Vehicle Routing Optimization for Humanitarian Logistics in Disaster Recovery: A Survey

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Abstract—The growing field of humanitarian logistics in disaster recovery and safety and security are driven by the frequent event of disasters throughout the world as can be seen by the 2017 Mexico earthquake, 2017 Columbia landslide, 2016 Columbia Matthew Hurricane and 2016 Taiwan earthquake. Due to uncertainties in relief effort operations, there is a need for novel Disaster Support System (DSS) for disaster recovery as compared to conventional techniques in terms of safety and security. This paper survey various advances of solution approaches in vehicle routing problems for disaster recovery bringing focus to dynamic and stochastic, real world application. The humanitarian logistics operational vehicle routing problems are classified into four categories, for which the limitations, strengths and applications are discussed.

Keywords: Survey, humanitarian logistics, disaster, transport, mobility, machine learning

1. Introduction

With countless events of disasters occurring of late, the rising need for innovative and efficient Disaster Support System (DSS) has been the growing topic in many fields. Humanitarian Logistics (HL) can be seen as the main contributor in dealing with post disaster recovery, to ensure that the supplies and relief aids are efficiently and effectively managed and distributed towards the end consumer, namely the victims [1]. One of the problems faced by HL is that conventional planning methods rarely account for the uncertainties that come with disasters. This in turns has inspired various novel and innovative optimization approaches within the field of Operations Research (OR) in disaster recovery, resource management as well as safety and security. At the center of these fields are the vehicle routing problems (VRPs). However real world problems especially in the area of OR in HL demands focus on the dynamic and stochastic aspects of VRPs.

Indeed, as can be seen in the limited literature that follows, most recent and advanced VRPs involve dynamic and stochastic elements, multi objectives, multi agents and many other complex optimization requirements. Typically such optimization problems no longer employ exact solution algorithms alone. Owing to the fact that even the basic VRP is known as a NP hard problem, exact algorithms or ML approaches are often limited and bounded by the problem size. Therefore a trade-off need to be made in terms of the quality of the solution seen often in heuristic and metaheuristic solution approach. In some cases, specific heuristics are constructed instead of opting for metaheuristics. These practical approaches are proven in literature as having the ability to solve for real world optimization problems and are often considered good enough solution. However, for the application in a disaster scenario, stochasticity is the key ingredient in representing a realistic model. Some machine learning (ML) approaches such as Markov Decision Processes (MDPs), offer a new kind of approach in modelling a more realistic model by incorporating stochasticity and the Markovian property. Stochasticity, however increases the complexity of the model. In such a case, neither an exact algorithm, ML nor metaheuristics or heuristics alone can offer a good solution to the problem. Hence the idea of combining them into hybrid approach would be the obvious choice.

The main motivation for the survey paper is to serve as an important foundation in the advance of research in optimizing HL operations in times of a disaster event specifically involving VRPs.

As such, the contribution of this paper is the classification of vehicle routing problems in HL operation during disasters into four categories followed by the classifications of the typical and new solution approaches applied, including additional focus on stochastic and dynamic characteristics of the problem.
Table 1: Literature on Routing Problem Classification

<table>
<thead>
<tr>
<th>Routing Problem Classification</th>
<th>Literatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply and Delivery</td>
<td>[2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34]</td>
</tr>
<tr>
<td>Search and Rescue</td>
<td>[35] [36] [37] [38] [39] [40] [41] [42] [43] [27] [44]</td>
</tr>
<tr>
<td>Intermodal Network</td>
<td>[35] [13]</td>
</tr>
<tr>
<td>Other Applications</td>
<td>[45] [46] [47] [48] [27] [49]</td>
</tr>
</tbody>
</table>

