Uncovering the Spatial Trilemma of Cost, Equity, and Resilience in Community Worker Allocation

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Abstract

In aging megacities, mobile community care workers represent a critical and reconfigurable elderly-care resource, whose spatial deployment and dispatch involve trade-offs among operational cost, service equity, and system resilience. We investigate this spatial trilemma through Tri-CORE, an integrated dispatch framework that quantitatively characterizes the trade-offs among the three objectives. Using survey data from 220 subdistricts in Shanghai, we compare three single-objective dispatch strategies with Tri-CORE under a 5 km intra-district constraint. Experimental evaluations reveal that optimizing a single objective leads to substantial degradation in other dimensions, exposing the inherent cost–equity–resilience trade-offs. Tri-CORE identifies a balanced operating point within this trilemma, improving equity by 21.4% and resilience by 16.9% while maintaining competitive dispatch cost. Furthermore, analysis across 98 weight configurations shows how different policy priorities reshape spatial results, demonstrating Tri-CORE's adaptability.

CCS Concepts

• **Information systems** → **Geographic information systems**.

Keywords

Spatial Resource Allocation, Spatial Equity, Urban Resilience, Trade-off Dispatch, Elderly Care Networks

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1 Introduction

The 2024 United Nations World Population Prospects estimate that people aged 65 or older will account for more than 16% of the global population by 2050 [12]. Population aging increases both demand for community-based elderly care and the spatial complexity of service provision. In dense cities, demand for care and service capacity are unevenly distributed across neighborhoods. Therefore, Mobile community workers become an important and reconfigurable resource. Unlike fixed facilities, they can be reassigned as local demand changes.

However, resource mobility does not eliminate the allocation challenge. There is an inherent conflict among cost, equity, and resilience in resource dispatch, where optimizing one objective can compromise the others. Prior research has largely studied these objectives independently. Classical transportation and spatial optimization primarily focus on cost-efficient resource allocation [4, 11]. Fairness-aware allocation extends efficiency-oriented approaches by incorporating equity considerations into task assignment and resource matching [8, 13, 15]. Resilience-oriented models further address service continuity under disruptions through backup coverage, facility deployment, and uncertainty-aware optimization [1, 5, 6]. However, the joint evaluation and optimization of cost, equity, and resilience for mobile workforce reallocation remain underexplored. This gap motivates our main research question: **Can we develop a quantifiable dispatch framework to uncover the trade-offs among cost, equity, and resilience, and reveal how different policy priorities reshape system performance and spatial outcomes?**

We address this question by proposing Tri-CORE, an interpretable and configurable framework that integrates the three competing objectives into a unified dispatch model. We compare Tri-CORE with three corresponding single-objective strategies, i.e., Pure Cost, Pure Equity, and Pure Resilience, using a unified setting based on Shanghai data covering 220 subdistricts, 48,500 community workers, and 84,301 older residents. The results reveal the limitations of single-objective optimization and characterize the dispatch trilemma. Pure Equity achieves the best equity performance but requires 23,089 km of dispatch and worsens the backup deficit for resilience by 19.6%. Pure Cost and Pure Resilience show relatively low dispatch distance and improved resilience, but lead to the largest equity deterioration, worsening the Theil index by 97.7% and 57.6%, respectively.

Rather than eliminating this trilemma, Tri-CORE provides an explicit way to represent different policy priorities through adjustable weight configurations. Under a representative balanced configuration, Tri-CORE improves equity by reducing the Theil index by 21.4% and the weighted Gini coefficient by 12.2%, while reducing the backup deficit by 16.9% and maintaining a dispatch distance comparable to the cost-oriented strategy. The analysis of 98 weight configurations further shows how different priorities reshape the cost-equity-resilience landscape, highlighting Tri-CORE's flexibility for scenario-based decision-making.

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2 Methodology

2.1 Problem Formulation

In this study, we use Shanghai as a case study, where the urban area is partitioned into administrative subdistricts serving as the basic spatial units for worker allocation. Each subdistrict represents a local community service region with its own supply of community workers and demand from older residents. For each subdistrict i, let W_i and E_i denote the numbers of community workers and older residents, respectively, and let $r_i = W_i/E_i$ represent the local worker-to-elder ratio. The citywide average ratio is defined as $\bar{r} = \sum_i W_i / \sum_i E_i$, which serves as the reference level for identifying spatial imbalance. Subdistricts with $r_i > \bar{r}$ are classified as supply-surplus regions S, whereas those with $r_i < \bar{r}$ are classified as demand-deficit regions D.

