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TOPICAL REVIEW

# Vehicle Routing Optimization for Humanitarian Supply Chain: A Systematic Review of Approaches and Solutions

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**ABSTRACT** Corona pandemic has revealed that the uncertainty associated with disaster management has rippling effects, resulting in severe human suffering across the globe. The severity and complexity of the relief operations increase the authority's response time. The Humanitarian Supply Chain (HSC) can be helpful and is one of the critical branches of Operations Research. This paper presents a systematic literature review using PRISMA in the Vehicle Routing Problem (VRP) for HSC papers published in SCOPUS and Web of Science databases during the last two decades. It aims to classify and review the literature on VRP models in HSC using fifteen different categorizations. This paper extensively describes objective functions and solution methodologies, including heuristics, commercial and exact solvers, uncertainties, resource types, and vehicle types. Several research questions are framed using the PICOS (Population, Intervention, Comparison, Outcomes, and Study) tool. Future research directions are accordingly proposed based on objective functions, uncertain approaches, heuristic approaches, vehicle types, resource types, model dimensions, sustainability, and scheduling. The results of this study show that there is still plenty of room for research and development in VRP for HSC.

**INDEX TERMS** Disaster management, humanitarian logistics, HSC, relief operations, VRP.

## I. INTRODUCTION

Numerous public health crises have caused severe pain and fatalities throughout history. COVID-19 is the most recent, causing 6,953,743 deaths, reported to WHO [1]. One example is the plague outbreak in Europe in the late medieval era, which caused many deaths. Another example is the Spanish influenza pandemic (1918–1919), which killed nearly 50 million people globally [2], [3]. Moreover, the influenza A(H1N1) virus outbreak in 2010 affected 214 countries, leaving 18,114 people dead [4]. Recently, in 2019, COVID-19 has an exponential growth. Around 768 Million confirmed cases are reported as of August 1st, 2023, and sadly, 6.9 million lives were lost [5].

Furthermore, natural disasters also have the power to destroy infrastructure and human life. The catastrophic 7.8 magnitude earthquake on February 6, 2023, struck northern and western Syria and southern and central Turkey, followed by a 7.7 magnitude aftershock. It inflicted widespread devastation, causing tens of thousands of casualties. Shockingly, it claimed 59,259 lives across 11 Turkish regions, with 50,783 fatalities in Turkey and 8,476 in Syria. This event now stands as one of Turkey's worst earthquakes, surpassing the historical 526 Antioch earthquake [6]. An examination of catastrophes over the previous two decades revealed that 44 percent, 28 percent, and 8 percent of all tragedies are due

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to floods, storms, and earthquakes [7]. Relief operations in such tragedies are directly linked to the Humanitarian Supply Chain (HSC). Logistics tasks in HSC are essential in the fight against an epidemic and natural disasters [4].

Numerous other diverse disease outbreaks are reported during epidemic control logistics operations, including influenza [8], Ebola [9], Cholera [10], and Malaria [11] pandemics, among others. Allocating resources in such situations is futile unless these resources (such as medical supplies, medications, and vaccines) are accessible at the appropriate time, location, and amount [12].

While optimizing resource allocation can provide valuable insights, innovative delivery practices and solutions for combating disaster aftermath remain scarce. To date, HSC has been critically examined by researchers due to the risk of fatality associated with disasters. Such risk warrants an efficient methodology to mitigate disaster risks related to human lives. Just in time (JIT) HSC is incomplete without JIT transportation, and JIT transportation is incomplete without vehicles and routing.

From many aspects of the HSC system, Vehicle Routing Problem (VRP) is the single, most crucial problem experienced at the operational level. It is rated as a particular class of combinatorial optimization problem in operations research. VRP model was initiated by Dantzig and Ramser [13]. Ever since, it has been addressed vastly in many variants. Over the last 60 years, vehicle routing issues have made substantial strides. Many novel and complex variants of VRPs have emerged since 1973 to handle more complex operational problems, and numerous variations of VRPs are currently under review. A few notable instances are the first multi-depot VRP examined by Tillman [14], the first time-dependent VRP (TDVRP) introduced by Cooke and Halsey [15], and the first study of stochastic VRP in 1969 [14], which included random customer demand. The location routing issue [16], periodic VRP [17], dynamic VRP [18], VRP with time frame [19], the inventory routing problem [20], fuzzy VRP [21], open VRP [22], multi-echelon VRP [23], and share VRP [24] are the additional noteworthy variations. The use of VRPs for disaster control is part of humanitarian logistics (HL). The first recorded use of VRPs in aiding relief endeavors occurred in 1988 [25].

Four comprehensive systematic literature reviews of HSC VRP have been conducted since 2010. These studies have concentrated on a variety of topics, including evacuation and rescue operations [26], modeling and solution of aid operations [27], and assistance routing issues [26], [28], [29]. These evaluations have mainly focused on disasters with fast onset, like cyclones, earthquakes, and tsunamis. Slow-onset disasters, like pandemics and droughts, have not gotten enough attention [26].

By using improved classifications, research methodologies, and result analysis to classify various published works between 2005 and 2022 on the subject of VRP in the context of humanitarian operations, this study seeks to improve existing research. The significant contribution is a literature

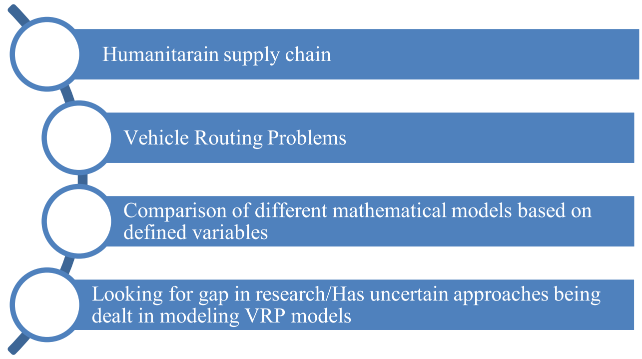


**FIGURE 1. PICO search terms.**

review of current VRP studies, emphasizing catastrophe kinds, management stages, modeling features, and solution approaches for humanitarian missions. The study highlights the difficulties in addressing certain humanitarian operations through model attributes and suggested solutions while observing and highlighting current trends.

This study systematically discovers recent advances and mathematical models developed in HSC VRP to determine relevant research questions. This analysis also includes PRISMA for classified solution strategy to supplement the available literature. The research began by searching for the following titles "Systematic literature review and meta-analysis of vehicle routing problem in humanitarian supply chain" and "Systematic review of VRP in HSC". The deliberate search for exploring these titles was to ensure that no such work had been carried out earlier. These terms were searched in Scopus, Web of Science, Emerald, and ScienceDirect.

Research questions were formulated with the help of a tool called PICOS (Population, Intervention, Comparison, Outcomes, and Study). Early literature indicates that initially, it was PICO; however, to limit the irrelevant articles, the study design aspect is also added. It is commonly used to identify components of clinical evidence for systematic reviews [30].

As shown in Figure 1, based on the PICOS, the following Research Questions (RQ) were framed.

RQ1: Current research state of vehicle routing mathematical models in HSC?

RQ2: What needs to be done yet in VRP for HSC?

RQ3: Status of uncertain approaches employed in VRP for HSC?

RQ4: Exact or heuristic approaches applied in solving VRP?

RQ5: Has any paper considered fuzziness in the objective function?

RQ6: Which commercial solver is commonly used for solving VRP models?

## II. METHODS

"Humanitarian supply chain is the flow of relief aid and the related information between the beneficiaries affected by a disaster and the donors to minimize human suffering

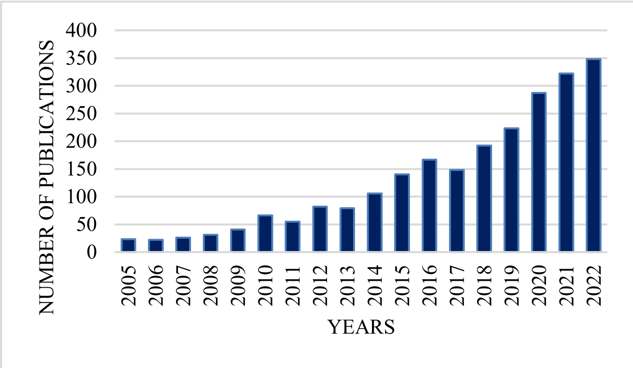


**FIGURE 2. Number of publications in HSC since 2005 (Science Direct Data Result).**

and death'' [31]. Although it has been more than a decade that research has been ongoing in HSC. However, after the COVID-19 pandemic, repetitive floodings and earthquakes, it has become imperative to devise plans and strategies to deal with such situations more efficiently.