Table 2: Classified VRPs with Corresponding Solution Approach

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Machine Learning</th>
<th>Exact Solution Methods</th>
<th>Heuristics &amp; Meta-heuristics</th>
<th>Hybrids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limitations</td>
<td>Complexity</td>
<td>[40] [48] [45] [35] [36] [12] [14] [37] [21] [26] [31] [13]</td>
<td>[4] [6] [9] [11] [16]</td>
<td>[11] [27] [33] [34]</td>
</tr>
<tr>
<td></td>
<td>BasicVRP</td>
<td>[2] [15] [24] [18] [42]</td>
<td></td>
<td>[3]</td>
</tr>
<tr>
<td></td>
<td>Deterministic</td>
<td>[5] [36] [37] [14] [21] [43] [26] [32] [13]</td>
<td>[16] [38] [39] [21] [22] [47] [41] [29] [28]</td>
<td>[5] [10] [17] [18] [19] [25] [27] [49]</td>
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<tr>
<td></td>
<td>Multi Objectives</td>
<td>[5] [26] [31]</td>
<td>[46] [10] [24] [29]</td>
<td>[3] [5]</td>
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<tr>
<td></td>
<td>Stochastics</td>
<td>[2] [40] [44]</td>
<td>[4] [6] [7] [8]</td>
<td>[30] [33] [34]</td>
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<tr>
<td></td>
<td>Dynamic</td>
<td>[2] [40] [45] [35] [31]</td>
<td>[37] [23] [48]</td>
<td>[20] [34]</td>
</tr>
<tr>
<td></td>
<td>Multi Agents</td>
<td>[2]</td>
<td>[13]</td>
<td>[34] [49]</td>
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<tr>
<td></td>
<td>Intermodal</td>
<td>[13] [35]</td>
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<td>[11]</td>
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Based on the literature surveyed so far, it is observed that no survey has yet been made, on a selective optimization method with regards to vehicle routing optimization in HL during disaster.

The rest of the paper is organized as follows. In Section 2, various VRPs solution approaches are addressed for the application of supply and delivery case followed by Section 3 with observed current trend of all categories collectively. The future trends and research gaps are elaborated in Section 4. Finally the conclusion is drawn in Section 5.

2. Problem Classification

In this paper, the relevant and recurring themes of the vehicle routing problem in HL are identified and classified into four different categories, namely: supply and delivery, search and rescue, intermodal network and other applications.

Based on these categories, the frequency and the focus of the literature available between 2001 and 2017 are shown in table 1. Furthermore various solutions applied are classified under ML, Exact Solution Approach, Heuristic and Meta-heuristic as well as Hybrids in Table 2. In the first column of Table 3, each of these solution approaches is further classified into their respective limitations and strengths.

2.1 Supply and Delivery in Routing Optimization Problems

The most common VRP in HL is routing for supply deliveries in various parts of the supply chain including delivery to the end consumer (the victims), delivery to the emergency centres and hospitals as well as delivery to the emergency booths in many strategic locations at a disaster zone.

The following subsection (2.1.1 - 2.1.5) discussed at length various literatures focusing on the first category (Supply and Delivery in Table 1) since this category dominates the literature in the scope of routing optimization in HL. Other categories are instead discussed briefly and collectively in Section 3 and Section 4.

2.1.1 Machine Learning Methods in Supply and Delivery VRPs

In all specified VRP classifications, the ML solution approach is not preferred due to the computation limit based
on instances. This can be seen in table 2 and table 3. However, there are some papers that applied ML approach with realistic instances based on a case study. [2], for example, addressed the coordination of relief distribution teams and relief assessment teams to allow assessment to be done on site as to estimate real demands at specified locations and thus ensuring efficient relief aid distribution. They addressed the problem as MDP model where the learning of both agents for each team is accomplished through a series of predictions during offline mode and real data based on online mode of the Decision Making Agent (DMA) which at the core is the MDP. The best action for each current state based on the computed policy is suggested to both teams predictively during offline mode while the online mode enables the DMA to access real data from both teams and suggest the best action dynamically.

