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## Fuzzy Supply-Chain Bunch Graphs for Cyclone Repair Planning

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### Abstract

Cyclone response must select repairs before road capacity, travel time, and restored demand are known precisely. A fuzzy supply-chain bunch graph is introduced for hub-and-branch relief networks. Each branch is an edge-disjoint path from a central depot, while travel capacity, survival, repair cost, and service value are represented by triangular fuzzy quantities. A branch-prefix dominance theorem proves that repairing a downstream edge without its failed upstream predecessors is never optimal. The repair problem consequently reduces from an arbitrary edge-subset problem to a multiple-choice knapsack over branch prefixes. An exact dynamic program is derived, together with monotonicity of the optimal guaranteed service across the alpha-confidence level and a perturbation bound. A four-branch cyclone example includes medical, food, water, and shelter routes. With an alpha level of 0.6, budget 100, and minimum medical and water access, the optimal plan repairs two medical edges, two water edges, and one shelter edge, producing guaranteed service 122. An unconstrained service-only solution produces 125 but leaves the medical branch inaccessible, demonstrating why equity constraints must be explicit. Budget and alpha profiles reveal repair-plan changes that a single deterministic calculation would conceal.

**Keywords:** Supply-chain resilience, Fuzzy bunch graph, Cyclone logistics, Repair optimization, Dynamic programming, Alpha cut.

## 1 | Introduction

Cyclones disrupt roads, ports, distribution centers, communication, and local demand simultaneously. Supply-chain resilience therefore depends not only on pre-disaster redundancy but also on the order in which failed links are repaired [2, 4, 6]. Repair decisions are made with incomplete information: travel time may be estimated from partial inspection, road capacity changes with water level, and demand grows as field reports arrive.

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Fuzzy optimization represents this imprecision without assuming a precise probability distribution [1, 3, 5]. Recent supply-chain studies combine fuzzy programming with resilience, low-carbon logistics, and multi-criteria evaluation [8, 11, 12]. Many models are general multi-echelon networks and require large mixed-integer programs. Cyclone relief around one functioning depot often has a more specific topology: several outward routes share the depot but then separate into branch corridors.

The attached concept uses supply-chain bunch graphs for cyclone-resilient logistics. We formulate a fuzzy version and exploit its branch structure. On a branch path, repairing a downstream edge gives no service if an upstream failed edge remains closed. Every useful repair set can therefore be replaced by branch prefixes, transforming the problem into a multiple-choice knapsack that can be solved exactly by dynamic programming.

The contributions are:

- (i) a fuzzy bunch-graph model with triangular repair costs and service values;
- (ii) an exact prefix-dominance theorem;
- (iii) an equity-constrained dynamic program;
- (iv) alpha-level and perturbation sensitivity results; and
- (v) a fully calculated four-branch cyclone case with cost, service, budget, and confidence profiles.

## 2 | Fuzzy Supply-Chain Bunch Graph

**Definition 2.1.** A supply-chain bunch graph is

$$\mathcal{B} = (h; P_1, \dots, P_q),$$

where  $h$  is a hub and each

$$P_b = (h = v_{b0}, v_{b1}, \dots, v_{b\ell_b})$$

is a path. Apart from  $h$ , the branch paths are vertex- and edge-disjoint.

The hub may represent a district warehouse or emergency port. Branch vertices represent local depots, health centers, water points, or shelters. Cross-links may be evaluated separately as contingency options; the exact prefix theorem applies to the branch backbone.

Each failed edge  $e$  has:

- a triangular fuzzy repair cost  $\tilde{c}_e = (c_e^L, c_e^M, c_e^U)$ ;
- a triangular fuzzy repair time;
- a fuzzy post-repair capacity; and

- a survival grade  $\rho_e \in [0, 1]$  for the planning horizon.