We formulate community worker reallocation as a spatially constrained bipartite network flow problem [11]. The goal is to determine an optimal dispatch vector $\mathbf{x} = x_{ij}$ under spatial and resource constraints, where x_{ij} represents the number of workers dispatched from surplus subdistrict $i \in S$ to deficit subdistrict $j \in D$.

2.2 Dispatch Methods

We compare three single-objective baselines with Tri-CORE, which jointly considers cost, equity, and resilience.

1) Pure Cost follows the classical transportation formulation [4] and minimizes the generalized dispatch cost

$$\min C(\mathbf{x}) = \sum_{(i,j)\in\mathcal{E}} c_{ij} x_{ij},$$

where c_{ij} is the composite unit dispatch cost from i to j, defined as:

$$c_{ij} = d_{ij}^{1.5} + \lambda(L_j - L_i).$$

Here, d_{ij} is the centroid distance between subdistricts i and j. The fixed exponent 1.5 imposes a superlinear penalty on longer dispatches, and the spatial-awareness term ($\lambda = 5.0$) favors movements toward relatively underserved areas. L_i represents the local supply level, computed as the distance-weighted average of W/E ratios within an 8 km radius [2].

2) Pure Equity minimizes inequality in the post-dispatch W/E distribution using the decomposed Theil index [10]:

$$\min T(\mathbf{x}) = w_{\text{within}} T_{\text{within}}(\mathbf{x}) + w_{\text{between}} T_{\text{between}}(\mathbf{x}).$$

The two terms measure inequality within and between administrative districts, respectively, allowing the objective to emphasize different spatial scales.

3) Pure Resilience. Following the backup-coverage concept in facility location [5], Pure Resilience seeks to preserve sufficient neighboring surplus to support a subdistrict when its local workforce becomes unavailable. We define the available backup capacity for subdistrict j and subsequently minimize the region's population-weighted shortfall as the resilience objective:

$$\text{backup}_j(\mathbf{x}) = \sum_{k\in N_j(5\text{km})} \text{softplus}\big(W_k - \bar{r}E_k\big),$$

$$\min R(\mathbf{x}) = \frac{1}{E_{\text{total}}} \sum_{j=1}^{n} E_j \cdot \text{softplus}\big(\bar{r}E_j - \text{backup}_j(\mathbf{x})\big),$$

where $E_{\text{total}} = \sum_j E_j$ and softplus$(\cdot)$ provides a smooth approximation to the positive-part function. A smaller $R(\mathbf{x})$ therefore indicates stronger neighborhood backup capacity.

4) Tri-CORE integrates the above three objectives through a normalized weighted formulation:

$$\min Z(\mathbf{x}) = \alpha \frac{C(\mathbf{x})}{C_{\text{ref}}} + \beta \frac{T(\mathbf{x})}{T_{\text{init}}} + \gamma \frac{R(\mathbf{x})}{R_{\text{init}}},$$

where C_{ref} is the dispatch cost reference, assuming 30% of workers are dispatched at the maximum distance, and T_{init} and R_{init} are the pre-dispatch equity and resilience baselines. Normalization places the three objectives on comparable scales, while (α, β, γ) explicitly represent different policy priorities.

3 Experiments and Results

3.1 Experimental Setup

Data. The case study uses 767 community-level survey records collected in Shanghai in 2025, covering 220 subdistricts across all 16 districts. The records contain 48,500 community workers and 84,301 older residents in aggregate. The resulting citywide worker-to-elder ratio is $\bar{r} = 0.575$.

Implementation. Pure Cost is solved as an integer linear program using PuLP with COIN-OR CBC under supply constraints, while Pure Equity, Pure Resilience, and Tri-CORE are optimized using L-BFGS-B. Continuous solutions are post-processed into integer-feasible allocations.

All experiments use the *Intra-5km* setting, restricting dispatch within the same district and a 5 km centroid radius. This constraint reflects territorial management and practical travel ranges for routine community care services.

Parameters. The initial Theil index decomposition indicates that within-district inequality dominates overall disparity (90.52%), motivating $w_{\text{within}} : w_{\text{between}} = 4 : 1$ for Pure Equity. We set $\alpha : \beta : \gamma = 1 : 4 : 4$ for Tri-CORE as the primary configuration, with full parameter sensitivity analyzed in Section 3.2.2.

