Optimized Location and Assignment of Emergency Response Assets in Offshore Energy Basins

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The global energy industry engages in exploration, drilling, production, and abandonment activities in pursuit of crude oil and natural gas. This paper provides a methodology to optimize the location and assignment of oil spill response containment systems to limit environmental damage. Utilizing 1,802 active offshore sites and 13 eligible service depots in the Gulf of Mexico's offshore energy basin, this study locates and assigns deployable land-based containment systems while evaluating the progressive enhancement of including additional service depots. The model solves the practical problem of locating and allocating oil spill containment systems to a global optimum. Adding service depots reduces the average distance, or travel time, of response vessels, which minimizes the dispersion of the oil spill. This study represents a critical component of a broader emergency oil spill response plan. Specifically, it addresses the preparation phase of a comprehensive oil spill response plan, which is preceded by the mitigation phase and followed by the response and recovery phases.

Keywords: offshore logistics, combinatorial optimization, emergency response

INTRODUCTION

In pursuit of crude oil and natural gas, numerous activities are performed in offshore basins across the globe. Typically, the chronological life cycle of a project entails exploration, development, production, and abandonment (Kaiser and Snyder, 2010). These hydrocarbon commodities are discovered, extracted, and transported from basins including, but not limited to, Australia, Brazil, Cyprus, Ghana, Guyana, Mexico, Nigeria, Norway, Philippines, Saudi Arabia, Trinidad, and the United Kingdom. To varying degrees, these basins' work environments pose risks to personnel and include environmental hazards. Regulators, trade unions, industry associations, and energy firms employ equipment and processes to prevent harm to personnel and the environment (Kilaparthi, 2014). However, incidents and accidents are likely to continue to be prevalent. In such instances, specific assets exist to mitigate the impact of such occurrences. Specifically, oil spill response vessels are deployed to contain and recover oil spills (Ventikos *et al.*, 2004; Hamlet, Irwin, and McGregor, 2020). While the public is typically only aware of major spills, such as the Horizon Deep Water disaster in 2010, many other spills occur and require remediation. Between 2012 and 2021, 194 oil spills greater than one barrel, or 42 gallons, were reported in the Gulf of Mexico (Bureau of Safety and Environmental Enforcement, 2023).

Environmental disasters in the offshore energy industry typically involve oil spills and yield detrimental economic and ecological impacts. Specifically, oil spills may potentially harm wildlife, vegetation, fisheries, and humans (MacKenzie, Baroud and Barker, 2016). Although major incidents are rare, their impact can be detrimental for decades (Grubesic, Wei and Nelson, 2019). Notably, Grubesic et al. (2019) identified that environmental impacts do not inherently correspond with the quantity of oil spilled and may differ due to the oil type (light or heavy) that enters the environment via human interaction or error. Once an oil spill occurs, the spill immediately spreads due to currents and wind. Therefore, the elapsed time to deploy containment and recovery systems is a key component when mitigating the overall impact of the spill (Toregas *et al.*, 1971).

The strategic location and assignment of emergency response assets have been and will continue to be studied by researchers, practitioners, and stakeholders. In essence, research regarding the strategic location and assignment of emergency response assets is subject to the nature of potential emergencies (i.e., oil spill, earthquake, wildfire) and those assets designed to prevent or respond to such emergencies. Therefore, decision tools are heterogeneous; consequently, their development and implementation remain rich opportunities for research and practice, respectively.

The current research applies combinatorial optimization modeling to the preparation stage of the emergency response plan in the context of a maritime oil spill. The abovementioned works focusing on the preparation stage are designed and evaluated to reflect or approximate environments that materially differ from the current study. The Gulf of Mexico represents a relatively large basin where crude oil and natural gas is produced and is the environment chosen for the current study. Specifically, idiosyncrasies resultant from emergency asset types (containment boom), service depot (port) and demand node types (offshore rig), and transportation modes (vessel) are prevalent in the current study. The extant literature includes optimization models in the maritime environment but mainly focuses on the response and recovery stages, whereas the current research focuses on the preparation phase. Almost universally, optimization models addressing emergency response networks emphasize the importance of response time minimization. Consequently, the current research also seeks to minimize elapsed travel time from service depots to demand nodes.