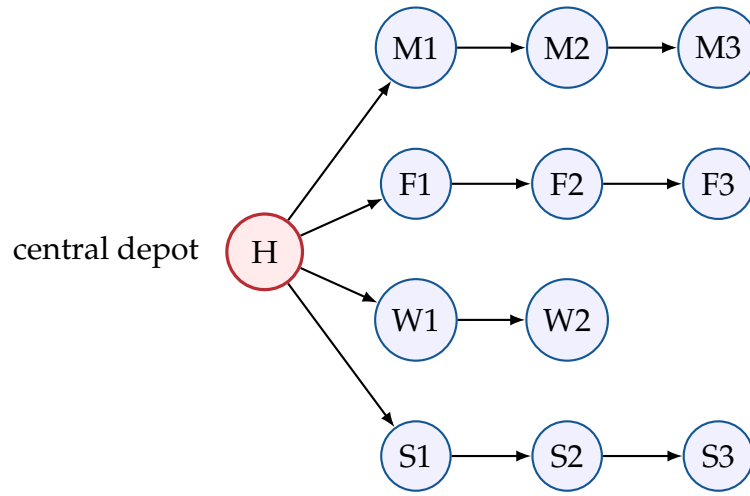
Vertex  $v$  has priority-weighted demand  $d_v \geq 0$  and a fuzzy service value if reached.

For triangular  $\tilde{c} = (c^L, c^M, c^U)$ , the upper endpoint of its alpha cut is

$$c^+(\alpha) = c^U - \alpha(c^U - c^M). \quad (1)$$

Using this value in a budget constraint is conservative at confidence level  $\alpha$ . For triangular service  $\tilde{g} = (g^L, g^M, g^U)$ , guaranteed service is the lower alpha endpoint

$$g^-(\alpha) = g^L + \alpha(g^M - g^L). \quad (2)$$



**Figure 1.** Four-branch relief bunch graph: medical, food, water, and shelter corridors.

The principal symbols are collected in Table 1.

**Table 1.** Symbols used in the bunch-graph repair model.

| Symbol                             | Meaning                                                                                                                  |
|------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| $\mathcal{B}, h$                   | Supply-chain bunch graph and its central hub.                                                                            |
| $q, b, P_b$                        | Number of branches, branch index, and branch path.                                                                       |
| $\ell_b, v_{bk}$                   | Number of edges on branch $b$ and its vertex at position $k$ ; $v_{b0} = h$ .                                            |
| $e_{br}, x_e$                      | Edge at position $r$ on branch $b$ and its binary repair indicator; an already functioning edge is treated as available. |
| $\tilde{c}_e$                      | Triangular fuzzy repair cost $(c_e^L, c_e^M, c_e^U)$ .                                                                   |
| $L, M, U$                          | Lower, modal, and upper parameters of a triangular fuzzy quantity.                                                       |
| $\alpha$                           | Alpha-cut level in $[0, 1]$ ; it specifies a membership cut, not a probability.                                          |
| $c_e^+(\alpha)$                    | Upper alpha-cut endpoint used as conservative edge repair cost.                                                          |
| $\tilde{g}_{bk}, g_{bk}^-(\alpha)$ | Fuzzy service value at $v_{bk}$ and its lower alpha-cut endpoint.                                                        |
| $d_v, d_{bk}$                      | Nonnegative priority-weighted demand at a vertex or branch position.                                                     |
| $\rho_e, \rho_{bk}$                | Edge survival grade and minimum survival grade along the route to $v_{bk}$ .                                             |
| $y_{bk}$                           | Binary indicator that $v_{bk}$ is reachable from the hub.                                                                |