2.1.2 Exact Methods in Supply and Delivery VRPs

Meanwhile, the application of exact method solutions particularly in the supply and delivery using VRPs are still small in number when compared to heuristic and metaheuristic solution approaches (Table 2). There are however some such as [12] that applied exact methods in the delivery VRP where a single vehicle is addressed when routing in 20 sites to 40 sites maximum. Interestingly [12] is able to show that a different approach of modelling the problem can actually lead to a more efficient computation. [13], however, shows that despite the limitations of the exact methods in terms of computing number of instances, it is still possible to model a complex representation of a VRP such as intermodal networks. Furthermore, [13] not only suggested the limits of exact methods in representing a complex model using exact method solutions, they also stressed at the same time the importance and potential of intermodal transport in delivering relief aid supply during a disaster event by also considering the vulnerability of the road during the disaster based on a case study.

Similarly, the multi - objectives problem were also addressed in [26] by considering depots of vehicles, distribution centres, as well as shelters through the approach of fuzzy and crisp formulation. [31] addressed multi - objectives, too, by considering the efficiency in terms of delivering maximum supplies within a short window of time as well as maximizing the demands from various emergency points through multiple depots. Adding to the complexity of the model, dynamic constraints are added in addressing the uncertainty of road conditions, randomness of donation as well as emergency demands through a dynamic continuous time flow network model. The challenges of exact methods when dealing with complex VRP models is also evidenced in [32], where the label-correcting algorithm is modified into two parts to calculate a primary path and an alternative secondary path, should the primary path fail due to disasters. Here, the large possible number of instances to represent the failure of each arc is reduced based on a proposed dominance rule.

A more detailed representation of delivery supplies in disaster event is addressed by [14], where the concept of efficiently sharing aid supplies among shelters based on priority and number of evacuees is modelled with mixed integer programming. It is worth nothing that [14] manage to address a detailed problem that can be solved by exact methods with realistic size based on the real data obtained from Chofu City, Japan. [15] however presented a typical small applicable instance model solution through two mixed integer linear programming models: a flow based model and set partitioning model, which were solved by an adaptation of the Bellman Ford algorithm. From the idea of transforming a multi-trip cumulative capacitated single VRP (mt - CCSVRP) into an resourced constrained shortest path problem, the computation is further reduced with the application of a dominance rule as well as lower and upper bounds.

[21] compare the solution approach of generalized VRP with flexible fleet size (GVRP - flex) between column generation (CG) and two metaheuristics based on iterative local search. In the results obtained [21] pointed out that more accurate results could be obtained through CG. The metaheuristics on the other hands solved for near optimal solution with minimal disparity as compared to the exact method’s solution. However it did so in a significantly reduced computation time.

2.1.3 Heuristics and Local Search in Supply and Delivery VRPs

Particularly in the problem of supply and delivery VRPs, different types of heuristic methods are proposed. [6] for instance proposed a decomposition based heuristic for solving a stochastic generalization of the multi dimension knapsack problem in order to maximize the quality of deliveries by modelling it as an Emergency Open Routing under Stochastic Travel Time and Dateline (EORSTTD). Interestingly [6] also addressed the punctuality of the delivery time by establishing a controlled upper bound. Furthermore, the heuristic proposed decomposed the problem into a subproblem which is further reduced into two daughter problems. Their respective solutions are then applied to the master problem, solving the optimization problem addressed.

In [22] the synchronization of medical supplies and on site supervision are addressed. The CVRP is expanded to accommodate for activity synchronization and precedence. A heuristic method is then developed with the ability to adapt to the geographical database in order to perform
synchronization between pick up and drop off for an aircraft carrier and on site supervisor. [23] extends the graphical usage further to provide both simulation and optimization platforms for DDS. In this proposed system, the routing is computed by the A Star algorithm guided by the heuristics approach while the facility location is optimized through Tabu Search in order to facilitate relief supply coordination.