The Systematic Literature Review (SLR) methodology, an all-inclusive strategy for literature reviews [32], was used in the present research. Before starting the literature search, this methodology's first step entails identifying the research's purview. In the second step, relevant and excellent studies were sought using various research sources, including Scopus and Web of Science. The last stage is to conduct a reference check on the chosen pieces to find any additional pertinent papers. ''Science Direct'' was selected to check the number of published works in HSC since 2005. The bar chart in Figure 2 supports the point that ever since the onset of COVID-19 pandemic, HSC has become more important. The number of publications is increasing and are highest in 2022.

This systematic review was conducted using PRISMA, which ensures transparent reporting. PRISMA stands for Preferred Reporting Items for Systematic Reviews and Meta-Analysis. PRISMA focuses on reporting studies evaluating randomized trials but can also be used as a basis for reporting systematic reviews of other types of research, particularly evaluations of interventions. It consists of several checklists that help the writer and reviewer write effective review papers [33].

The first PRISMA checklist was presented in 2009, having fourteen (14) items. In 2020, PRISMA guidelines were updated by adding thirteen (13) items, making the total number of items twenty-seven (27) [34]. PRISMA also includes a four-phase diagram. While writing this review, all those items relevant to the systematic review have been considered and are listed with a flow diagram, as shown in Figure 3 and Figure 4.

In a supply chain model, VRP is one of the most critical and vital elements reported in various supply chain domains. However, for this systematic review, vehicle routing problems in the context of HSC are considered only. Further, only mathematical-based models were deemed relevant. The HSC got its fame after the Indian Ocean Earthquake tsunami natural disaster occurred in 2004. Therefore, this research restricted its scope to 2005-2022 publications. Moreover, only journal and conference publications were investigated, while book searches were ignored.

The two databases that were selected are Web of Science and Scopus. As some journals are available in multiple databases, the initial results extracted from all these databases were merged into one MS Excel spreadsheet to avoid duplication. Then, all research papers were sorted based on their titles. All duplicated papers were then eliminated. The last search date for Web of Science was conducted on December 10th, 2022, while for Scopus, it was on December 1st, 2022.

Choosing the appropriate terminology and keywords is critical in conducting a systematic review. The similar keywords previously utilized by [35] and [36] in the context of the Humanitarian Supply Chain are considered for this research. As the scope of this review is VRP, the keywords related to Vehicle Routing Problems (VRP) were also introduced. After several iterations and refinements, the list of keywords was ultimately settled upon. Expressly, for VRP, the following terms were incorporated: ''Vehicle Routing'' and ''Vehicle Transportation or Transport''.

The'' Advanced Search'' option was used for all databases, which helped us refine the search, particularly for the research questions. The search was customized for the years 2005-2022. Afterward, subject area filtration was carried out for computer science, mathematics, social sciences, and economic sciences. Later, the following keywords with Boolean operators were used: ''vehicle routing'' OR ''vehicle transportation'' AND ''disaster relief operation'' OR ''Disaster Response'' OR ''emergency response'' OR ''emergency relief operations'' OR ''humanitarian supply chain'' OR ''humanitarian relief operations''.

After putting these search terms along with Boolean operators and searching in the ABSTRACT-TITLE-KEYWORDS section specifically, only few research articles were retrieved, as shown in Table 1. It was realized that the search result is limited with these keywords and Boolean operators. Hence, ''Routing'' was included in VRP terms, resulting in more publications, as shown in Table 1. Table 1 indicates that selecting proper keywords is crucial to conducting a better qualitative systematic review.

As shown in Table 1, a total of 597 results were found. All results were then imported into a Microsoft Excel spreadsheet. Since numerous journals are available across various databases, the likelihood of duplication is high. Out of 597 articles, 187 were duplicates; hence, eliminated. Once all results of databases were merged and duplication was removed, the next stage was screening the papers. Initial screening was done based on the title solely. A coding system was created to methodically determine whether to include or exclude an article during the initial screening phase, as outlined in Table 2. This identical coding system was also applied during the screening of abstracts.

**TABLE 1.** Database search results based on keyword "routing".

| Database | Web of Science | Scopus | Total |
|---|---|---|---|
| Search without the Keyword "Routing" | 4 | 38 | 42 |
| Search with the keyword "Routing" | 135 | 420 | 555 |
| Grand Total | | | 597 |

**TABLE 2.** Title and abstract inclusion and exclusion code scheme.

| | |
|---|---|
| Include for Title | 0 for No<br>1 for Yes |
| Exclude for Title | 0 for Not Applicable<br>1 for Non-Vehicle Routing Problem<br>2 for Review paper<br>3 for Non-Mathematical Model Paper<br>4 for non-HSC context |

**TABLE 3.** Screening for" title exclusion'.

| Reason of Exclusion | No. of papers |
|---|---|
| Non-Vehicle Routing Problem | 93 |
| Review paper | 3 |
| Non-Mathematical Model | 2 |
| Non HSC context | 120 |
| Total | 218 |

After removing duplications, 410 articles were left. Each article was checked for its title based on the coding scheme presented in Table 2. A total of 218 papers were excluded during "Title Screening". The reason for exclusion and the respective number of excluded papers are listed in Table 3. For the next stage, 192 articles were left.

For the 192 publications, the abstract of each paper was read, and 66 articles were again eliminated based on the reasons listed in Table 4. The total remaining publications for the next stage were 126.

In recent years, research in vehicle routing of HSC has attracted much attention due to extreme uncertainty in the occurrence of natural and manmade disasters. To illustrate the necessity, previous review papers of VRP for HSC are considered. Although review papers are out of context for this article. However, to check the novelty of the approach used in this study, five review papers were found from the title include-exclude criteria whose review is presented below.

A brief survey was presented by [37] to implore that vehicle routing requires multiple mode optimization of various constraints, including time, route, distance, capacity,

**TABLE 4.** Screening for "abstract exclusion".

| Reason for Exclusion | No. of Papers |
|---|---|
| Non-VRP | 41 |
| Review Paper | 5 |
| Non-Mathematical Model | 20 |
| Non-HSC Context | 0 |
| Total | 66 |

and feasibility in disaster situations. Hence, developing a mixed-mode model to solve the problem is mandatory. Recent literature also focused more on facility location than transportation techniques. However, the paper is more of a small survey problem than a proper literature review. It only presented the gap without mentioning previous literature.

Shao et al. [38] provided a detailed literature review showing whether facility location problems interact with vehicle routing or transportation networks. The hypothesis was tested through extensive review analysis of the location-routing model, location models embedded with travel time, location models embedded with accessibility, and mathematical location models and, further presented a review study on vehicle routing optimization during a pandemic restraint. The research objective was to comprehensively analyze the literature concerning the use of VRPs (Vehicle Routing Problems) for controlling pandemics. The study aimed to aid scholars in enhancing understanding of the various models, solution techniques, and performance metrics implemented in pandemic-related supply chain operations.

Guiteirrez et al. [39] carried out a taxonomic review of VRP variants based on the collection of donations. The main aim of the paper was to categorize issues of VRPTW (Vehicle Routing Problem with Time Windows), PDP (Pickup and Delivery Problem), and PVRP (Periodic Vehicle Routing Problem) that are relevant to collecting donations. This categorization was based on various characteristics, solution approaches, and mathematical expressions.

A literature survey based on transportation of hazardous materials (HAZMAT) is presented by [40]. The proposed classification was based on routing, risk, scheduling routing, emergency response, network design, and analysis of accidents. Reference [41] presented an ideal prototypical implementation and its assessment in a relief organization through conducting a structured literature analysis. The results derived the main essentials for an integrated logistics and transport planning approach. However, the research revolves not particularly around vehicle routing but around decision makers' and information system inadequacy.

A distinctive literature review based on new variants of the VRP model is presented by [42]. The study is based on general VRP models, not particularly in the context of HSC. To outline a roadmap for future research, [43] presents challenges in devising realistic and applicable optimization models in the shelter location and evacuation routing models. It concluded that researchers should aim at evolving more complex models merging multiple objectives, dynamic perspective, uncertainty, and behavioral aspects.

The literature review of the above review papers indicates that none of them provide a systematic review, nor has anyone done an exclusive review of VRP in HSC. The additional novelty of this review paper is the systematic literature review of VRP for HSC using PRISMA guidelines, which would help the readers and decision makers in areas where VRP in HSC still needs to be addressed. Various cross tables and graphs enrich this study and imply that future research should be conducted in VRP models for HSC.

After the initial screening for the title and abstract, the next critical stage was data extraction. An objective examination of these research articles was required to determine the structural features of the review, which handles all publications in different aspects. However, it was not clear which term should be added with VRP. As more and more research articles were scrutinized, the similarity and uniqueness of different VRP models became evident, and a coding scheme was devised to address it. The categorization extracted from full read view was given names of variables and sub-variables as varied from one research article to another. A total of 15 dimensions were chosen, as presented in Figure 3.