Evaluation Metrics. We evaluate each dispatch strategy using four categories of metrics:

- Equity: Theil index and population-weighted Gini (WGini) coefficient measure spatial inequality in worker allocation. Lower values indicate more equitable distributions.
- Resilience: The backup deficit R measures the shortage of neighboring surplus workers available for emergency support. Lower values indicate stronger resilience.
- Dispatch Cost: Total dispatch distance measures aggregate worker travel. Lower values indicate lower operational cost.
- Cost-Efficiency: To evaluate practical economic viability, we introduce two cost-efficiency indicators: Theil Eff. and Resilience Eff., each measuring the corresponding performance improvements per 10,000 kilometers of dispatch distance. Higher values indicate higher operational efficiency.

3.2 Quantitative Results

3.2.1 Single-Objective Polarization vs. Multi-Objective Balance. Table 1 demonstrates the limitations of single-objective optimization and characterizes the cost-equity-resilience trilemma. Pure Equity achieves the best equity performance, reducing the Theil and WGini

Table 1: Performance of each dispatch strategy. Parentheses are improvements from the initial allocation. Underlines mark the best single-objective performance for each metric. Tri-CORE is in Bold.

Method	Equity ↓		Resilience ↓	Cost ↓	Efficiency ↑	
	Theil (Δ%)	WGini (Δ%)	R (Δ%)	Distance (km)	Theil Eff.	Resil. Eff.
Initial State	0.1184 (—)	0.2719 (—)	118.04 (—)	0	—	—
Pure Cost	0.2341 (−97.7)	0.3133 (−15.2)	108.16 (+8.4)	9,826	−0.1177	10.05
Pure Equity	0.0685 (+42.1)	0.2034 (+25.2)	141.16 (−19.6)	23,089	0.0216	−10.01
Pure Resilience	0.1866 (−57.6)	0.3172 (−16.7)	68.65 (+41.9)	7,335	−0.0930	67.33
Tri-CORE	**0.0931** (+21.4)	**0.2387** (+12.2)	**98.06** (+16.9)	**9,854**	**0.0257**	**20.28**

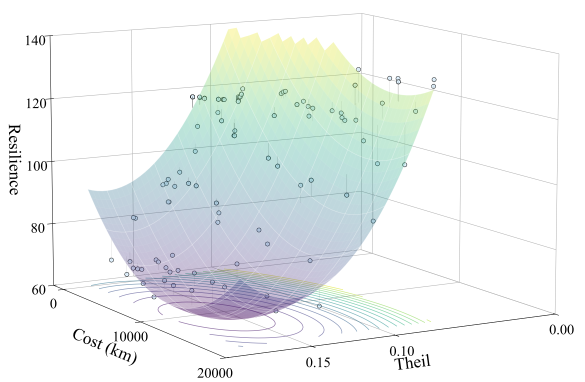

Figure 1: Quadratic fitted surface mapping cost and equity to resilience across weight configurations.

measures by 42.1% and 25.2%, respectively, but requires 23,089 km of dispatch and worsens the backup deficit by 19.6%. In contrast, Pure Cost and Pure Resilience maintain relatively low dispatch distances and improve resilience, but at the expense of equity. Specifically, Pure Cost increases the Theil index by 97.7%, while Pure Resilience, despite achieving the largest resilience improvement (41.9%) and shortest dispatch distance (7,335 km), increases the Theil index by 57.6%. These results show that optimizing a single objective inevitably degrades other dimensions.

In contrast, Tri-CORE achieves a more balanced solution across all three objectives. It improves equity by reducing the Theil index by 21.4% and the WGini coefficient by 12.2%, while reducing the backup deficit by 16.9%. Meanwhile, its dispatch distance remains comparable to Pure Cost (9,854 km vs. 9,826 km), indicating that these improvements are achieved without substantial additional travel. The efficiency metrics further confirm this balance: unlike Pure Equity and Pure Resilience, which improve one dimension at the expense of another, Tri-CORE achieves positive gains in both equity and resilience per unit travel. These results indicate that Tri-CORE does not eliminate the underlying trilemma, but provides an effective compromise between competing objectives without introducing the severe side effects observed in single-objective strategies.

3.2.2 Parameters Sensitivity Discussion and Representative Configurations. Based on this comprehensive experiment, Fig. 1 illustrates a

Table 2: Performance under representative weight configurations for Intra 5km.