Although numerous activities exist to mitigate the coastal and ecological impacts of oil spills in the maritime environment, containment booms effectively aggregate the spilled oil and mitigate dispersion (Grubesic, Wei and Nelson, 2019). Once deployed, container booms are floating barriers that enclose floating oil and eliminate or mitigate the spilled oil from dispersing across an otherwise larger ecological system or reaching vulnerable coastlines. Grubesic et al. (2019) developed and evaluated a model that prioritized protecting shorelines and monetizing the deployment of containment booms. Also, the researchers demonstrated the functionality and efficacy of the model in the context of a tanker spill near Mobile Bay, Alabama, United States. The current research differs in that the multi-objective function assigns the location and assignment of containment systems based on 1,802 potential oil spill sites or offshore rigs. The objective of the model is to minimize the average distance, or response time, of the containment systems and offshore sites. The results are used to evaluate the progressive enhancement, or reduction of the average distance from service depot to demand node, of staging additional assets across the Gulf of Mexico basin’s ports. In summary, this research is novel in the following ways:

- The context of this study is the containment response to an offshore oil spill in the Gulf of Mexico.
- The transportation network evaluated includes onshore service depots (or ports), deployment of containment boom via vessel, and potential demand sites (or offshore rigs)
- The quantity of onshore service depots, or ports, is iteratively increased, allowing stakeholders to measure the progressive reduction in average distance from the ports to the potential spill sites.

LITERATURE REVIEW

Broadly, the extant literature encompasses various perspectives of emergency response facility location problems due to the idiosyncratic nature of societal emergencies and facilities designed to prevent or respond to such emergencies (Liu et al., 2021).For example, studies evaluating or proposing the strategic location of emergency response assets are conducted in wildfires, widespread illness, pandemics, natural disasters, industrial accidents, crime, and others. Liu et al. (2021) published a literature review of related studies and identified that, in addition to emergency location problems directly interacting with transportation networks, most studies are contained in one of four main categories, location-routing models, location models including accessibility, location models including travel time, and location models with mathematical programming accompanied by equilibrium constraints. Overall, the literature review identifies diverse topics of inquiry, a plethora of models employed to solve emergency response location problems and, importantly, the necessary parameters to be considered in defining and solving such problems. Yang et al. (2021) evaluated decision support tools' approaches, challenges, and future research perspectives on oil spill response. Specifically, the evaluation of the literature above related to decision tools for responding to oil spills focuses on five main categories: risk assessment, oil spill detection, oil spill modeling, selection of countermeasures, and optimization of response operation (Yang et al., 2021).The researchers proposed that research be conducted to address the continuation of worldwide oil spills, environmental impacts heightened by climate change, and inherent challenges posed by complex, or NP-hard, problems. The extant literature includes works evaluating emergency responses before, during, and after accidents. Also, a few studies perform analyses related to marine oil spills, which are particularly relevant to the current study.