The coding scheme shown in Figure 3 ensured that extracted data from each reviewer was in line. As described in the previous section, two tools are utilized to guarantee that appropriate structural dimensions are chosen [44]. The very first is each aspect must encompass at least 50% of all papers, according to the criterion. The second criterion considers the correct number of sub-categories or sub-variables in each category. Each category and sub-category is represented by a numerical value that was further used in an Excel spreadsheet for data analysis.

The first dimension is disaster type, further categorized into four sub-categories. The second dimension is the objective function. As all utilized literature was refined to mathematical model papers, each research article has an objective function. This category has two sub-categories: single and multi-objectives, which are further subcategorized into the type of objective function, such as time minimization, cost minimization, or any other objective function. It was of keen interest to check whether any research paper considered uncertainty in the objective function. Hence, that, too, was categorized into yes or no sub-category. The fourth dimension is model type, which defines the complexity of the model. Another critical dimension is the disaster stage, i.e., pre and post.

As papers were reviewed, it was observed that some articles only presented software-based solutions using optimization solver approaches, while in others, either exact or heuristic approaches were used. In some papers, both exact and heuristic methods were utilized. Hence, three distinct dimensions were defined for solution methodologies. The first relates to exact approaches, including the e-constraint method, k-mean clustering, dynamic programming/goal programming, knee Solution, Dijkstra's Algorithm, and Branch and Bound methods. The second one is related to heuristic approaches, which encompasses Tabu, GA/ NSGA (Genetic Algorithm/Non-Sorted Genetic Algorithm), Differential EA (Evolutionary Algorithm), PSO (Particle Swarm Optimization), SA (Simulated Annealing), VNA (Variable Neighborhood Algorithm) and ACO (Ant Colony Optimization). The third one is related to modeling software, which includes MATLAB, CPLEX/GAMS, Python, C++, and Java, etc.

| | |
|---|---|
| **Disaster type** | 1. Any; 2 Earthquake; 3. Pandemic; 4. Flood; 5. Other |
| **Disaster Stage** | 1. Pre; 2. Both ; 3. Post ; 4. Not Mentioned |
| **Vehicle Type** | 1. NA; 2. Homogenous; 3. Heterogenous; 4. UAVs; 5. Other |
| **Objective Function** | 1. Single ; 2. Multiple |
| **Uncertainty in the objective function** | 1. No; 2. Yes |
| **Solution Methodology (Exact Algorithms)** | 0. NA; 1. Epsilon Constraint; 2. K-mean clustering; 3. Dynamic Programming; 4. Branch and Bound; 5. Knee Solution; 6. Dijkstra Algorithm; 7. Not mentioned |
| **Solution Methodology (Heuristic Algorithms)** | 1.Tabu; 2. GA/NSGA/NSGA-II; 3. DEA; 4. SA; 5. Not mentioned; 6. VNA; 7. ACO; 8. PSO; 9. Other |
| **Sensitivity Analysis** | 0. No ; 1. Yes |
| **Real World Data Consideration** | 0. No ; 1. Yes |
| **Static / Dynamic Model** | 1. Static; 2. Dynamic |
| **Resource Type** | 1 . NA ; 2. Expandable ; 3. Non-Expandable ; 4. Both ; 5. Not mentioned |
| **Data Type** | 1 . Stochastic; 2. Deterministic; 3. Fuzzy; 4. Robust optimization ; 5. Not mentioned |
| **Model Type** | 0 . NA ; 1 . IP ; 2 . MIP/ MILP ; 3. MINLP ; 4. Path Planning ; 5. Not mentioned |

**FIGURE 3. Coding for data extraction.**

The next dimension is sensitivity analysis. If done repeatedly, sensitivity analysis can give all the insights required for a fully functional decision model. It aids analysts, managers, and decision-makers in comprehending the uncertainties, advantages, and disadvantages, as well as the limitations and breadth of a model.

The data set is another broader aspect, classified into three dimensions. One is related to real-world data consideration, the other to the size of data: small, medium, and large, and lastly, data type: deterministic, probabilistic, fuzzy, or robust.

As most of the VRP models consider vehicle and resource types, the two dimensions focusing on each were also included. Lastly, the model was categorized into static or dynamic sub-categories.

It is worth mentioning that diversity is expected in any paper. Therefore, for each respective dimension, "Not applicable", "Other", and "Not mentioned" sub-categories were added. From the full text read, 16 articles (ten non-mathematical and six non-HSC) were excluded. Towards the

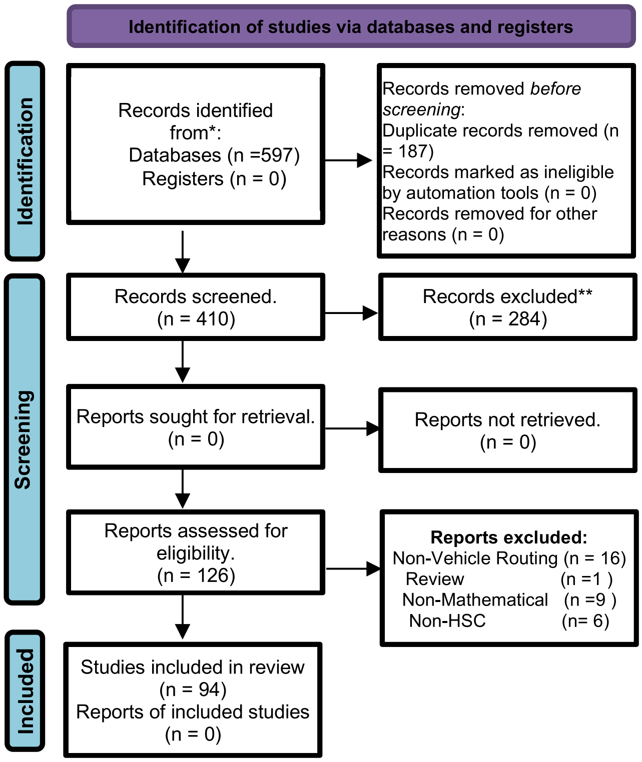


**FIGURE 4.** PRISMA flow diagram.

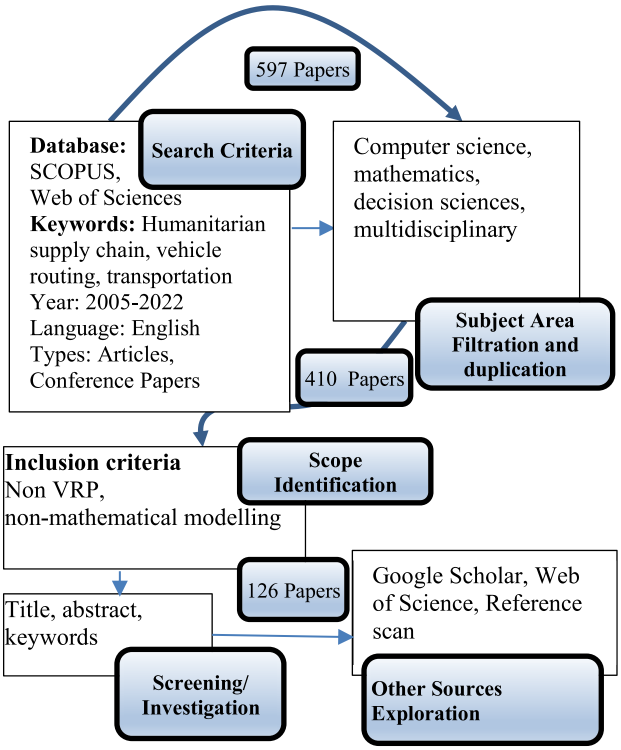


**FIGURE 5.** Flow diagram with screened papers detail.

end of this deductive process, 94 publications were left for data extraction and synthesis.

## III. RESULTS

Details of the screening of all papers are shown in Figure 4 and Figure 5. After a full read review and data extraction, the data was synthesized based on PRISMA guidelines.

### A. DISASTER TYPE

The type of disaster and its impact on health correlates, specifically with the occurrence of wounds. Earthquakes, for instance, cause many shocks that demand medical examination. Floods tend to deliver relatively fewer injuries. Some of the disasters do not have an instant impact on public health but can cause a potential danger. Inhabitants' displacements and ecological changes may increase the spreading risk of infectious diseases [45]. Owing to the importance, disaster type is added as one of the characteristics in this review paper.

53.19 % of the papers implored a generalized model, which can be used in any kind of disaster. 30.85 % considered earthquakes, which is one of the recurring disasters. Many researchers in HSC, mainly from Iran, Turkey, Malaysia, and Pakistan have focused on earthquakes.

The ratio of paper considering flood and pandemic was found to be the same. Other disasters include bushfires and Marine accidents. Figure 6 shows trends of different types of disasters over the years and the respective number of published papers. Figure 6 clearly shows that the generalized model dominates other disaster types, and there was a sudden surge in the pandemic-based models after 2019.