Table 1 (continued)

| Symbol                           | Meaning                                                                                           |
|----------------------------------|---------------------------------------------------------------------------------------------------|
| $X, X'$                          | Repair set and a service-equivalent repair set consisting of branch prefixes.                     |
| $G_b(x; \alpha)$                 | Guaranteed restored service on branch $b$ for repair vector $x$ .                                 |
| $k_b$                            | Chosen repair-prefix option for branch $b$ ; zero means no repair.                                |
| $C_{bk}(\alpha), G_{bk}(\alpha)$ | Conservative cost and guaranteed service of prefix option $k$ on branch $b$ .                     |
| $B, z$                           | Total repair budget and budget state in the dynamic program.                                      |
| $\mathcal{E}, r_b, K_b$          | Essential-branch set, required minimum prefix, and admissible prefix options.                     |
| $F_b(z)$                         | Maximum feasible service from the first $b$ branches with budget at most $z$ .                    |
| $V^*(\alpha)$                    | Optimal guaranteed service at the chosen alpha level, budget, and essential-service requirements. |
| $\varepsilon_b$                  | Bound on the change in service of an option on branch $b$ .                                       |
| slack                            | Budget remaining after the selected prefix repairs.                                               |
| $M, F, W, S$                     | Medical, food, water, and shelter branch labels in the case study.                                |

### 3 | Reachability and Guaranteed Service

Let  $x_e \in \{0, 1\}$  indicate repair. Vertex  $v_{bk}$  is reachable if every failed edge in the prefix from  $h$  to  $v_{bk}$  is repaired. Its indicator is

$$y_{bk} = \prod_{r=1}^k x_{br}. \quad (3)$$

The route survival grade is the bottleneck

$$\rho_{bk} = \min_{1 \leq r \leq k} \rho_{br}.$$

For a chosen alpha level, guaranteed restored service on branch  $b$  is

$$G_b(x; \alpha) = \sum_{k=1}^{\ell_b} d_{bk} \rho_{bk} g_{bk}^-(\alpha) y_{bk}. \quad (4)$$

The min bottleneck can be replaced by a product when independent survival is the intended interpretation; the choice must be stated.

**Theorem 3.1** (Branch-prefix dominance). *For every feasible repair set  $X$ , there is a repair set  $X'$  with no larger cost and the same restored service such that, on every branch, the repaired failed edges form a prefix.*

*Proof.* Suppose  $X$  repairs downstream edge  $e_{bk}$  but leaves an upstream failed edge  $e_{br}$  unrepaired for some  $r < k$ . Then every vertex at or beyond  $k$  remains unreachable by Eq. (3); consequently,  $e_{bk}$  contributes no service. Removing it from  $X$  does not change any  $y_{bj}$  and weakly decreases cost. Repeat until no such edge remains. The remaining repaired edges on each branch form a prefix.  $\square$

The theorem is stronger than a heuristic. It removes all dominated nonprefix decisions before optimization.

## 4 | Prefix-Option Formulation

For branch  $b$ , option  $k \in \{0, \dots, \ell_b\}$  repairs the first  $k$  failed edges. Let

$$C_{bk}(\alpha) = \sum_{r=1}^k c_{br}^+(\alpha), \quad G_{bk}(\alpha) = \sum_{j=1}^k d_{bj} \rho_{bj} g_{bj}^-(\alpha). \quad (5)$$

Choose exactly one option per branch:

$$\max \sum_{b=1}^q G_{b,k_b}(\alpha), \quad (6)$$

$$\begin{aligned} \text{s.t. } & \sum_{b=1}^q C_{b,k_b}(\alpha) \leq B, \\ & k_b \in \{0, \dots, \ell_b\}. \end{aligned} \quad (7)$$

Essential-service constraints are lower bounds

$$k_b \geq r_b \quad (b \in \mathcal{E}), \quad (8)$$

where  $\mathcal{E}$  is the set of critical branches. These constraints prevent a service-maximizing model from abandoning a medically essential corridor.

## 5 | Exact Dynamic Program

Assume integer-scaled costs. Let  $F_b(z)$  be the maximum guaranteed service obtainable from the first  $b$  branches with budget at most  $z$ . Initialize  $F_0(z) = 0$  and use

$$F_b(z) = \max_{\substack{k \in K_b \\ C_{bk} \leq z}} \{F_{b-1}(z - C_{bk}) + G_{bk}\}, \quad (9)$$

where  $K_b = \{r_b, \dots, \ell_b\}$  for essential branches and  $K_b = \{0, \dots, \ell_b\}$  otherwise.