2.1.4 Metaheuristics in Supply and Delivery VRPs

A popular approach for solving real world instances problem, metaheuristic are also widely applied throughout the literature in this problem classification. [4], for instance, look into the approach of robust optimization and chance constrained programming. An equivalent deterministic model is then modified to create a stochastic representation solved by the Tabu search method. Meanwhile [8] argues that selective VRPs should replace conventional VRPs when dealing with uncertainties, as the quality of the solution does not reflect the critical needs of the victim served where hard choices sometimes need to be made. This means not all nodes can be served hence the selective VRP model approach is proposed. They formulate a selective VRP model based on fuzzy stochastic vehicle routing problem (SVRP), reliable SVRP, as well as robust SVRP along with the solution algorithm based on parallel genetic algorithms that aim to communicate changes within parallel population as well as eliminating repeated chromosomes.

[9] instead models the delivery problem as min max Multi Depot VRP (MDVRP), which stresses critical delivery to emergency points by minimizing longest tour performed by any vehicle. By applying Ant Colony Optimization (ACO), customers are partitioned to respective depots, thus reducing the min max MDVRP model to multiple single depot VRPs (SDVRP). [24] proposed a Simulated Annealing (SA) method in solving multi objective emergency VRPs with the aim of reducing rescue time and rescue cost. [24] also considered dynamic demands as to propose a more realistic model of emergency. Their model however applied to only a simplified case.

In [28], the Adaptive Large Neighbourhood Search (ALNS) is applied to a Cummulative Capacitated VRP (CCVRP) for a disaster scenario. Here 3 insertion and 7 removal heuristics are chosen iteratively based on their weighted score while searching for the optimal solution. Furthermore [29] proposed a delivery model that considers the congestion level based on the destruction of the road network while tries to optimize both the total delivery time as well as the total cost incurred using the weight coefficient transformation method, where priority is represented weight.

Finally, an interesting approach can be seen in [18] where a machine learning method, K -Means Clustering Algorithm is applied to cluster various emergency location into groups before they are assigned to each route computed by the Particle Swarm Optimization (PSO).

2.1.5 Hybrid Optimization in Supply and Delivery VRPs

In this specified category, [16] for instance adapted Large Neighborhood Search (LNS) into Variable Neighborhood Search (VNS) in proposing a new Adaptive Variable Neighborhood Search (AVNS), where two stages of search are performed and optimized as information were gathered to improve local search in stage 2. Here the LNS is applied to improve the diversification based on the concept of intelligence gathering in searching for local optima in order to solve for the CCVRP with min sum and min max objectives.

[25] proposed a hybrid algorithm by combining exact solutions within SA during it’s perturbation phase to ensure the two functions of routing and allocating demands can be optimized together in their solution structure. A quite similar structure is applied in [27], although greedy and local search are applied instead in a four phase algorithm that also employs exact solutions in the second phase. This structure is deemed necessary due to the complex model of multiple logistics operations: the supply distribution, victims treatment and relief workers assignment, which is based on priorities.

To address multi - objectives problem, [3] proposed a model that applied the concept of a pareto optimal solution within the iteration of SA. In [5], a version of hybrid SA is applied to address multi - objectives blood donation problem. Here the problem of strategically placing blood - collection mobile efficiently is solved by converting a multi objective fuzzy programming model into crisp multi - objectives linear model, before solving the second model that deals with VRPTW. Fuzzy programming is then applied based on the probabilistic setting formed by the optimistic, pesimistic parameter formulations in searching for a solution that considered both crisp models.