### B. OBJECTIVE FUNCTIONS

#### 1) SINGLE OBJECTIVE TRENDS

There are several ways to investigate the objective functions in HSC. The most common is based on the number of objectives: single or multi. Out of 94 papers, 57 papers had a single objective, while 37 had multiple objectives. Figure 7 shows eight different types of objective functions. In HSC, time is an important factor. The pie graph indicates that minimizing time has the highest percentage of 33.

The time components have been treated differently by researchers. Total travel time minimization is considered by [46]. Moreover, studies of [47] and [48] minimized the weighted sum of all vehicles' total delay time and total visit time. Bodaghi et al. [49] minimized the weighted sum of completion time. Wex et al. [50] minimized the weighted sum of completion times for overall incidents, and [51] minimized the weighted total travel time at any time. Wang et al. [52] minimized the sum of delay time for each unit of relief. The study of Davela et al. [53] reduced the time required to provide humanitarian aid to all the victims and [38] minimized the time of all routes. The model presented by [54] was based on the minimization of travel time of evacuees. Further, [55] tried to decrease the sum of arrival times of vehicles in the affected area. Reference [56] minimized the range of delivery time. Moreover, [57] and [58] lessened emergency response time. Evacuation time was minimized by [59].

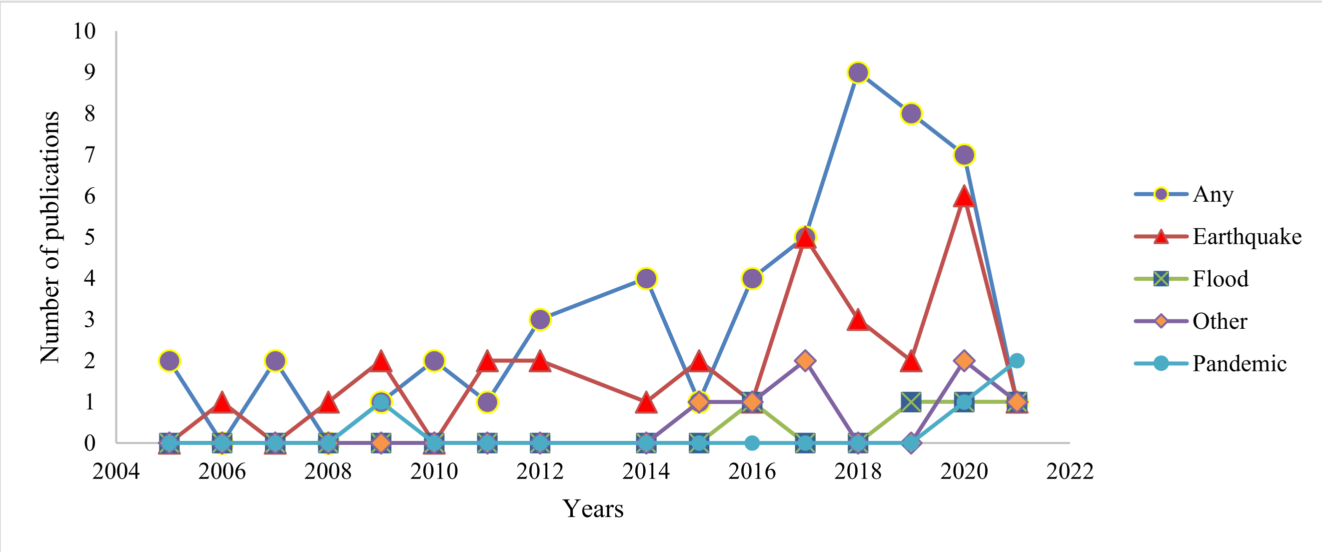


**FIGURE 6.** Disaster types.

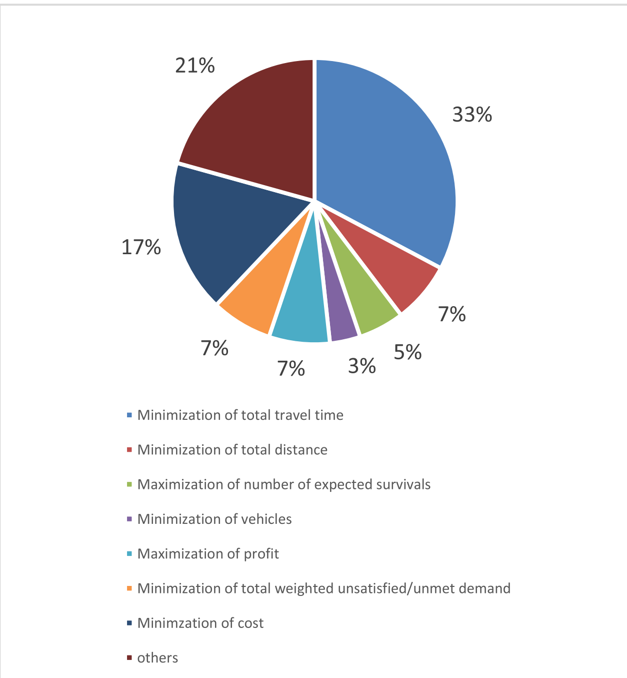


**FIGURE 7.** Objective function pie chart.

Victoria et al. [60] Minimized the sum of arrival time and [61] minimized the sum of the establishment time of aid station and the sum of relief time.

21% of the paper had objectives that are not so common. Bruni et al. [62] tried to maximize the utility. Chowdhary et al. [63] tried to optimize overall Distribution, [64] took fairness criteria as their objective. Huang et al. [65] maximized fulfillment equity. Cankaya et al. [66] worked on stack value among all dispensing sites. Zhao et al. [67] maximized load recovery. Ajam et al. [68] minimized latency in road clearance. Lei et al. [69] minimized the expected outage duration of loads. Yu et al. [70] optimized the efficiency of the evacuation process. Wang et al. [71] focused on the minimization of risk. Krasko et al. [72] minimized the value of total expected damage, and [73] maximized the coverage.

As shown in Figure 7, the third most common objective function is cost minimization. 18% of papers considered cost minimization as their single objective function. References [74] and [75] minimized total transportation costs. [76] devised a model to minimize rental, transportation, handling, and penalty costs. [77] solved the model for warehouse establishment cost and vehicle travel cost. Reference [78] minimized routing and fixed cost. Reference [79] minimized total transportation cost and total cost of vehicle assignment. References [80] and [81] and lessened the total cost for a set of routes. Reference [82] minimized transportation and fixed costs and [83] considered social and vehicle costs.

Some papers targeted distance. References [84], [85], and [86] minimized total distance. Reference [87] minimized the total length of the paths selected. References [88], [89], and [90] maximize the number of expected survivals. Reference [91] maximized total profit, [92] maximized the total prize collected by connecting components with the depot nodes, and [93] maximized expected profit for the routing scheme.

From the demand perspective, [94] minimized total weighted unmet demand, [95] minimized the total amount of weighted unsatisfied demand, [96] and [97] minimized total unsatisfied demand. References [92] and [98] considered minimization of vehicles.

Figure 8 above shows the trends of single and multi-objective models over the years. The graph shows that single-objective models dominate over multi-objective throughout the research of HSC. It makes sense, as

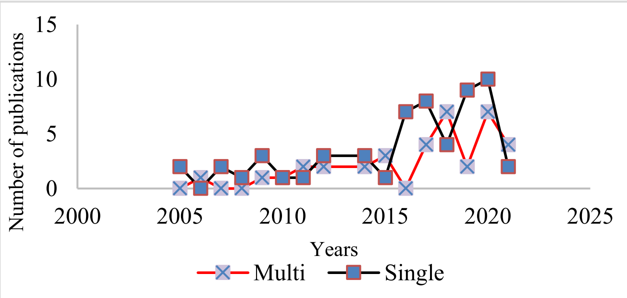


**FIGURE 8.** Single versus Multi-objective trends.

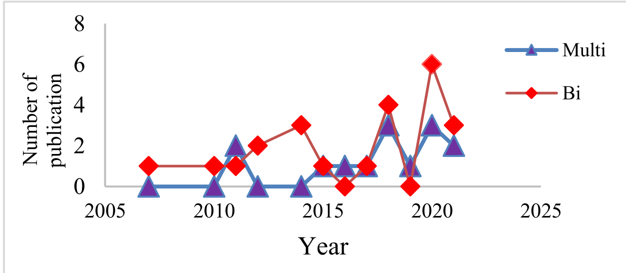


**FIGURE 9.** Bi versus multi objectives.

introducing more objectives in the model solution increases complexity.