**Theorem 5.1** (Dynamic-programming optimality). *The value  $F_q(B)$  from Eq. (9) is the optimal value of Eqs. (6)–(8).*

*Proof.* By Theorem 3.1, an optimal repair is represented by one prefix option per branch. Condition on the option  $k$  selected for branch  $b$ . The remaining decision is an optimal solution for the first  $b - 1$  branches with residual budget  $z - C_{bk}$ , which has value  $F_{b-1}(z - C_{bk})$  by induction. Maximizing over feasible  $k$  proves the recurrence and optimality.  $\square$

The time complexity is  $O(B \sum_b |K_b|)$  and memory is  $O(B)$  when only two rows are stored. Back-pointers recover the repair plan.

## 6 | Confidence-Level Properties

Increasing  $\alpha$  moves triangular costs toward their modal values and guaranteed services toward their modal values. Hence costs in Eq. (1) weakly decrease and services in Eq. (2) weakly increase.

**Theorem 6.1** (Alpha-level monotonicity). *Let  $V^*(\alpha)$  be the optimal guaranteed service for fixed budget and essential-branch constraints. If costs use upper alpha endpoints and service uses lower alpha endpoints, then  $V^*(\alpha)$  is nondecreasing in  $\alpha$ .*

*Proof.* For  $\alpha_2 > \alpha_1$ , every option feasible at  $\alpha_1$  remains feasible at  $\alpha_2$  because its conservative cost does not increase. Its guaranteed service does not decrease. Therefore, the optimum over the enlarged feasible set at  $\alpha_2$  is at least the optimum at  $\alpha_1$ .  $\square$

**Proposition 6.2** (Service perturbation). *If every selected option service changes by at most  $\varepsilon_b$ , then the value of any fixed plan changes by at most  $\sum_b \varepsilon_b$ . If the same bound applies to all options, the two optimal values differ by at most  $\sum_b \varepsilon_b$  provided feasibility is unchanged.*

Cost perturbations can change feasibility discontinuously near the budget boundary. Therefore, the budget slack

$$\text{slack} = B - \sum_b C_{b,k_b}$$

must be reported with the selected plan.

## 7 | Cyclone Repair Case Study

Figure 1 contains four branches: Medical (M), Food (F), Water (W), and Shelter (S). Table 2 gives triangular aggregate prefix costs and services. These values already include route bottleneck survival and priority weights. Option zero is (0,0,0) for both cost and service.

**Table 2.** Triangular prefix options  $(C^L, C^M, C^U)$  and  $(G^L, G^M, G^U)$ .

| Branch | Prefix | Fuzzy cost   | Fuzzy service | Operational interpretation |
|--------|--------|--------------|---------------|----------------------------|
| M      | 1      | (17, 20, 25) | (15, 20, 24)  | Clinic access              |
| M      | 2      | (31, 36, 41) | (34, 44, 50)  | Clinic and medicine point  |
| M      | 3      | (52, 59, 64) | (62, 72, 79)  | Full medical corridor      |
| F      | 1      | (13, 16, 21) | (13, 18, 23)  | Local food depot           |
| F      | 2      | (27, 32, 37) | (31, 41, 48)  | Two food depots            |
| F      | 3      | (47, 54, 59) | (57, 67, 76)  | Full food corridor         |
| W      | 1      | (19, 23, 28) | (26, 36, 42)  | Primary water point        |
| W      | 2      | (39, 45, 50) | (64, 74, 82)  | Both water points          |
| S      | 1      | (10, 13, 18) | (9, 14, 19)   | First shelter              |
| S      | 2      | (23, 27, 32) | (24, 34, 41)  | Two shelters               |
| S      | 3      | (41, 46, 51) | (49, 59, 68)  | Full shelter corridor      |

Use  $\alpha = .6$  and  $B = 100$ . Equations (1)–(2) produce Table 3.