[10] employs a hybrid of Adaptive Variable Neighborhood Search (AVNS) and LNS as part of its diversification strategy to solve for the min - sum and min - max CCVRP as contrast to the typical shaking steps where the local search operator is selected intelligently through information gathered iteratively. In [17] a Multi Start Iterated Local Search (MS - ILS) is applied to initialize Iterated Local Search (ILS) with a number of initial solutions resulting more diversification while Variable Neighbourhood Descent (VND) is applied to allow wider exploration among neighbourhoods. The two methods combined in improving the solution from greedy randomized heuristics further by utilizing VND at each
Looking into the hybrid of metaheuristics and heuristics, [19] proposed to combine 2-opt heuristics within ACO in solving a cumulative Multi Depot VRP (cum - MDVRP). The hybrid known as multiple round ACO (ACOMR) applies 2-opt heuristic in achieving diversity at each of its iterations while a tabu list is added for every infeasible ant path adding to the efficiency of the computation. Another ACO hybrid is observed in [20] where a dynamic status of emergency demands and vehicle allocation is addressed through a route allocation algorithm based on dynamic programming (DP). Here the DP is computed from the disaster areas based on the ACO algorithm.

In stochastic domain, the uncertainty demands and road travel time are estimated in [30] based on the hybrid of Cellular Automata (CA) and GA (Cellular Genetic Algorithm (CGA)). Here the chromosomes selected from the mutation process of GA is converted to cellular cells in CA where the chromosomes are then randomized in order to diversify the chromosomes which increases the convergence efficiency of the GA making sure that the constraints are satisfied before they are passed back to the GA for selection process. [33] looks further into stochasticity by proposing a model based on uncertainty theory to describe the routing problem of dispatching medical supplies towards emergency locations. In order to solve the proposed models a hybrid solution, based on a proposed uncertain-simulation and GA, was presented. The proposed uncertain-simulation is utilized to determine the feasibilities of the solution represented by the chromosomes. Finally [34] seeks to address the stochastic demands in VRP by modelling the problem as MDP model. The complexity of the VRP Stochastic Demands and Duration Limits (VRPSDL) model is addressed through selecting the optimum action based on a rollout policy algorithm. It consists of a local search heuristic based on a utility function\(V(s)\) of the current state \(s\) known as the fixed route heuristic. Additionally the complexity of the problem is further reduced by introducing decomposition method thus assigning vehicles to selective customer. Moreover [34] proceed further by proposing variants of rollout policies for the VRPSDL namely the one step rollout policies, post decision rollout policies as well as hybrid rollout policies to adapt to the increasing complexity of the VRPSDL based on the number of instances.

3. Current Trends

The findings of the literature reviewed is presented in detail in Table 3. At first glance it can be seen that more researchers opted for metaheuristic or heuristic approaches, when solving VRPs with regards to disaster operations. This is probably due to the fact that metaheuristics are generally more suitable for solving real world problems, which involve large instances. Neither exact solution approaches nor ML approaches are deemed to be adequate, when dealing with a large instance problem. Furthermore, more complex representations of VRPs are being solved by exact solution approaches as can be seen in [13], [31], [14], [35] and [44], where the instances are at the very least realistic in nature. On the other hand, the applications of ML towards solving combinatorial optimization problems (COPs) or VRPs are actually quite rare within the field of OR and sometimes are regarded as novel. This barrier, based on our opinion, will soon be blurred as more and more attention is given to ML. Additionally, Table 2 also shows that the hybrid approach is also widely accepted among applied solutions, to the point that the numbers are comparable to that of heuristic and metaheuristic solutions combined. This is perhaps due to increasingly difficult and complex VRPs with strict requirements, such as number of instances and computation time, as can be seen from [3] and [5].

By looking at the rows under classification of strengths in Table 3, it can be observed that the stochasticity of VRPs during disasters is widely addressed as compared to solving for Multi - Agents’, Multi - Objectives’ and Dynamic’ problems. To our knowledge ML is perhaps the best medium, when dealing with dynamics variables and stochastics model as can be seen in [2], [40] and [48]. While the fact that the curse of dimensionality is in fact hindering the advancement of ML as a solution approach for VRPs during disasters, the growth of hybrid solutions on the other hand could one day fully utilize the advantages of ML in this area, as one could see for example in [11]. A further example of such a hybrid is illustrated in [34],which is the only work in our review that applied ML as it’s main model and solution technique, while implementing heuristics as substitution for the dynamic policy iteration. In [30] on the other hand, metaheuristics dominate the solution and a ML approach is only added to represent stochasticity in the model and solution.