### 2) MULTI-OBJECTIVE TRENDS

39.36 % of papers covered multi-objective functions (including bi and many). Figure 9 shows trends of bi versus multi (three or more objectives) over the years. It can be observed that the trend of using bi-objective models is more than considering three or more objectives. 62.16% (23 papers) of the multi-objective papers considered bi-objectives. Ten papers considered cost and time as their objectives.

Tavakkoli et al. [99] minimized service completion time and cost of temporary emergency centers. Reference [100] minimized cost and time of travel. Reference [101] minimized total logistics cost, total time of relief operation, and variation between upper and lower bounds of transportation cost of distribution centers. Reference [102] minimized procurement & preparation costs before disaster occurrence, transportation cost of products whose lifetime is remaining, the total relief operational cost, and the total operational relief time in the action phase. Time delivery and operational cost minimization were done by [103]. Reference [52] minimized average waiting time and scheduling costs. References [104] and [105] minimized overall time and cost. Reference [106] minimized time to save people and the cost of alternative options for the primary objective. Reference [107] minimized the sum of arrival times of vehicles and costs, including setup cost to open a Distribution Centre (DC) and fixed operating cost of vehicles.

Shamsi et al. [83] considered social cost and vehicle cost minimization. Reference [108] minimized total delay, total distance, and number of vehicles, [109] minimized drone distance and drone path risk. Reference [110] considered effectiveness and fairness. Reference [111] minimized unserved injured people and total cost. Reference [112] maximized route reliability and minimized total cost. Reference [113] designed model to minimize total travel time and number of vehicles. Reference [114] optimized the transportation cost and expected covered demand. Reference [58] minimized travel time and unmet demand. Reference [115] maximized the number of evacuees and minimized the number of assigned vehicles & shelters. Reference [116] minimized both unmet demand and cost. Reference [117] targeted demand coverage maximization and minimization of the weighted sum of completion time. Reference [118] minimized the weighted sum of unsatisfied demand and the weighted sum of wounded people waiting.

Bozorgi et al. [119] minimized total unsatisfied demand, total travel time, and pre-post-disaster cost. Xu et al. worked on multi-objectives for oil refinery station problems [120]. Similarly, Cao et al. [121] and Xiao et al. [122] worked on multi-objective problems for multi-vehicle heterogeneous problems and continuous routing problems respectively. Yang et al. [123] maximized overall satisfaction (effectiveness), fairness, and cost minimization. Reference [124] reduced unsatisfied demand penalty, fixed cost, and time. Reference [125] minimized total unsatisfied demand, total travel time, and difference of service rate, [126] considered effectiveness, equity, and efficiency (minimization of total unsatisfied demand, total travel time, and equity), [127] proposed model for vehicles and total travel cost minimization and also latency maximization. Reference [128] tried to lessen the total walking time of evacuees, total transit-based transportation, and the number of vehicles. Reference [129] minimized network Origin-Destination (OD) connectivity, network vulnerability, and network length. Reference [130] focused on minimizing rescue time, maximizing life-saving utility, and minimizing delay costs. Reference [131] minimized average response time, infectious risk possibility, and number of vehicles. Reference [132] minimized cost, response time, and energy use. Reference [133] implemented their model for traveled distance, cost, and travel time. Reference [134] minimized quantities of unsatisfied demand, unserved wounded and non-transferred workers. Reference [135] minimized the maximum vehicle route travel time, the emergency relief cost, and $CO_2$ emissions.

## C. MODEL TYPE

Model types were categorized into four classes, including Mixed Integer Programming or Mixed Integer Linear Programming (MIP/MILP), Integer Programming (IP), Mixed Integer Nonlinear Programming (MINLP), and Path Planning.

As visualized in Figure 10, 60 out of 94 models were based on MIP/MILP, and 22 were based on Integer programming. 08 considered MINLP in their initial model. However, the models were later transformed into the MILP Model. Four

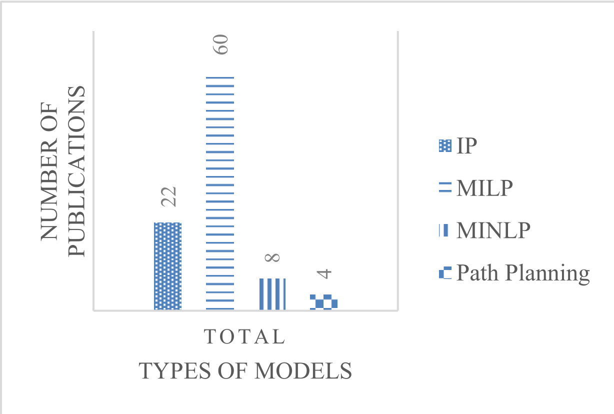


**FIGURE 10.** Model types trends.

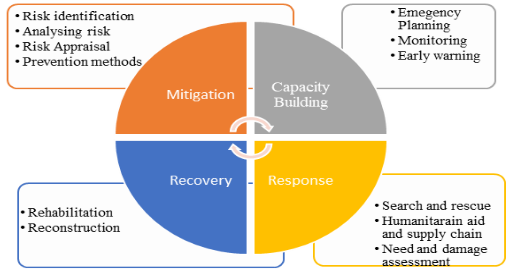


**FIGURE 11.** Disaster stages.

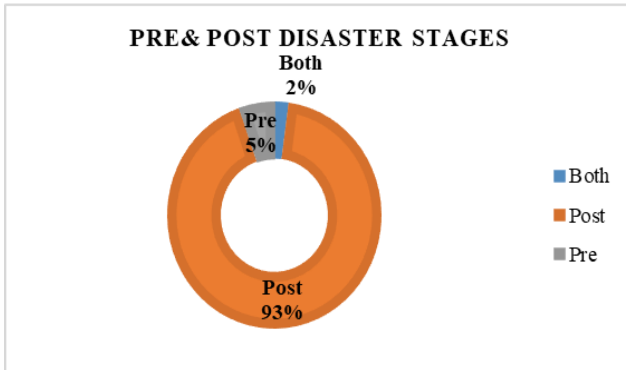


**FIGURE 12.** Trends of disaster stages.

(4) papers were categorized as path planning. Three path planning models reported in [70], [71], and [89] were simulations where vehicle paths were simulated for a disaster area. Refrence [109] considered Unmanned Aerial Vehicles (UAVs) for a path planned in a disaster area.

### *D. DISASTER STAGE*

The disaster management cycle contains the following stages: warning, threat, impact, inventory, rescue, remedy, and recovery [136]. According to [137], there are at least six major components in disaster management, which are: (1) prevention; (2) mitigation; (3) preparedness; (4) response and relief; (5) rehabilitation; and (6) reconstruction. The US Federal Emergency Management Agency (FEMA, 2006) indicated that the disaster management cycle is open-ended. Broadly used disaster phases are four [138], as shown in Figure 11.

Vehicles are the primary component of search and rescue operations, and also for need and damage assessment during the response and recovery phase. However, VRP models can also be considered in the pre-disaster phase. As shown in Figure 12, 93 % of the paper reviewed in this article accounted for post-disaster scenarios, 5 % for pre, and only 2 % accounted for both cases.

### *E. SOLUTION METHODOLOGIES (EXACT, HEURISTICS, AND COMMERCIAL SOLVER)*

Figure 13 categorizes HSC research papers based on their chosen solution methodologies, enabling a clearer understanding of the diverse research landscape within the field. This classification aids researchers in selecting the most relevant papers for studies and facilitates discussions and comparisons of different research approaches in the HSC domain.

Figure 14 shows a comprehensive display of the primary classes of solvers employed to tackle HSC (High School Certificate) problems. These solvers can be broadly categorized into three groups: exact solvers, heuristic solvers, and commercial solvers. Furthermore, the graph in Figure 14 points out a significant trend: the increasing application of heuristic approaches in HSC problem-solving, starting from the year 2015. This suggests a shift in research and practice towards more efficient and practical problem-solving techniques, possibly driven by advancements in heuristic algorithms and computational capabilities

As shown in Figure 15, 47% of the papers used heuristic approaches, 30% applied exact methodologies, 9% used exact and heuristic methods, and 11% solved the model using commercial solvers. In comparison, 3% did not mention the method of solution.

### *F. EXACT APPROACHES*

As shown in Figure 16, out of 28 papers that used exact approaches, 4 used the epsilon constraint method, 4 used Dijkstra's algorithm, 4 used the k-mean algorithm, while only one paper used branch and bound and clustering methods. Twelve articles used different techniques. Reference [114] used sample average approximation, [98] used an LP-based algorithm, [47] used Floyd's shortest path algorithm, [90] applied simulation, and used an agent-based simulation method. Reference [84] applied chance constraint method, [108] applied other methods, [123] used fuzzy hierarchical dispatching rule, [54] used Oak Ridge evacuation modeling system. Reference [87] used goal programming, [118] used a Pseudo-polynomial routing algorithm, [63] used the Continuous approximation method in drone routing, and [69] used Scenario Decomposition ( SD) Algorithm.