**Table 3.** Conservative option values at  $\alpha = .6$ .

| Prefix         | Medical | Food  | Water | Shelter |
|----------------|---------|-------|-------|---------|
| 1 cost/service | 22/18   | 18/16 | 25/32 | 15/12   |
| 2 cost/service | 38/40   | 34/37 | 47/70 | 29/30   |
| 3 cost/service | 61/68   | 56/63 | –     | 48/55   |

Require at least one medical and one water prefix edge. The dynamic program selects

$$(k_M, k_F, k_W, k_S) = (2, 0, 2, 1).$$

Its cost is

$$38 + 0 + 47 + 15 = 100,$$

and guaranteed service is

$$40 + 0 + 70 + 12 = 122.$$

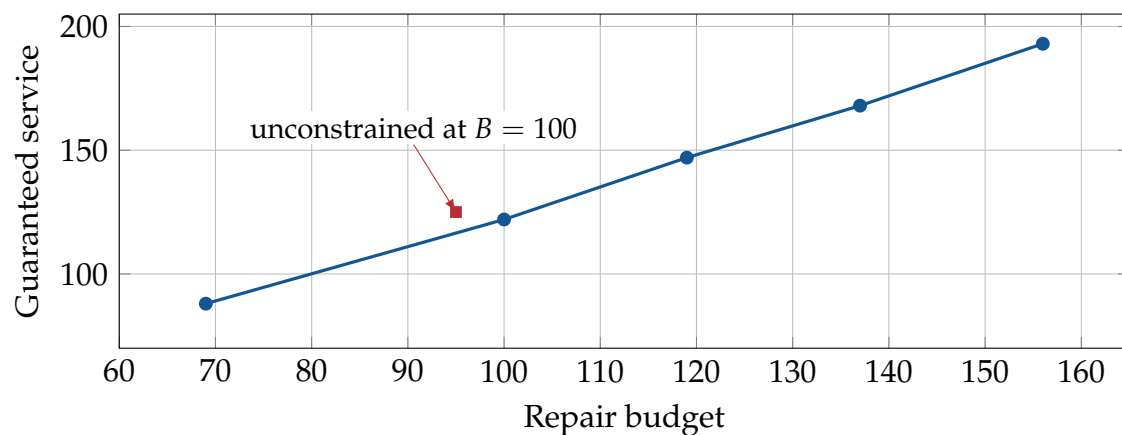
The budget slack is zero.

Without essential-service constraints, the highest service at the same confidence and budget is obtained by  $(0, 0, 2, 3)$ , with cost  $47 + 48 = 95$  and service  $70 + 55 = 125$ . The three-unit gain abandons the medical branch. The comparison demonstrates that equity cannot be expected to emerge automatically from a total-service objective.

**Table 4.** Optimal equity-constrained plan as budget grows at  $\alpha = .6$ .

| Budget | Guaranteed service | Cost | Prefix plan $(M, F, W, S)$ |
|--------|--------------------|------|----------------------------|
| 80     | 88                 | 69   | (1,0,2,0)                  |
| 100    | 122                | 100  | (2,0,2,1)                  |
| 120    | 147                | 119  | (2,2,2,0)                  |
| 140    | 168                | 137  | (3,0,2,2)                  |
| 160    | 193                | 156  | (3,0,2,3)                  |

The plan need not be nested in budget: at 120 the optimizer drops Shelter 1 and opens Food 2 because the combination yields more total guaranteed service. Operationally required continuity can be added as a multi-period constraint when budgets arrive sequentially.



**Figure 2.** Budget-service profile. Coordinates use the actual cost of each optimal plan.

### Effect of the alpha level.

At fixed budget 100 and the same essential-service constraints, exact optimization gives: The jumps at .6 and .8 are plan changes, not arithmetic discontinuities in a fixed option. This distinction is important for managerial interpretation.