Within the extant literature covering the optimal location and assignment of emergency assets or facilities, contexts for such studies include urban environments, land-based petrochemical sites, inhabited remote sites, and maritime environments. These studies exhibit similarities due to the inherent need for the efficient deployment of effective emergency assets; however, the studies differ in the challenges posed to deploy emergency assets resulting from the idiosyncrasies their respective environments yield. Wang and Ma (2021) developed and evaluated a dual-objective mixed integer nonlinear programming (MINLP) model in the context of a COVID-19 response in the Beijing-Tianjin-Hebei region. The MINLP minimized rescue time while, simultaneously accounted for the maximization of satisfaction rate of demand fulfillment (H. Wang & Ma, 2021).Men et al. (2020) proposed a multi-objective emergency rescue facilities location (ERFL) model to solve emergency assets logistics problems in the context of catastrophic interlocking chemical accidents (CICAs) at industrial sites, or chemical parks. Notably, the model's results, derived from matrix encoding, accompanied by associated evolutionary operators and coupled with Pareto-based multi-objective evolutionary algorithms, showed the potential for effective location decisions based on decision criteria assigned by stakeholders (Men et al., 2020).Yu and Liu (2020), embedding the max-flow problem of the reachability guarantee into the emergency facility location problem, evaluated the location of emergency assets while accounting for damage tolerances in lieu of link failure. In essence, the model optimized the location of emergency assets assuming some links, as part of the deployment of such assets, would first require restoration (Yu & Liu, 2020).Overall, the bi-objective optimization model assessed combinations of primary depots and secondary depots for demand points, which minimized network costs and enhanced reachability, respectively. Yu (2021) incorporated randomness and uncertainty within two stages of the pre-disaster location and storage model. The model, developed and evaluated in the Sioux Falls transportation network context, was solved via a modified column-and-constraint generation method (Yu, 2021).Combining the randomness of impacted sites and uncertainty of the severity of the damage, the model was hypothesized to yield lower emergency preparedness costs, yield more accurate results over time due to an increase in available historical data and, importantly, yield results more efficiently than other proposed methods. Wang et al. (2018) developed a multi-objective model to minimize the quantity of emergency materials and the transportation cost of transporting those materials in the maritime environment. In essence, the model assigned service depots to demand nodes within the maritime environment, which included nuances not found in other emergency logistics networks and excluded irrelevant parameters common in unrelated networks (W. Wang et al., 2018).The maritime environment is a unique environment warranting specialized emergency response assets and models for the location and assignment of such assets. Specifically, an effective model will reduce the elapsed time from the service depot to the demand site, which will minimize the environmental impacts associated with oil spills (Huang et al., 2020; Sarhadi et al., 2020).The pre-disaster actions taken to mitigate the impact of emergencies is considered the preparation stage of four consecutive stages in emergency network planning, mitigation, preparation, response, and recovery (Yu, 2020).

Huang et al. (2020) developed a particle swarm optimization with particle mutation (MPSO) model to dispatch emergency response assets to spilled and drifting oil. Using hydrological and meteorological phenomena, the research proposed an emergency response plan for dispatching oil spill response assets to sites receiving adrift oil (Huang et al., 2020).MacKenzie et al. (2016) developed a static and a dynamic optimization model to reduce economic impacts during and after a maritime oil spill. Specifically, the models were evaluated in the context of one of the largest oil spills ever, the Gulf of Mexico's Deepwater Horizon oil spill in 2010, and sought to minimize the economic impact to numerous industries (MacKenzie et al., 2016).Notably, MacKenzie et al. (2016) focused on activities during and after the oil spill emergency and can be categorized, as defined by Yu (2020), as the response and recovery stages of an emergency network plan.

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MATERIALS AND METHODS

Optimizing the location and assignment of emergency response oil spill containment systems is achieved via linear programming. Specifically, the problem class is a pure integer quadratic programming problem and iteratively yields a global optimum, a preferable multi-stage programming technique for the current problem (Sutrisno and Tjahjana, 2017).

Demand assignments, *x*, are binary and subject to a series of constraints, further described in this section. The objective function minimizes the total distance, *d*, between all designated service depots, *i*, and demand nodes, *j*, and is represented via the following formula:

Minimize:

$$d = \sum_{i=1}^{n} \sum_{j=1}^{m} d_{ij} x_{ij} \tag{1}$$

Subject to:

To account for all demand nodes, or offshore locations, that may yield an oil spill and require the deployment of containment systems, the following constraint ensures that each demand node, *j*, is assigned a single service depot, *i*:

$$\sum_{i=1}^{n} x_{ij} = 1 \; \forall j \in J \tag{2}$$

Binary constraints are explicitly required for service depot to demand node, *i*,*j* , combinations, and for service depot selections, *y*. In essence, as is further described in the concluding constraint, varying quantities of eligible service depots, *y*, are evaluated. The following constraints ensure fractional assignments of, *x*, and service depots, *y*, are not prevalent:

$$x_{ij} = 0 \; or \; 1 \forall i \in I, \forall j \in J \tag{3}$$

$$y_i = 0 \; or \; 1 \forall i \in I \tag{4}$$

Lastly, to evaluate the progressive improvement resultant from staging containment systems across varying quantities, *k*, of service depots, *y*, the concluding constraint dictates the total quantity of service depots, *y*, that can be utilized in the global optimum:

$$\sum_{i=1}^{n} y_i = k \; \forall i \in I, \; \forall k \in K \tag{5}$$

where:

- *n* = number of locations at which a service depot, or port, may be opened, which will include a response vessel
- *m* = the number of demand points, or potential spill sites, each of which must be assigned a service depot, or port
- d_{ij} = distance between service depot *i* and demand point *j*
- y_i = service depot at location *i*
- *k* = total number of service depots that are to be opened

DATA AND DATA SOURCES

A sample of Gulf of Mexico offshore locations, or demand nodes, was collected from the Bureau of Safety and Environmental Enforcement's (BSEE) data center, which lists 1,802 platform structures. The structures are operated by numerous energy firms and are identified by their respective area and block, which is a 9-square-mile geographic location and identifiable via global positioning system (GPS) coordinates (Bureau of Safety and Environmental Enforcement, 2023). Notably, clusters of offshore facilities, or demand nodes, may exist in the same area and block.

Spatial distances between service depots and demand nodes are utilized to specify the objective function to be minimized. Intuitively, assuming direct paths over water for service vessels to locate spills and deploy containment systems, distance is a function of time and, therefore, a suitable parameter for optimization. Nautical mile distances between service depots and demand nodes are calculated using a method used in spherical trigonometry called great circle distances (Mwemezi and Huang, 2011). The following formulae yield nautical mile distances to form the network's distance matrix.

$$D_{nm}^{s} = \infty r \tag{6}$$

where: $D_{nm}^{s} = \text{Spherical distance in nautical miles between GPS locations}$

$$\alpha = 2\, arcsine\left(\sqrt{sine^2 \frac{\Delta\theta}{2} + cosine\theta_1\, cosine\theta_2\, sine^2 \frac{\Delta\emptyset}{2}}\right) \tag{7}$$

where: α = Central angle measure
Θ_1 = Latitude at GPS location 1
Θ_2 = Latitude at GPS location 2
$\Delta\Theta$ = Difference between latitude at GPS location 1 and GPS location 2
$\Delta ø$ = Difference between longitude at GPS location 1 and GPS location 2
r = Nautical mile radius,or 3440.0487

Service depots, or coastal ports, utilized to deploy containment systems are selected from Kaiser (2015), which lists ports commonly utilized in the Gulf of Mexico's offshore basin. These ports were forecasted to host supply vessel trips supporting offshore activities in the Gulf of Mexico from 2012–2017 (Kaiser, 2015). These ports are still utilized in the Gulf of Mexico's offshore industry. In all, there are 13 eligible service depots, or coastal ports, and are located in Port Isabel, Texas (Port Isabel), Port Aransas, Texas (Port Aransas), Freeport, Texas (Freeport), Galveston, Texas (Galveston), Sabine, Louisiana (Sabine), Cameron, Louisiana (Cameron), Intracoastal City, Louisiana (Intracoastal), New Iberia, Louisiana (New Iberia), Morgan City, Louisiana (Morgan City), Houma, Louisiana (Houma), Port Fourchon, Louisiana (Fourchon), Venice, Louisiana (Venice), and Pascagoula, Mississippi (Pascagoula). The map in Figure 1 shows the locations of service depots (identified by the "ship" icon). The gray dots in the Gulf of Mexico identify the offshore rigs. (Note that some rigs appear to be onshore, but those are in coastal wetlands).