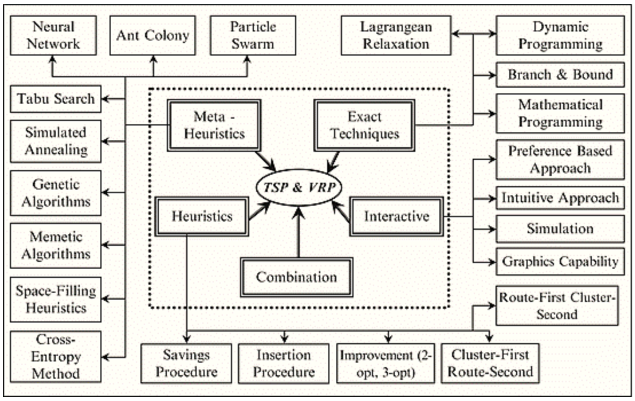


FIGURE 13. Classification of solution methodologies.

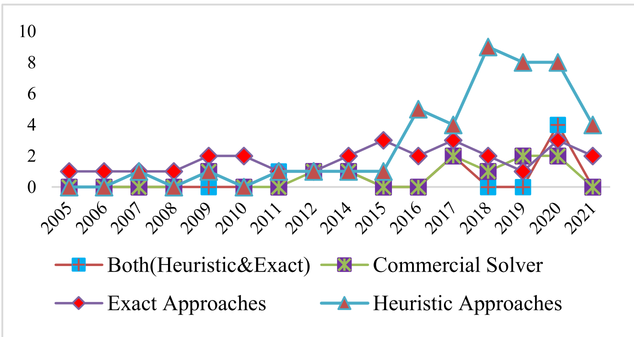


FIGURE 14. Solution methodologies trend.

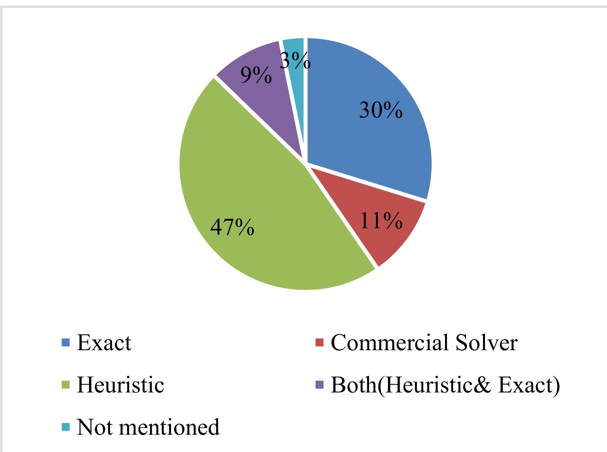


FIGURE 15. Solution methodologies pie chart.

## G. HEURISTIC APPROACHES

Figure 17 depicts a predominant pattern where Genetic Algorithm (GA)-based heuristics have been prominently featured in most research papers. However, different versions of GA were used, including NSGA (Non-Sorted Genetic Algorithm), Non-Sorted Genetic algorithm Stochastic Neighborhood Search (NSGA-SNS-II), Hybrid Genetic Simulated Annealing Algorithm (HGSAA), and Memetic Algorithm (GA with local search). Reference [61] used both GA and

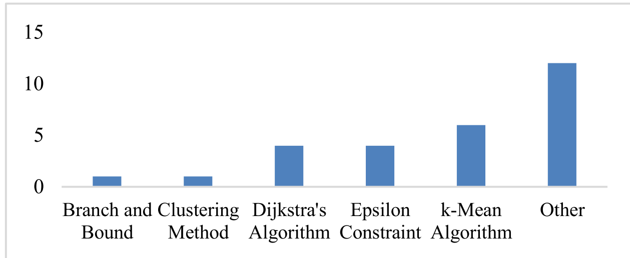


FIGURE 16. Types and number of exact approaches used.

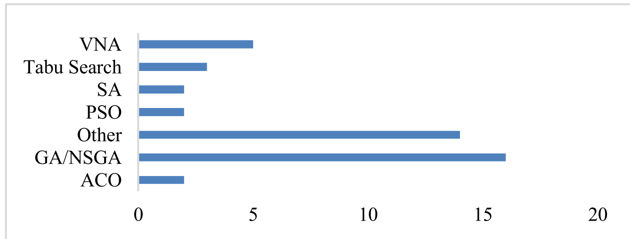


FIGURE 17. Types and number of heuristic approaches used.

discrete version of imperialist competitive algorithm-meta heuristic.

Variable Neighborhood Search Algorithm was also used with different versions, including the largest and nearest neighborhood approaches. Other heuristics include column generation by [79] and [89]. Reference [100] used hybrid decomposition heuristics, [62] used iterated greedy, [108] preferred hierarchical clustering and route procedure, [139] progressive hedging algorithm, [140] used grasp meta-heuristic, [106] implied fast approximation algorithms, [60] multi-start iterated local search, [75] iterated local search, [134] used other, [66] cluster route improve heuristic, [59] K-shortest path with Lagrangian relaxation, and [133] grasshopper optimization algorithm.

## H. COMMERCIAL SOLVER

Only ten (10) papers used any software to solve their model. Wang et al. [59] used the Gourbi solver package in Python. Manopiniwes et al. [96] and Ahmed et al. [117] used a commercial solver but didn't mention the name of the software. Yu et al. [70] used VISSIM simulation software. Hannoun et al. [46] used Netlog simulation software. Rennemo et al. [110] used the Xpress-IVE optimization suite. Karasko and Rebenack [72],Rabata et al. [141] used GAMS. Afshar and Hoghani [95] and Gokce et al. [91] used CPLEX to solve their model.

## I. PAPER WITH BOTH HEURISTIC AND EXACT APPROACHES

Nine (9) papers used both exact and heuristic models. Yu et al. [109] used the knee-based exact method and Differential Evolutionary (DE) heuristic methods. Salama and Srinivas [104] used the epsilon constraint exact method, an unsupervised machine learning heuristic method. Bodaghi et al. [49] used

Greedy, Augmented Greedy, k-node Crossover, Scheduling, Monte Carlo, and Clustering as exact methods and GA as a heuristic method. Akbari and Salman [92] implemented the model using exact mixed integer programming algorithm and Relaxation Based Neighborhood Search (RBNS) heuristic algorithm, Tavana et al. [102] used epsilon constraint exact method and GA heuristic simultaneously. Wex et al. [50] solved the model using the Monte-Carlo-based exact method and GRASP meta-heuristic, Afsar et al. [80] used column generation and Iterated Local Search (ILS) heuristic, Gokce et al. [92] applied Lagrangian relaxation exact method, and Successive Single Vehicle Algorithm (SSV) and Mills et al. [64] applied Markov Decision Process (MDP), myopic approach and policy improvement approach.

### J. SOFTWARE'S

As demonstrated in Figure 18, the graph reveals that CPLEX Software has been the most commonly employed tool, followed by GAMS and MATLAB. Other software includes simulation using a pro model for different scenarios, GIS, GEO DBMS, HAZUS, Arc GIS, VISSIM simulation, Xpress-IVE optimization suite, Net log simulation, RStudio, LINGO, and BARON.

### K. DATA TYPE

Uncertainties in the model can be incorporated by using different techniques. The most common techniques are scenario-based, probabilistic, or stochastic. The number of papers using different deterministic and non-deterministic approaches is shown in Table 5.

### L. SOLUTION SIZE

Considering populations is crucial in disasters. Practical models are needed to tackle large-scale problems efficiently. Decision-makers rely on such models for resource allocation and risk assessment, aiding effective disaster management. As per the coding scheme, a problem size with 5-15 data points is considered small, 15-30 is considered medium, and more than that is taken as large-size problems. Table 6 shows the number of papers with small, medium, and large size problem considerations.

### M. REAL-WORLD DATA CONSIDERATION

It can be seen in Figure 19 that the use of real-world data is less compared to the hypothetical data. Forty-five used the real-world data, whereas 49 used the hypothetical data.

### N. SENSITIVITY ANALYSIS

Sensitivity analysis (SA) is the technique of knowing how the ambiguity in the output of a model can be assigned to various sources of uncertainty. SA, therefore, is believed to be a prerequisite for model construction in any setting [142]. Sensitivity analysis is essential to check the designed algorithm's functionality [143]. However, only 50 papers used sensitivity analysis to check the functionality of the proposed algorithms. As shown in Figure 20, the sensitivity analysis was used more for both single and multi-objective models. However, the respective percentage of multi-objectives is on the higher side. As adding more objectives increases complexity and uncertainty, checking model functionality for multi objectives becomes more critical.