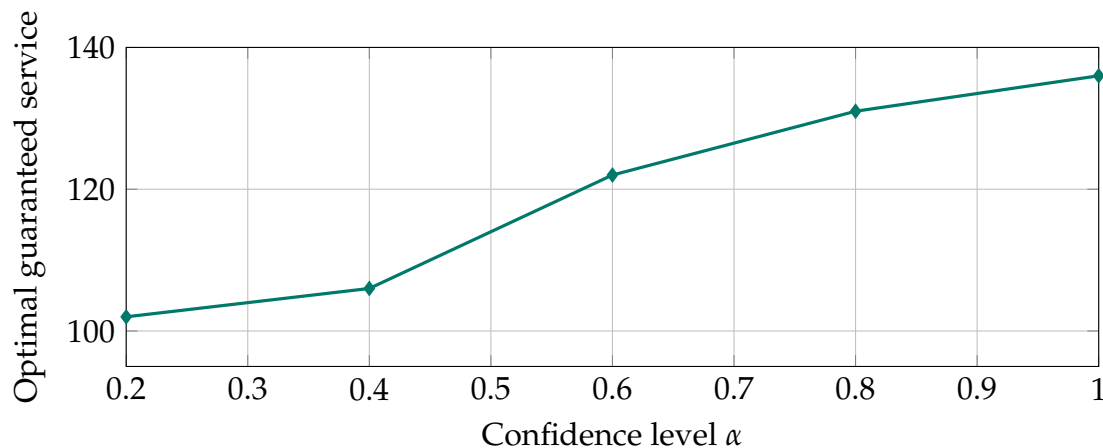
## 8 | Discussion and Conclusion

Several extensions preserve the main structure:

- multi-period repair with crew continuity and travel time;

**Table 5.** Confidence-level sensitivity at budget 100.

| $\alpha$ | Guaranteed service | Cost | Plan ( $M, F, W, S$ ) |
|----------|--------------------|------|-----------------------|
| .2       | 102                | 89   | (2,0,2,0)             |
| .4       | 106                | 87   | (2,0,2,0)             |
| .6       | 122                | 100  | (2,0,2,1)             |
| .8       | 131                | 100  | (2,1,2,0)             |
| 1.0      | 136                | 97   | (2,1,2,0)             |

**Figure 3.** Confidence-level profile. Higher  $\alpha$  narrows fuzzy quantities toward their modal values, expanding feasibility and guaranteed service.

- stochastic cyclone scenarios outside the fuzzy within-scenario quantities;
- cross-links modeled as optional branch-switch projects;
- carbon or fuel budgets in addition to repair cost;
- minimum service by population group; and
- rolling re-optimization as inspection information narrows the fuzzy numbers.

The model is a planning aid, not an emergency command rule. Medical urgency, road safety, legal access restrictions, and real-time field instructions override numerical priority. Fuzzy values should be elicited from engineers and logistics officers and revised as evidence arrives.

A fuzzy bunch-graph model has been developed for cyclone-resilient supply-chain repair. The branch-prefix theorem eliminates dominated downstream repairs and converts the decision into an exact multiple-choice dynamic program. Triangular costs and services give alpha-level service bounds. In the four-branch example, the equity-constrained plan at  $\alpha = .6$  and budget 100 restores service 122 through Medical 2, Water 2, and Shelter 1. The service-only plan reaches 125 but leaves medical access closed, showing why essential-service constraints must be written explicitly. Budget and confidence profiles reveal the points at which the optimal repair plan changes and therefore provide more information than one deterministic solution.

## Author Contributions

All authors contributed equally.

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## Data Availability

All fuzzy option data and optimization results used in the cyclone illustration are printed in the article.

## Competing Interests

The authors declare no competing interests.

## Generative-AI Assistance

Generative AI assisted with language, LaTeX preparation and technical representation of the paper.