4. Future Directions and Research Gaps

Based on the survey findings, it could be concluded that metaheuristics and heuristics will remain prevalent in the coming future despite competing numbers of exact solution and hybrid solution approaches in VRPs in terms of HL and post-disaster operations. Despite advances in technologies that would enable faster computing time, the gap between theoretical instances and practical instances that can be solved through heuristics and metaheuristics remain large. This is clearly highlighted in [39]. However, this does not mean that exact solutions are becoming obsolete. In fact, more exact solution approaches are applied for more complex problems involving multi-objectives, stochastic and dynamic modelling as can be seen in [31], [44] and
Furthermore, hybrid solutions are indeed becoming more relevant in the OR field, where more requirements and demands lead to more complex VRPs. It is important to note that the hybrid approach could perhaps become the bridge for merging ML approaches and metaheuristics in addressing complex VRPs. The hybrid could be the answer to one of MLs best known limitation, the curse of dimensionality, as can be seen in [34]. Other types of important hybrids such as those that combined clustering methods in VRPs such as [11] as well as those that addressed multi-objectives such as [3] and [5] will also be more relevant in the future. In addition, it is interesting to observe the trend of employing external data to include more details in the VRPs during disaster such as graphical data and even building landscape data as can be seen in [22], [43] and [40]. Moreover, these trends could also morph into the application of simulation tools in aiding DDS already seen in [23] and [40]. It is our believed that this will continue to be the case in the future especially in the application of HL, where a visual approach would indeed be an effective tools for decision makers.

Finally through the brief future outlook of solution approaches in the application of VRPs in HL, a few research gaps could be identified. One example would be the appeal of ML in addressing stochastic and dynamic VRPs and the hybrid version of it, provided that the curse of dimensionality is addressed properly. Based on the review, it is clear that ML approaches are limited when addressing realistic instances. However the same could not be said for hybrids of metaheuristics and heuristics. Having said that, it is also important to note that there is still room for addressing stochastic and dynamic VRPs, since such problem gradually gains more attention. To that end, we still consider the stochastic and dynamic VRP based on the limited published work available as one of the research gaps. Furthermore, the application of graphical data in simulation is much desired, as this could be a future tool in aiding HL in times of disasters. Additionally, there is an abundance of research done on VRPs involving supply and delivery as well as search and rescue operations in times of disaster. Other complex yet important optimization problems in the field of HL should also be addressed.

5. Conclusions

In this paper, various publications on advanced VRP solutions as part of HL operations in time of disaster are reviewed, where special focus is given to stochastic and dynamic VRPs in the supply and delivery problems. Based on this review, it can be concluded that metaheuristic and heuristic solutions remain the preferred approach when solving VRPs. Here various innovations were made in DSS to accommodate critical requirements such as stochasticity and dynamics of real world problems especially in providing decision support in achieving safety and security through proper management planning and disaster recovery. Surprisingly, exact solution approaches on the other hand remain relevant, since the advancement of technology allows for better performance in computation. Furthermore, the rise of new hybrid solution methods is especially noted, where various mechanisms are added to complement the core solution approach. This would prove useful when dealing with the curse of dimensionality in machine learning, especially when solving stochastic and dynamic VRPs. The application of these methods however are rather scarce and more focus should be given therefore to such realistic cases. More importantly perhaps is the advancement of hybrids, where the role of ML becomes important. Throughout this paper few research gaps were also identified, such as the application of simulation approaches as well as the usage of external graphical and design data. Finally, there is a need to accommodate other VRPs in disaster recovery application besides the supply and delivery case as well as search and rescue problem. One practical problem that lacks attention for example is the intermodal VRP which would be of high importance in the field of international HL, involving various modes of transports.

References