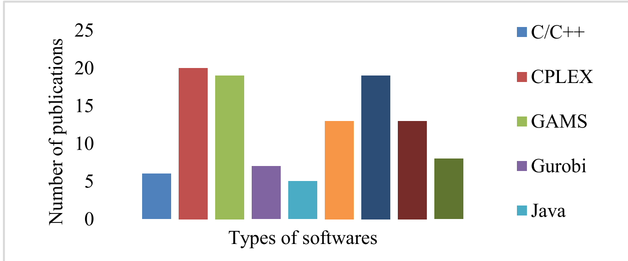


**FIGURE 18.** Number of publications using different software and their applications.

**TABLE 5.** Distribution of papers by deterministic and non-deterministic approaches.

| Data Type | Number of Publications |
|---|---|
| Deterministic | 34 |
| Deterministic, Stochastic | 01 |
| Fuzzy | 02 |
| Human's belief degree | 01 |
| Probabilistic | 17 |
| Deterministic, Robust | 01 |
| Scenario Based | 04 |
| Stochastic | 34 |
| Stochastic, Probabilistic | 01 |

**TABLE 6.** Publication statistics on solution size in vrp research.

| | |
|---|---|
| Large | 32 |
| Medium | 14 |
| Small | 48 |

### O. VEHICLE TYPE

A real-world disaster situation mostly requires a heterogeneous kind of vehicle. However, it can be seen in Table 7 that most of the models have considered homogenous vehicles only.

### P. RESOURCE TYPE

Forty-two (42) papers considered resource type. Twelve (12) papers mentioned both consumable and non-consumable items. Fifteen papers considered only consumable products. Only four considered non-consumable things. Nine papers did not mention the type of resource. Reference [140] considered pallets, which may have multiple supplies but are

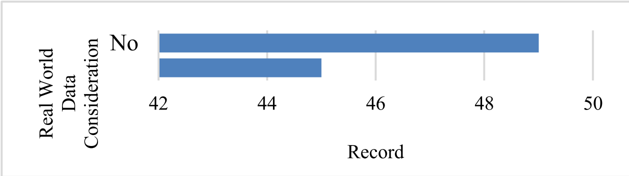


**FIGURE 19.** Real-world data versus hypothetical.

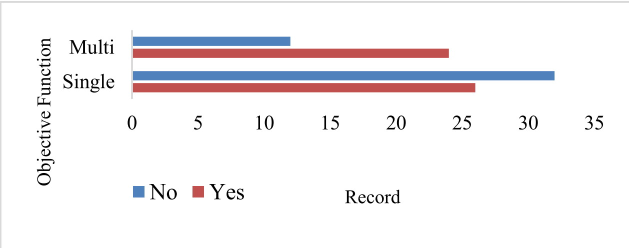


**FIGURE 20.** Sensitivity analysis of single vs multi-objective model.

**TABLE 7.** Vehicles taxonomy.

| Vehicle Type | Number of Publications |
|---|---|
| Heterogenous | 31 |
| Homogenous | 56 |
| Not Mentioned | 3 |
| SAR (Search and Rescue) Routing | 1 |
| UAVS | 3 |

considered a single commodity. Although injured people are not resource type, [61] considered it.

### Q. FUZZINESS IN OBJECTIVE FUNCTION

One of the research questions was about consideration of fuzziness in the objective function. Only three papers were found that considered uncertain objectives in their model. Reference [62] considered travel time uncertainty, while [116] considered travel cost and demand uncertainty. Reference [101] is the only paper found that considered fuzziness in their objective function.

### R. STATIC OR DYNAMIC MODELS

Sixty-nine (69) papers were based on static models, while twenty-five articles addressed the dynamic models.

## IV. INSIGHTS FOR POLICYMAKERS

This review study offers policymakers a solid groundwork to develop more efficient disaster management and humanitarian supply chain policies. Classifying and assessing VRP models within humanitarian supply chains provide policymakers with a formidable tool for decision-making. The proposed systematic classification of VRP models in HSC is based on various parameters, including objective functions, solution methodologies, uncertainties, resource types, and vehicle types. It provides a valuable resource for policymakers. In this regard, when faced with complex resource allocation tasks during a disaster, practitioners and policymakers can utilize the study's findings to select VRP models that best suit the specific characteristics of the crisis. Whether it is a sudden-onset catastrophe like an earthquake or an extended emergency like a refugee crisis, the ability to precisely tailor response strategies can significantly enhance the efficiency and effectiveness of interventions.

Furthermore, this research underscores the importance of addressing emerging challenges in disaster response planning, such as sustainability considerations and scheduling optimization. Policymakers can seize this opportunity to proactively incorporate environmentally friendly practices and advanced scheduling techniques into their policies, resulting in more resilient and eco-conscious disaster response efforts. Ultimately, this review study empowers policymakers to make evidence-based decisions, adapt to evolving disaster scenarios, and optimize resource allocation strategies, all of which can lead to more effective and efficient disaster management and humanitarian supply chain operations that benefit diverse stakeholders and communities in need.

## V. DISCUSSION

Many generalized models are developed to solve any kind of disaster. However, different disasters have different constraints that need to be considered. For Example, time and temperature constraints [vaccine expiry time and vaccine surrounding temperature] are important factors for vaccination. In an earthquake model, road blockage constraint was considered [123]. Limitation for compatibility of fresh Agri products transported to refrigerated vehicles was assessed by [131]. In a rescue operation, moving obstacles constraint was considered by [71]. This shows that although a generalized model may theoretically seem perfect practically, it may not be suitable. To the best of the authors' knowledge, only the models above considered specific constraints for a particular type of disaster.

The Covid pandemic is one of the most uncertain pandemics of this era. It is the need of the hour to develop novel HSC models for dealing with such disasters in the future. Only four papers [49], [83], [100], [131] were found that considered pandemic as per the research timeline 2010-2022. However, this year, much work and research have been published on COVID-19. A contactless joint distribution service for managing COVID-19-related food distribution challenges in gated communities was introduced by Chen et al. [107]. The PEABCTS algorithm, a fusion of artificial bee colony and tabu search, optimizes multi-vehicle routing. Rigorous comparative experiments confirm the algorithm's superiority. The service reduces direct courier interactions and enhances safety while significantly improving resident satisfaction, food distribution rates, and efficiency. The paper also introduces adaptable parameters for administrators. In summary, this research offers a timely and practical solution for pandemic management within gated communities, setting a precedent for similar scenarios.

The critical issue of optimizing vaccine supply chain logistics, particularly the challenging "last-mile" distribution, with a focus on pandemics and resource-constrained settings, is addressed by Theeb et al. [144]. The study presented a novel multi-objective mixed-integer linear programming (MILP) model by integrating the two-echelon vehicle routing problem (2E-VRP) and vaccine supply chain (VSC) to minimize unsatisfied customer doses. To tackle the complexity of the problem, a heuristic solution based on greedy random search is introduced. Comparative experiments demonstrate that this approach outperforms the CPLEX solver for medium and large-scale datasets. The study emphasizes the trade-offs inherent in optimizing conflicting objectives within the vaccine distribution context, offering decision-makers flexibility. To test the applicability of the proposed model, it is implemented on a real problem in distributing COVID-19 vaccines in the Irbid district of Jordan, showcasing an average 11.97% improvement in the number of doses delivered over four days. Overall, this research presents a practical and efficient solution for vaccine distribution logistics during pandemics, underscoring its superiority over traditional optimization approaches.

Guo et al. [145] address efficient vaccination management challenges during pandemics by introducing a two-level decision framework, tackling vaccination station operations and vaccine delivery logistics. Key aspects include station operation decisions, resident allocation, staffing levels, and optimizing refrigerated vaccine transport routes. The study employs a hierarchical mixed-integer linear program (MILP) to address these challenges comprehensively. A case study on COVID-19 vaccine administration in Wuhan, China, demonstrates increased operational stations, reducing community travel costs. The study emphasizes balanced station openings and community allocation for cost optimization, offering practical tools and insights with broader applications in public health coordination.

Yazdani et al. [146] investigated the critical challenge of optimizing healthcare resource allocation during pandemics and disease outbreaks. The study introduced a decision model integrating optimization techniques for ambulance routing, accounting for variable healthcare facility capacities, particularly hospitals. The model's precision is enhanced by introducing lemmas and local search methods, ensuring improved solution accuracy, and guiding the algorithm toward global optimization. Comprehensive computational tests using real-world data from a Sydney case study demonstrate significant time savings. This research underscores the paramount importance of effective healthcare resource management during crises, contributing to advancing the field and preserving public health.