α	β	γ	Theil	Cost (km)	Resilience	Theil Eff.	Resil. Eff.
5	2	2	0.1137	647	115.76	0.073	35.25
1	1	1	0.1058	2,729	107.23	0.046	39.61
1	4	4	0.0931	9,854	98.06	0.0257	20.28
1	10	5	0.0760	13,820	105.30	0.031	9.22

quadratic fitted surface with a strong goodness of fit ($R^2 = 0.9664$):

$$\hat{Z} = 89.38 - 25.92\hat{X} - 17.22\hat{Y} + 7.75\hat{X}^2 + 6.00\hat{Y}^2 + 2.62\hat{X}\hat{Y},$$

where $\hat{X}$, $\hat{Y}$ and $\hat{Z}$ denote the standardized Theil, cost and resilience, respectively. This surface exhibits a distinct concave bowl shape, geometrically confirming the impossibility trilemma among multiple objectives. The linear coefficients of the surface equation indicate that the trade-off between equity and resilience forms the primary competition. The degradation of the Theil index damages resilience performance far more than the cost factor.

Table 2 further presents four representative parameter configurations that correspond to real-world dispatch. When cost dominates (e.g., $\alpha : \beta : \gamma = 5 : 2 : 2$), the commuting distance is minimized and Tri-CORE essentially transfers to the Pure Cost strategy. Conversely, assigning an extreme weight to equity (e.g., $\alpha : \beta : \gamma = 1 : 10 : 5$) turns Tri-CORE into Pure Equity. The $\alpha : \beta : \gamma = 1 : 4 : 4$ configuration achieves the optimal balance of conversion efficiency, providing a baseline reference for municipal decisions that consider both efficiency and feasibility.

3.3 Dispatch Flow Visualization

To further examine the spatial characteristics of different allocation strategies, Fig. 2 visualizes the top 25 dispatch flows under the Intra-5km setting. Each arrow represents a worker transfer between subdistricts within the same district, where arrow width indicates dispatch volume and bubbles represent the initial worker-to-elder ratio W/E.

The visualization reveals distinct redistribution patterns among different strategies. Pure Cost tends to generate localized flows with relatively short distances and smaller transfer volumes, reflecting its preference for reducing generalized dispatch costs. Pure Equity produces broader and denser redistribution patterns, transferring more workers across subdistricts to reduce spatial disparities. However, such aggressive equalization requires substantially larger movement and may weaken local backup capacity. Pure Resilience exhibits a different pattern by directing resources toward locations

(a) Pure Cost (b) Pure Equity (c) Pure Resilience (d) Tri-CORE

Figure 2: Top 25 dispatch flows under the Intra-5km setting. Arrow width indicates dispatch volume, and bubbles represent initial W/E ratios.

with stronger neighborhood support potential, resulting in concentrated flows around strategic areas rather than directly minimizing inequality.

Compared with these single-objective strategies, the multi-objective Tri-CORE achieves a more balanced spatial redistribution pattern. Its dispatch flows are neither as localized as Pure Cost nor as extensive as Pure Equity, while avoiding excessive concentration observed in resilience-oriented allocation. This visualization further supports the quantitative results, showing that Tri-CORE provides a practical compromise among cost efficiency, spatial equity, and neighborhood resilience under constrained worker mobility.

4 Related Work

Existing research has extensively investigated cost, spatial equity, and resilience considerations in allocating resources in urban services. Cost-oriented resource allocation has evolved from classical transportation models [4] to spatial allocation and facility location frameworks with geographic constraints [3, 11]. Recent studies further integrate learning-based approaches, such as reinforcement learning, into spatial optimization to improve adaptive decision-making under dynamic environments [9, 14]. Fairness-aware allocation extends traditional efficiency-oriented optimization by incorporating fairness considerations into task assignment and resource matching [16]. Existing studies have explored fairness constraints in spatial allocation and crowdsourcing markets, achieving trade-offs among efficiency, fairness, and incentive compatibility [7, 13, 15]. Resilience-oriented allocation focuses on maintaining service continuity through backup coverage and redundancy planning under disruptions [1, 5]. Recent studies have developed multi-objective and robust optimization models to jointly consider facility deployment, backup capacity, and uncertainty-aware decisions [1, 6].

5 Conclusion

This paper investigates community-worker reallocation as a spatial trilemma among cost, equity, and backup resilience using Shanghai as an empirical case. The results demonstrate that single-objective strategies lead to polarized outcomes, while Tri-CORE provides an interpretable framework for exploring trade-offs among competing priorities. By incorporating adjustable policy preferences, the proposed framework helps reveal how different objectives reshape spatial allocation outcomes and supports informed multi-objective decision-making. Future research will extend this framework by incorporating dynamic demand variations, heterogeneous workers, and cross-city validation.

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