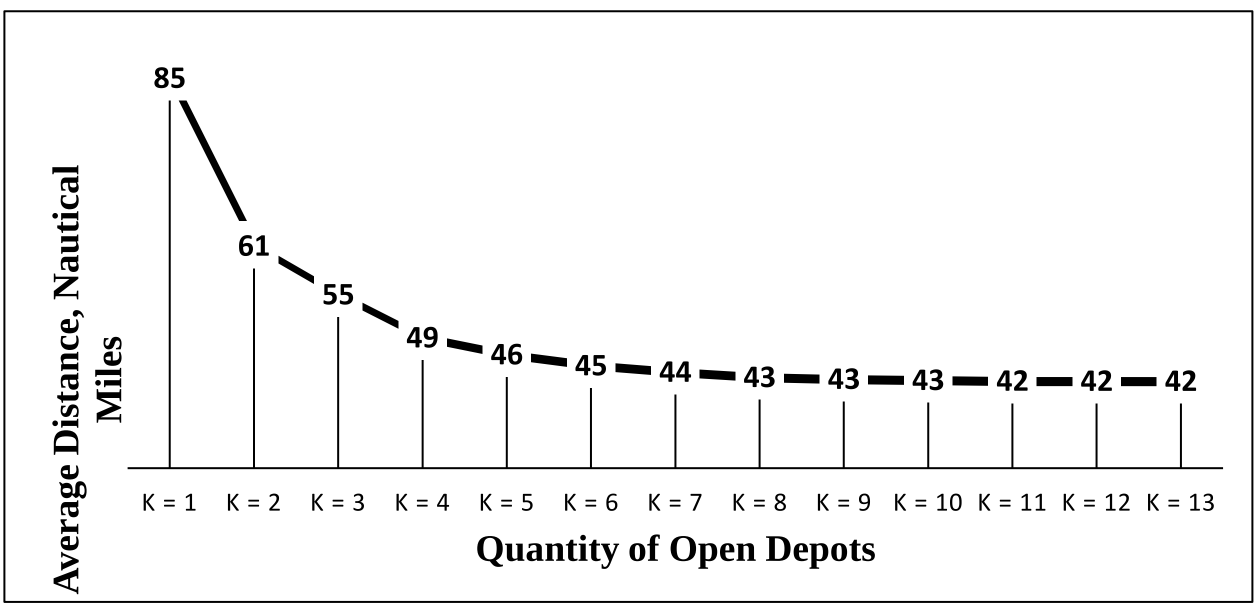
The model's output yields service depot location(s), service depot to demand node assignments, and progressive distance reduction by adding additional service depots. The results are itemized and displayed in the next section.

FIGURE 1
MAP OF POTENTIAL SERVICE DEPOT LOCATIONS ALONG THE GULF OF MEXICO

RESULTS

Results obtained using Lingo version 19.0 show that increasing the number of open depots materially decreases the average distance from depots to offshore nodes. Specifically, the addition of the second, third, and fourth open depot reduces the average distance by 28.2%, 9.84%, and 10.9%, respectively. However, the progressive decrease in the average distance beyond four open depots is less than 5% per additional open depot. Furthermore, the progressive decrease in the average distance beyond eight depots is less than 1%. Figure 2 depicts the progressive reduction in average distance resulting from additional open depots.

FIGURE 2
AVERAGE DISTANCE PER OPEN DEPOT



The optimal location of a single depot, *k*=1, is in Fourchon, which yields an average distance to all offshore nodes of 85 nautical miles. The network of two open depots yields optimal locations in Fourchon and Intracoastal. Fourchon and Intracoastal are optimally assigned 59.4% and 40.6% of offshore nodes, respectively. The addition of Intracoastal reduces the average distance of 24 nautical miles, or approximately 28.2%. An additional increase in the number of depots to *k*=3 yields a reduction in average distance of 6 nautical miles, or 9.8%. The utilized depots are located in Fourchon, Intracoastal, and Venice and are assigned 38.1%, 40.6%, and 21.3% of the potential spill sites, respectively. The last material reduction in average distance from depots to offshore nodes results from an additional depot, *k*=4, located in Sabine. The network consisting of 4 depots yields a reduction of 6 nautical miles, or approximately 10.9%. The 4-depot network assigns 38.1%, 27.1%, 21.3%, and 13.5% of offshore nodes to Fourchon, Intracoastal, Venice, and Sabine, respectively.

Network configurations consisting of additional depots, *k*=5 through *k*=13, do not yield significant reductions in average distance from depots to offshore nodes. Specifically, additional depots, *k*=5 through *k*=13, yield marginal reductions in average distance of 6.1%, 2.1%, 2.2%, 2.3%, 0%, 0%, 2.3%, 0%, and 0%, respectively, and consequently, provide negligible reductions in average distance from service depots to demand nodes.

Results reveal important and unique characteristics in emergency response assets' locations and assignments for a potential oil spill in the Gulf of Mexico. Intuitively, a reduction in the average distance from depots to offshore nodes will be enhanced via additional depots. However, the results indicate that the average distance reduction beyond four depots is negligible. The implications of the results are discussed in the proceeding sections and promote and guide future research and practice.