The intricate task of optimizing vaccine supply chain management amid the framework of the COVID-19 pandemic is studied by Valizadeh et al. [147]. The research introduced a robust bi-level optimization model that considers the multifaceted concerns of governments and organizations, including the profound risks associated with mortality due to delayed vaccine supply and the potential for inequitable vaccine distribution. The model comprehensively covers vaccine supply chain costs, encompassing the entire spectrum from procurement and allocation to maintenance, logistics, and penalties for vaccine shortages. It also navigates the intricate challenge of addressing uncertain vaccine demand by incorporating multiple demand scenarios into its framework. Through a series of real-world numerical experiments conducted for Kermanshah, Iran's vaccine supply chain, the study effectively demonstrates the model's capability to significantly mitigate mortality risks, rectify distribution inequalities, and curtail overall costs. These compelling results furnish indispensable insights for healthcare decision-makers, facilitating the enhancement of coordination within vaccination networks, especially during pandemic crises.

One of the destructive and lethal repercussions of COVID-19 is the exposure of non-responsive healthcare systems. Vaccine distribution and supply chain models for safe, equitable, and effective delivery of diagnostics and human factor engineering have given plenty of space for researchers to work on.

Objective functions are the backbone of a mathematical model. Most models have considered a single objective in their models. Time is more important than cost in HSC. Hence, minimizing time is the most used objective. After "time", demand satisfaction is the second most significant objective. In multi-objective models, mainly time and cost have been considered. Single objectives lessen the complexity of a model; however, it can also make a model unrealistic. New models should be devised considering time and demand satisfaction or unmet demand simultaneously.

Another new VRP venture in HSC is considering Unmanned Aerial Vehicles (UAVs). It can help humanitarian organizations in gathering information accurately and swiftly. It can help save lives and be beneficial during a pandemic to minimize human interaction and avoid spreading the disease. Another potential advantage can be in logistics and delivering rescue items. For that, more innovative designs and system tools are required. However, very few researchers have shown keen interest in this area. Only three papers were found that solely considered UAVs and one paper considered heterogeneous vehicles, including drones in their designed model. Reference [109] did UAV path planning considering distance and risk of the path, [132] presented a novel bi-stage operational planning approach consisting of a trajectory optimization algorithm and a hub selection-routing algorithm. Reference [93] considered the kinematic constraints of UAVs and introduced the Dubbin's curve to fit the shortest flyable path for each UAV that would meet the maximum curvature constraint. It also presented a multi-UAV rapid-assessment routing problem (MURARP) for actual need assessment in a post-disaster case. Reference [63] proposed a Continuous Approximation (CA) model that offers drones to supply emergency relief in a disaster-affected area by determining the optimal distribution center locations, service regions, and quantities to minimize the overall distribution cost. Furthermore, the rapid advancements in autonomous vehicle technology [148], [149], [150], [151] and the exploration of its role within the context of humanitarian supply chain VRP become increasingly significant, promising more efficient, resilient, and timely delivery of critical resources to those in need during times of crisis. Similarly, modern urban planning relies on intelligent traffic control technologies to reduce congestion, increase safety, and boost transportation efficiency [152], [153], [154], [155], [156]. These advances are important for urban and humanitarian supply chain logistics, especially for solving the Vehicle Routing Problem (VRP) for relief distribution.

Sustainability is currently a societal concern. Researchers are trying to design a long-term emergency logistic network. However, the proposed emergency logistic network must consider environmental and social aspects and economic elements [26], [157]. However, little or no research has been done in this area. Only one paper considered sustainability. Reference [135] constructed an uncertain multi-objective location-routing programming model for emergency response by considering travel time, emergency relief costs, and carbon dioxide emissions.

Heuristic algorithms are the dominant methods in the HSC VRP model, indicating the significance of this approach. The widely used heuristic is the Genetic Algorithm (GA). Different versions of GA were combined with other metaheuristics in solving HSC VRP models. Hence, researchers should try integrating GA with other meta-heuristics and approximation approaches, which may provide better results.

Uncertainties are primarily dealt with through probabilistic and stochastic models, but very few researchers have used fuzzy logic or quantum computation, chaos theory, and other uncertainty theories. Moreover, the combination of these approaches was also scarcely found. Reference [74] established a fuzzy multi-objective optimization model with traffic constraints and capacity limits. Reference [116] used probabilistic, deterministic, and robust optimization theories to solve their model. Reference [135] introduced Human's belief degree (uncertainty theory) for dealing with uncertainty in their model.

While designing VRP models for an HSC area, few researchers considered both expendable and non-expendable resources. Only 12 papers out of 94 considered both types of resources. At the same time, most of them didn't even consider resources and solely designated the model for vehicle routing. Vehicle routing and resource scheduling problems are dealt separately by researchers. Limited literature is available where both are dealt simultaneously.

In manufacturing and service industry, sequencing and scheduling are requirements for on-time delivery and customer satisfaction. In HSC, the sequencing and scheduling of resources is mandatory for saving lives and reducing risks. Dynamic scheduling algorithms and models are yet to be developed, which offer on-time delivery and involve risk factors associated with the HSC network. Reference [49] formulated the Multi-Resource Scheduling and Routing Problem (MRSRP) for emergency relief and developed a solution framework to deliver expendable and non-expendable resources in emergency recovery operations effectively. Reference [131] integrated multi-item packaging and vehicle routing with split delivery to improve the emergency supply capacity.

With the advances in digital technology, every sector is introducing digital solutions. Many new software and applications are developed and implemented to ease the jobs. Many software applications have built-in AI packages that can directly be applied to solve complex models. Gourbi is one of those packages of Python that can effectively be used to solve VRP-based models in much less time and with better solution quality. It was observed that computational time had not been considered in solving VRP-based models. It should be included in the result analysis to check the smartness and quickness of the developed model.

As stated earlier, static models dominate over dynamic models. As the situation and demand in a disaster change rapidly, a dynamic or rolling horizon approach must be stimulated in future models.

This review paper is only limited to mathematical models in VRP in HSC. Non-mathematical models, review articles, non-HSC models, and non-VRP models are out of context for this systematic review. Further, two databases, including Web of Science and Scopus results, were extracted with the last search done on December 10th, 2022, and December 1st, 2022, respectively. Publications from 2005 till the last search date are included only.

## VI. CONCLUSION

This article presents a systematic literature review of 94 papers using the PRISMA tool to address the current research state of the vehicle routing mathematical models in HSC. What can be the research directions in VRP for HSC? How uncertain approaches are used in developing VRP for HSC? How and which exact or heuristic approaches are used? Has any paper considered fuzziness in the objective function? Which commercial solver has been broadly used for solving VRP models? To answer all these questions, 15 categorizations were devised to extract data. Data analysis based on all those characteristics has been conducted in the result section. It is observed that most papers have considered a single objective MILP model. The literature mainly focuses on post-disaster situations. Solution methodologies are classified as heuristics, exact, and commercial solvers. Heuristics methodologies dominate exact methods, and exact methods dominate commercial solvers. Deterministic and stochastic models were developed. However, limited research is available on the use of fuzzy and other new uncertainty approaches. Most papers did consider large-scale hypothetical data, which are challenging to implement. Most of the multi-objective models applied sensitivity analysis to check the functionality of their model. Homogenous vehicle types are used more than heterogenous vehicles. It is also observed that UAVs are also being considered. Very few researchers have combined expendable and non-expendable resource types in their models. Uncertainty in the objective functions is only presented in three papers. Lastly, static models dominate over dynamic models.

## VII. FUTURE RESEARCH DIRECTION

Based on the extensive discussion and conclusions drawn from this systematic literature review, a range of future research directions can be outlined for Vehicle Routing in HSC or Emergency Response Operations (ERO). These directions include the development of advanced VRP models that optimize multiple objectives concurrently, taking into account aspects such as time, cost, and demand satisfaction with more realistic and intricate objective functions. Additionally, specialized VRP models tailored to distinct disaster scenarios, such as earthquakes, pandemics, floods, and bushfires, should be explored, addressing unique factors like road blockages, vaccine supply chains, dynamic road closures, and resource allocation. Investigating the integration of Unmanned Aerial Vehicles (UAVs) into HSC VRP models for improved information gathering and logistics, as well as incorporating sustainability considerations encompassing environmental, social, and economic factors, is essential. Furthermore, the research should focus on hybrid metaheuristics, uncertainty handling approaches, resource types integration, dynamic models adapting to rapidly changing conditions, real-world validation, human factor engineering, digital solutions, data availability challenges, and sensitivity analysis in multi-objective models. These interconnected dimensions offer a comprehensive outlook on the future of VRP in HSC and ERO, potentially stimulating further research initiatives in this domain.

## CONFLICT OF INTEREST

The authors declare no conflict of interest concerning this submission's research, content, and findings.

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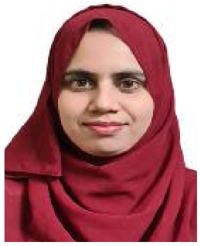

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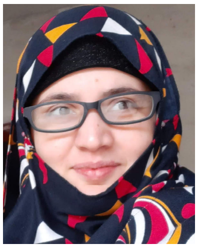

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