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Economic and environmental evaluations in the two-echelon collaborative multiple centers vehicle routing optimization

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A B S T R A C T

The two-echelon collaborative multiple centers vehicle routing problem (2E-CMCVRP) integrates collaboration mechanism and the vehicle routing problem. Combining k-means clustering algorithm and an improved Non-dominated Sorting Genetic Algorithm-II (Im-NSGA-II), this paper proposes a three-phase approach to simultaneously minimize the aggregate operating cost and reduce carbon dioxide emission. To ensure the initial population's quality, the sweep algorithm is integrated as modification of the standard NSGA-II. The chromosome population consists of multiple depots and corresponding customer nodes independently assessed to find local solutions, and latterly combined to yield suboptimal routes. The nodes scan principle of the sweep algorithm is employed to enforce optimization constraints, and the non-dominated sorting of the population efficiently improves the solution search accuracy. Further, the Minimum Cost-Remaining Savings (MCRS) method is used to determine appropriate profit distribution schemes, and the selection of the optimal sequential coalition is executed on the basis of the strictly monotonic path principle. Computational comparisons on benchmark instances indicate the superiority of Im-NSGA-II over NSGA-II and MOGA, and an empirical study in Chongqing, China confirms the practicability of our solution approach. The evaluation of MCRS solution's stability displays outperformance over other methods including the Shapley value model, CGA and GQP, and suitable coalition sequences are selected and assessed to improve the efficiency of logistics network optimization as well as the achievement of environment-friendly objectives.

1. Introduction

The rapid increase in urban populations has essentially influenced the growing complexity of logistics distribution networks, and resulted in the intensification of pollution in metropolitan areas. From an economic point of view, logistics companies are either confronted with the increase in operating costs owing to long distance transportations, or the incapacity to properly cover their distribution network due to transportation resources shortage. Concerning the environmental influence of the expanding network, the inappropriate design of distribution routes leads to irrational vehicle trips and traffic congestion, which essentially increase the emission of carbon dioxide (CO_2). With regard to these challenges, network optimization is necessary to find more sustainable solutions, and companies should closely cooperate with government institutions to regulate carbon emission.

In modern logistics management, multiple echelons distribution networks are increasingly adopted to optimize operations, efficiently manage customers, and mitigate urban congestion (Mousavi et al., 2015; Zhang et al., 2017). For instance, a two-echelon distribution network can be designed with Logistics Centers (LCs) at the first level, Distribution Centers (DCs) at the second

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level, and final customers zones (Soysal et al., 2015). As the network's downstream component, customers can exogenously select distribution centers by evaluating criteria such as their proximity, service cost, service quality, delivery capacity, delivery equipment, etc. However, several scenarios of supplier selection without assessing the proximity criterion have emerged as the consequence of company investments in diverse marketing events. Subsequently, customer groups enlarge but with potential operational problems. In fact, distribution centers are sometimes required to operate long haul transportations which generate more expenses and carbon emission. Despite numerous research conducted on vehicle routing problems, the aforementioned problems continue to exist. Therefore, more sustainable strategies should be developed to improve the reliability of existing logistics networks.

In recent years, several researches have proposed the cooperation between distribution centers as a good measure to achieve urban logistics networks sustainability. Practical analyses have also proven that forming collaborative alliances is beneficial to both suppliers and customers since costs and travelled distances can be reduced. Its implementation in real-world mainly consists in the reasonable sharing of participants' resources (customers, vehicles, warehouse, etc.). Subsequently, the contribution of each participant is considered for the collective profit's distribution. Therefore, cooperation can also be viewed as a mechanism which evaluates participants' cooperative behaviors for profit distribution (Kumoi and Matsubayashi, 2014). On that basis, many scholars conducted extensive works on the distribution of profit applying cooperative game theory. Dai and Chen (2012) studied a centralized collaborative framework and proposed three profit distribution mechanisms based on the Shapley value, the proportional allocation concept, and the contribution of each participant in the accomplishment of services. Zhang and Geng (2012) applied a multi-agent simulation technique to analyze the influence of profit distribution on the cooperation's reliability and the average income of participants. Results showed that a profit reduction coefficient around 0.5 would maintain the cooperation at a relatively higher level, the reasonable difference between the average participants' income, and the knowledge spillover income. Lozano et al. (2013) presented a linear model to evaluate the total savings of companies after consolidating transportation needs. Panda et al. (2015) applied a contract negotiation process to resolve channel conflicts, and allocated residual profits to members. Feng et al. (2017) introduced a collaboration and decision-making mechanism to achieve autonomous control in multi-dimensional collaboration environments. In summary, state-of-art findings support that cooperation and the reasonable distribution of profit are adequate to simultaneously minimize expenses and maximize profit. Nevertheless, ensuring the reliability of cooperative logistics networks requires solving two critical issues: (a) the optimization of the collective distribution network in order to increase profit and eventually contribute to environment protection; (b) the reasonable allocation of profits among participants.