CONCLUSIONS

The current study utilizes a combinatorial optimization approach to determine the optimal location and assignment of emergency response assets for an oil spill in the Gulf of Mexico, which can be efficiently applied to all offshore basins where oil spills are possible. This model solves the problem while evaluating the progressive reduction in average distance, or response time, from depots to offshore nodes resulting from additional service depots. Results provide invaluable insight to researchers, practitioners, and regulators.

Implications for Future Practice

Stakeholders within the upstream energy industry, including federal and state regulators, integrated energy firms, energy service firms, and emergency response teams, are tasked with preparing for and responding to many accidents and incidents. Containment is critical and time-sensitive in the case of accidental oil spills. Therefore, a data-driven approach to locating and assigning containment systems is relevant and timely. In lieu of arbitrarily locating and allocating containment systems across the Gulf of Mexico's coast, these results guide such decisions subject to operational and monetary constraints. Specifically, additional investment beyond four depots may yield enhanced capabilities if diverted to other phases such as mitigation, response, and recovery. The current model emphasizes the importance of time-sensitive containment systems. However, the model can be modified to solve other problems within the other phases of a comprehensive oil spill emergency plan.

Implications for Future Research

The current study addresses a practical problem within the Gulf of Mexico and similar offshore energy basins while promoting future research endeavors. Past and future research can be combined with the current study's methodology and results to create a holistic representation of and solution to a potential oil spill. For example, relatively less time-sensitive assets like recovery systems may be evaluated for optimal location and assignment. Also, future research may complement the current study by evaluating sites conducting operations that are more prone to oil spills. For example, if future research determines that drilling operations are more prone to accidents relative to production operations, the data set may include probabilistic demand to account for such instances. Lastly, the relationship between increasing drilling complexity and a meaningful attempt to preserve the environment should promote future research to benefit practice, research, and society.

Implications for Society

Society continues to rely on nonrenewable energy derived from crude oil in many facets of life and industry. Although progress has been made to reduce society's reliance on such energy sources, a viable industry remains for extracting crude oil on land and in water. The energy industry, whether voluntarily or involuntarily, contributes to the phases of an oil spill response plan, which entails mitigation, preparation, response, and recovery. To optimize the location and assignment of limited resources within the holistic emergency response plan, data-driven analyses are beneficial and will preserve the industry and environment upon which society relies. Specifically, as society relies on nonrenewable energy and a healthy and sustainable environment, society will benefit from effective and scientific emergency preparation.

Summary

The current study, utilizing combinatorial optimization in the context of the optimal location and assignment of emergency oil spill containment systems, provides a systematic approach to solving a practical problem and evaluating the progressive enhancement of additional depots. The research is unique among the studies evaluating similar networks and yields important implications for future practice, research, and society. Although no limitations exist, diminishing the contribution of the study's methodology and results, some prevalent limitations promote future research endeavors to provide a more holistic approach to a potential oil spill.

REFERENCES

Bureau of Safety and Environmental Enforcement (2023). *Bureau of Safety and Environmental Enforcement*. Retrieved from https://www.bsee.gov/

Grubesic, T., Wei, R., & Nelson, J. (2019). Protecting sensitive coastal areas with exclusion booms during oil spill events. *Environmental Modeling and Assessment*, *24*(5), 479–494. doi:10.1007/s10666-018-9634-2

Hamlet, O.E.D., Irwin, A., & McGregor, M. (2020). Is it all about the mission? Comparing non-technical skills across offshore transport and search and rescue helicopter pilots. *The International Journal of Aerospace Psychology*, *30*(3–4), 215–235. doi: 10.2307/3615019

Huang, X., Ren, Y., Zhang, J., Wang, D., & Liu, J. (2020). Dynamic scheduling optimization of marine oil spill emergency resource. *Journal of Coastal Research*, *107*(sp1), 437. https://doi.org/10.2112/jcr-si107-097.1

Kaiser, M.J. (2015). Offshore service vessel activity forecast and regulatory modeling in the U.S. Gulf of Mexico, 2012-2017. *Marine Policy*, *57*, 132–146. doi: 10.1016/j.marpol.2015.03.022

