable for solving multi-objective combinatorial optimization problems like VRPTW than other multi-objective meta-heuristics. Review of literatures in HazMat routing showed lack of multi-objective Pareto based HazMat-related VRPTW studies.

Chapter 3 firstly illustrates advantage of single step optimization over two step optimization to obtain complete Pareto front in HVRPTW. Accordingly, a new formulation to the HVRPTW is presented. To carry out single step optimization, the formulation introduces a new set P (set of all non-dominated solutions for path choice). The bi-valued variable x_{ijp}^{k} then determines whether a path p from customer i to customer j is used in the optimal routing or not. Strict hard time windows requirements are maintained at customers and depot. Minimizing total travel time and total risk are the objectives for path choice while minimizing the total scheduled travel time (sum of travel time, waiting time and unloading time) and the total risk of all vehicle in operation are the objectives for routing. Risk formulation is carried out using traditional risk model. To appropriately determine the consequence value, detail on possible methods to determine radius of impact area λ is also given.

Chapter 4 provides details on the proposed meta-heuristic solution algorithm for HVRPTW. The algorithm works based on MOACS and applies concept of Pareto optimization to deal both multi-objective path choice and multi-objective routing. Further, it carries out the two processes together in single step. The algorithm derives its basic idea from MOACS for VRPTW. However, to carry out single step optimization, it shows some significant differences to MOACS for

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VRPTW, mainly in terms of three procedures: the labeling algorithm, the solution construction and the local search. Labeling algorithms in the proposed MOACS provide non-dominated paths for path choice. A set of all non-dominated paths between all customer vertices including depot (P) is determined performing labeling algorithms at all customers and depot locations. Solution construction in the algorithm is modified accordingly utilizing P. Contrary to the ants in the MOACS for VRPTW which construct their solution with selection of feasible customers, ants in the proposed algorithm are made to construct their solutions with selection of path p from P. Additionally, an insertion based local search is used to improve the routing solutions.

Chapter 5 presents evaluations of the algorithm based on its performance on Solomon's benchmark instances in VRPTW as well as on a HVRPTW test instance in virtual road network. Results on benchmark instances showed its efficient performance to wide variety of VRPTWs. For the clustered (C) customers' problems, the algorithm was observed to provide solutions as competitive as the best known solutions from exact approaches, unaffected by the size of the problem. A negligible deviation in optimal distance (maximum 0.27%) was observed. The performances on random (R) and mixed (RC) customers' problems were found slightly affected by the size of the problem, and the deviations were observed increasing for larger problems (about 7%-11% for 100 customer problems). However, deviation of this range for 100 customers' size problem is the common range obtainable with meta-heuristics approaches. Quality of solutions in HVRPTW instance was investigated examining the Pareto fronts, the range of objective values and the individual Pareto optimal solutions obtained in ten consecutive runs. For the test instance, the algorithm was successful to determine excellent Pareto sets within a very short computation time ranging from 30 to 50 seconds. Pareto fronts were found to reveal wide classes of Pareto optimal solutions extending their extremities in close proximity to the ideal solutions obtained with single objective minimization of scheduled travel time and risk objectives. Trade-off between the objectives was clear. Also the solutions were consistent over different test runs. Apart from it, it was observed that the Pareto sets composed of many Pareto optimal solutions having exactly similar customers visiting orders but using different paths. These solutions which could never exist in case if single path was used for path choice, proved importance of single step optimization to predict complete Pareto front in HVRPTW.

Chapter 6 evaluates applicability of the algorithm to solve HVRPTW instances in real road network. Analysis was performed on a HVRPTW instance, derived from the practical road network in Osaka prefecture. For appropriate risk calculation, λ for the instance was obtained performing detail analysis of various possible accident scenarios. As the practical network is much larger in size and irregular in shape than the test network, a large increase in the number of non-dominated paths for path choice was observed in this case. The computation time increased accordingly. The computation time of the practical instance was found around 20 times of that obtained for the test instance. Nevertheless, it remained about 1000 seconds in most test runs which is a satisfactory figure for solving practical instance of this size. More importantly, changes in the network properties were found insignificant in affecting the quality of the solutions. In all test runs, the algorithm was observed to yield efficient Pareto optimal sets with large extents and centrally well distributed solutions.

Finally, chapter 7 provides the main contribution, the concluding remarks and the future research aspects of the study.

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（論文審査の結果の要旨）

本論文は、危険物輸送における時間指定付き配車配送計画について、多目的アントコロニーシステムを用いて最適解を求めるためのモデル化を行っている。このモデルにいては、配送コストおよび危険物輸送中の交通事故による住民への被害のリスクの２つの目的を最小化することを目指しており、パレート最適解を求めるため、ラベリングアルゴリズムを用いた解法を開発している。また、このモデルを仮想ネットワークおよび実際の道路ネットワークに適用することを目標に研究しており、得られた主な成果は次のとおりである。

１．　ここで開発したモデルにおいては、配車配送を行う集配トラックが各顧客を訪問するときの顧客間の経路選択および訪問順序を同時に決定することができる。このことによって、多目的最適化のパレートフロントにおける最適解が、経路選択および訪問順序を２段階とした場合に比べて、多数得られることが明らかになった。

２．　ここで開発したラベリングアルゴリズムを用いたアントコロニーシステムをソロモンの時間指定付き配車配送計画のベンチマーク問題に適用した結果、顧客数が 25 の場合の誤差は最大で 0.27%になっており、顧客数が 100 の場合においても誤差は 7-11%程度であり、十分な精度で近似解が得られることがわかった。

３．　多目的アントコロニーシステムを用いて危険物輸送における時間指定付き配車配送計画のパレート最適解を求めることができることを明らかにした。このことによって、意思決定者が集配トラックの経路および顧客の訪問順序を決定するときに、コストのみならず交通事故によって発生する爆発や火災による住民に与える被害リスクも考慮することができる。

４．　ここで開発したモデルを大阪中心部の実際の道路ネットワークに適用した。交通事故発生確率をリンクごとに与えて計算を行った結果、危険物輸送における住民への被害のリスクおよび配送コストの両方を考慮したパレート最適解の近似解が得られた。また、同じようなリスクおよび配送コストを与える解においても配送経路はかなり異なっていることが明らかになった。

以上の内容により、本論文は、危険物輸送における時間指定付き配車配送計画において、多目的アントコロニーシステムを用いて最適化を行うことによって、公共側から要請される住民へのリスクの低減および民間企業のコスト削減の２つの目的を考慮した配車配送計画が可能であることを示しており、学術上・実用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、平成 22 年 8 月 4 日、論文内容とそれに関連した事項について試問を行った結果、合格と認めた。