Vehicle Routing Problems (VRPs) are classical optimization issues generally approached when designing logistics networks. Studies on VRPs attracted several scholars and variants were also proposed to find appropriate routes between suppliers and supplied units. Recent studies have intensively concentrated on accessing multiple echelons distribution networks, while complex heuristics, meta-heuristics and dynamic optimization tools are developed for solutions search. In addition, multiple DCs are frequently considered to evaluate the relevance of proposed optimization methodologies over large scale networks. Hemmelmayr et al. (2012) developed an adaptive large neighborhood search heuristic to study two-echelon distribution networks where final customers would be served by DCs through satellite facilities. Narasimha et al. (2013) discussed a variant of Multiple Depots VRPs (MDVRPs) called the min-max MDVRP which aimed at minimizing vehicles travelled distance, and introduced an extended ant-colony algorithm to explore feasible solutions. Luo and Chen (2014) proposed a multi-phase shuffled frog leaping algorithm to solve traditional MDVRPs, MDVRPs with time windows, and capacitated VRPs. Oliveira et al. (2016) adopted a different approach for MDVRPs optimization, introduced a cooperative co-evolutionary algorithm, and incorporated a parallel evolution environment for local search. Grangier et al. (2016) discussed the two-echelon multiple-trip vehicle routing problem with satellite synchronization, presented an Adaptive Large Neighborhood Search (ALNS) and confirmed its application on practical problems. Mancini (2016) combined ALNS with a matheuristic approach to optimize the multi-depot multi-period VRP with a heterogeneous fleet of delivery vehicles. Extending VRPs to a larger network, Chan et al. (2016) focused on a three echelon supply chain, modified the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) to improve solutions' accuracy and proved its relevance through a practical case study. More recently, Du et al. (2017) studied the MDVRP for hazardous products distribution and introduced a fuzzy bi-level programming model to minimize the total expected transportation risk. Similarly, some researchers addressed different types of products distribution, while others included specific objectives in accordance with real-world situations.

Due to the awareness of global warming and the consequences of greenhouse gas emission, more research lately focused on the environmental objectives of the vehicle routing optimization. For instance, Zhang et al. (2014) presented an Environmental Vehicle Routing Problem (EVRP) to study the environmental influences of carbon emission, developed a hybrid Artificial Bee Colony Algorithm (ABC) and verified its performance in comparison with the original ABC algorithm. Besides, strategies such as low carbon enforcement through governmental regulations were also used to reduce the negative impacts logistics' activities have on the environment. Garg et al. (2015) addressed environmental issues related to the design of closed loop logistics networks, and introduced an interactive multi-objective programming methodology to optimize products flow in both forward and reverse chains as well as the number of vehicles used for during distribution. Li et al. (2016a) proposed a mixed integer nonlinear programming model for the two-echelon time-constrained vehicle routing problem and suggested that the optimization of facilities locations and the elimination of empty-load transports were conducive to reduce CO_2 emission. Li et al. (2016b) applied the simulated annealing algorithm to VRP and proved that total distance is a crucial factor affecting carbon emission. Suzuki (2016) studied pollution routing problems, evaluated the effects of payload and distance on fuel consumption, and designed a dual-objective meta-heuristic approach to increase Pareto efficiency. Xiao and Konak (2017) developed a dynamic programming algorithm for time-based VRP and scheduling problem to determine optimal vehicle routes favorable to reduce CO_2 emission and fuel consumption.

With the expansion of optimization datasets, heuristics and dynamic programming methods sometimes require significant computational time when solving large scales problems. Therefore, to meet nowadays demand for high speed computations, researchers combined clustering approaches to reduce the complexity of optimization problems or for the effective management customers (Kuo et al., 2012; Vidal et al., 2015; Tang et al., 2018). Li et al. (2011) applied the LRFM customer relationship model to group a large number of customers into smaller units. Four dimensions were considered to cluster customer: relation length (L), recent transaction time (R), buying frequency (F), and