Kaiser, M.J., & Snyder, B. (2010). An empirical analysis of offshore service vessel utilization in the US Gulf of Mexico. *International Journal of Energy Sector Management*, *4*(2), 152–182. doi:10.1108/17506221011058687

Kilaparthi, J. (2014). Assessment of safety culture in global offshore environments. *Journal of Environmental Protection*, *05*(11), 1003–1021. doi: 10.4236/jep.2014.511101

Liu, Y. *et al.* (2021). Emergency response facility location in transportation networks: A literature review.*Journal of Traffic and Transportation Engineering (English Edition)*, *8*(2), 153–169. doi:10.1016/j.jtte.2021.03.001

MacKenzie, C.A., Baroud, H., & Barker, K. (2016). Static and dynamic resource allocation models for recovery of interdependent systems: application to the Deepwater Horizon oil spill. *Annals of Operations Research*, *236*(1), 103–129. doi: 10.1007/s10479-014-1696-1

Men, J., Jiang, P., Zheng, S., Kong, Y., Zhao, Y., Sheng, G., . . . Zheng, S. (2020). A multi-objective emergency rescue facilities location model for catastrophic interlocking chemical accidents in chemical parks. *IEEE Transactions on Intelligent Transportation Systems*, *21*(11), 4749–4761. https://doi.org/10.1109/tits.2019.2946209

Mwemezi, J.J., & Huang, Y. (2011). Optimal facility location on spherical surfaces: Algorithm and application. *New York Science Journal*, *4*(7).

Navarre, J.T. (2021). Randomized greedy algorithm for helicopter optimization in the energy industry: A practical approach to model development and solution deliverance. *International Journal of Energy Sector Management*. https://doi.org/10.1108/IJESM-12-2020-0022

Sarhadi, H., Naoum-Sawaya, J., & Verma, M. (2020, May). A robust optimization approach to locating and stockpiling marine oil-spill response facilities. *Transportation Research Part E: Logistics and Transportation Review*, *141*, 102005. doi: 10.1016/j.tre.2020.102005

Sutrisno, W., & Tjahjana, R.H. (2017). Dynamic optimization approach for integrated supplier selection and tracking control of single product inventory system with product discount. *IOP Conference Series: Materials Science and Engineering*. doi: 10.1088/1742-6596/755/1/011001

Toregas, C., Swain, R., ReVelle, C., & Bergman, L. (1971). The location of emergency service facilities. *Operations Research*, *19*(6), 1363–1373.

Ventikos, N.P. *et al*. (2004). A high-level synthesis of oil spill response equipment and countermeasures. *Journal of Hazardous Materials*, *107*(1–2), 51–58. doi: 10.1016/j.jhazmat.2003.11.009

Wang, H., & Ma, X. (2021). Research on multiobjective location of urban emergency logistics under major emergencies. *Mathematical Problems in Engineering*. doi: 10.1155/2021/5577797

Wang, W., Huang, L., & Zhang, X. (2018). Optimization of maritime emergency materials allocation based on network reliability. *Journal of Coastal Research*, *83*, 691–696. doi: 10.2112/SI83-115.1

Yang, Z., Chen, Z., Lee, K., Owens, E., Boufadel, M.C., An, C., & Taylor, E. (2021). Decision support tools for oil spill response (OSR-DSTs): Approaches, challenges, and future research perspectives. *Marine Pollution Bulletin*, *167*, 112313. https://doi.org/10.1016/j.marpolbul.2021.112313

Yu, W. (2020). Reachability guarantee based model for pre-positioning of emergency facilities under uncertain disaster damages. *International Journal of Disaster Risk Reduction*, *42*, 101335. doi:10.1016/j.ijdrr.2019.101335

Yu, W. (2021, May). Pre-disaster location and storage model for emergency commodities considering both randomness and uncertainty. *Safety Science*, *141*, 105330. doi: 10.1016/j.ssci.2021.105330

Yu, W., & Liu, J. (2020). Optimization model based on reachability guarantee for emergency facility location and link reinforcement. *Journal of Advanced Transportation*. doi:10.1155/2020/4648908