## References

- [1] Zimmermann, H. J. (1978). Fuzzy programming and linear programming with several objective functions. *Fuzzy sets and systems*, 1(1), 45-55. [https://doi.org/10.1016/0165-0114\(78\)90031-3](https://doi.org/10.1016/0165-0114(78)90031-3)
- [2] Sheffi, Y. (2005). *The resilient enterprise*. MIT Press. <https://mitpress.mit.edu/9780262250627/the-resilient-enterprise/>
- [3] Peidro, D., Mula, J., Poler, R., & Verdegay, J. L. (2009). Fuzzy optimization for supply chain planning under supply, demand and process uncertainties. *Fuzzy sets and systems*, 160(18), 2640-2657. <https://doi.org/10.1016/j.fss.2009.02.021>
- [4] Snyder, L. V., Atan, Z., Peng, P., Rong, Y., Schmitt, A. J., & Sinsoysal, B. (2016). OR/MS models for supply chain disruptions: A review. *Iie transactions*, 48(2), 89-109. <https://doi.org/10.1080/0740817X.2015.1067735>
- [5] Ghahremani-Nahr, J., Kian, R., & Sabet, E. (2019). A robust fuzzy mathematical programming model for the closed-loop supply chain network design and a whale optimization solution algorithm. *Expert systems with applications*, 116, 454-471. <https://doi.org/10.1016/j.eswa.2018.09.027>
- [6] Ivanov, D. (2020). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation research part E: Logistics and transportation review*, 136, 101922. <https://doi.org/10.1016/j.tre.2020.101922>
- [7] Rajesh, R. (2019). A fuzzy approach to analyzing the level of resilience in manufacturing supply chains. *Sustainable production and consumption*, 18, 224-236. <https://doi.org/10.1016/j.spc.2019.02.005>

- [8] Kungwalsong, K., Mendoza, A., Kamath, V., Pazhani, S., & Marmolejo-Saucedo, J. A. (2022). An application of interactive fuzzy optimization model for redesigning supply chain for resilience. *Annals of operations research*, 315(2), 1803-1839. <https://doi.org/10.1007/s10479-022-04542-5>
- [9] Nikian, A., Khademi Zare, H., Lotfi, M. M., & Fallah Nezhad, M. S. (2023). Re-design of a sustainable and resilient closed-loop supply chain network under uncertainty and disruption caused by sanctions and COVID-19. *Operations management research*, 16(2), 1019-1042. <https://doi.org/10.1007/s12063-022-00330-3>
- [10] Kiani Mavi, R., Kiani Mavi, N., Hosseini Shekarabi, S. A., Pepper's, M., & Arisian, S. (2023). Supply chain resilience: A common weights efficiency analysis with non-discretionary and non-controllable inputs. *Global journal of flexible systems management*, 24(1), 77-99. <https://doi.org/10.1007/s40171-024-00380-5>
- [11] Shi, Y., Li, B., Dulebenets, M. A., & Lau, Y. Y. (2025). A fuzzy robust optimization model for dual objective forward and reverse logistics networks considering carbon emissions. *PloS one*, 20(3), e0316197. <https://doi.org/10.1371/journal.pone.0316197>
- [12] Samhour, M., Abualeenein, M., & Al-Atrash, F. (2025). Enhancing supply chain resilience through a Fuzzy AHP and TOPSIS to mitigate transportation disruption. *Sustainability*, 17(16), 1-31. <https://doi.org/10.3390/su17167375>
- [13] Shekarabi, S. A. H., Mavi, R. K., Mavi, N. K., Macau, F. R., & Arisian, S. S. (2025). A novel robust optimization approach for supply chain resilience: The role of flexibility and collaboration. *International journal of production economics*, 287, 109686. <https://doi.org/10.1016/j.ijpe.2025.109686>
- [14] Verma, P., Kumar, V., Verma, P., Lai, K. K., & Kaur, P. (2025). Leveraging innovative logistics for strengthening supply chain resilience in the face of disruptions. *Asian journal of interdisciplinary research*, 8(2), 35-55. <https://doi.org/10.54392/ajir2523>