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Repositioning in Bike Sharing Systems with Broken Bikes Considering On-site Repairs

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1. Background & Motivation

The Problem: Bike Sharing Systems (BSS) face two critical challenges:

- **Demand-Supply Imbalance:** Stations become empty or full, causing user dissatisfaction
- **Broken Bikes:** Barcelona: 12% severe + 55% light damage; NYC: 2% need daily repairs

Research Gap: No existing study jointly optimizes:

1. Vehicle-based repositioning (usable & broken bikes)
2. **Labor-based on-site repairs**


On-site repairs


Off-site repairs

2. Contributions

1. **Novel Problem:** First study to integrate on-site repairs with vehicle-based repositioning operations
2. **MILP Model:** Time-indexed formulation minimizing user dissatisfaction + CO_2 emissions
3. **HGSDAC-SBC:** Hybrid Genetic Search algorithm with Station Budget Constraint for large-scale instances
4. **Managerial Insights:** Cost-effectiveness analysis framework for repairer deployment decisions

3. Problem Illustration

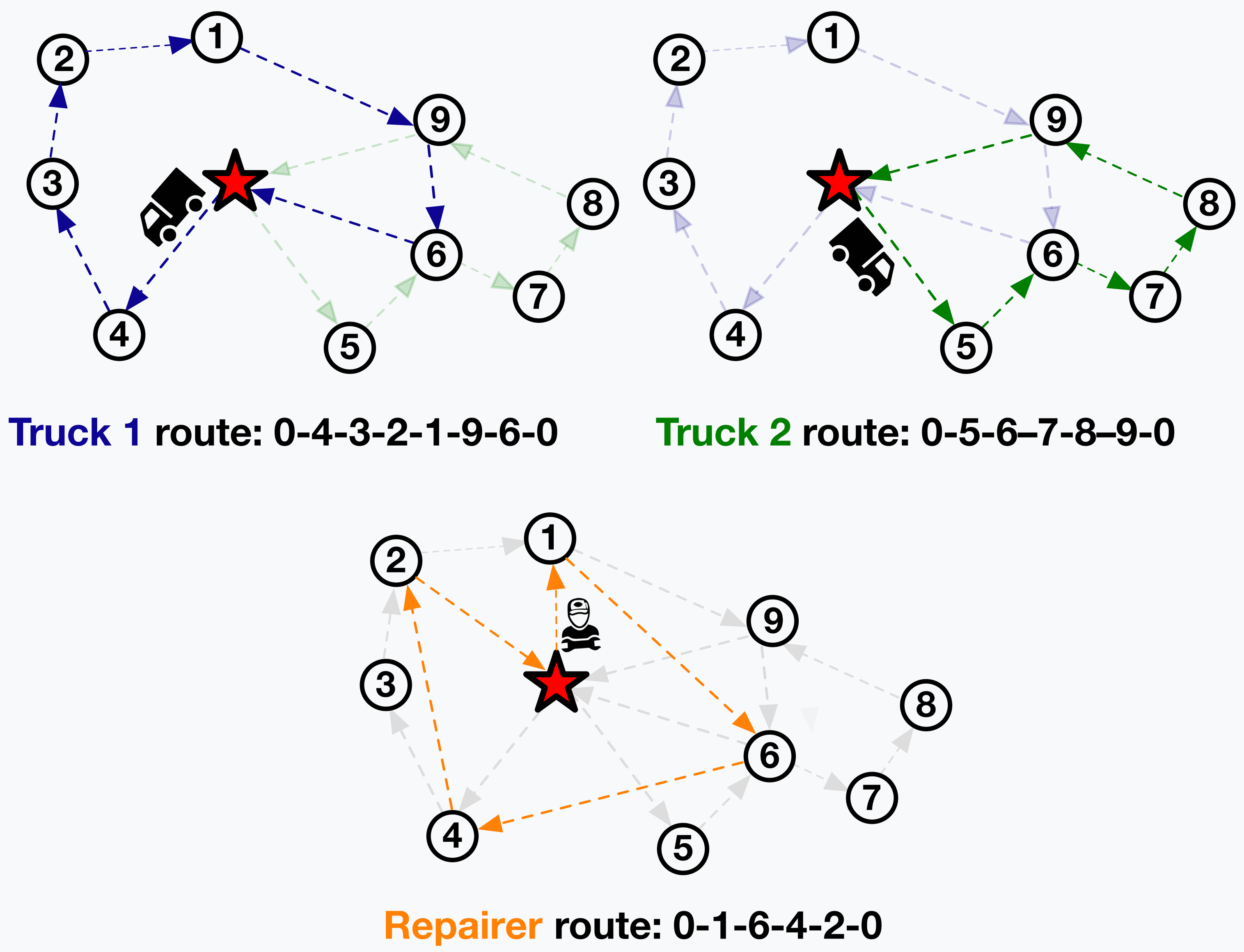


Fig. 3.1: Network with 10 stations, 2 trucks, 2 repairers. Shows vehicle routes and loading/unloading quantities.

4. Mathematical Model

Objective: Minimize total penalty cost (dissatisfaction + emissions)

$$\text{minimize } c^{p}\sum_{i\in S}F_i(p_{i,T'},b_{i,T'}) + c^{e}\sum_{i\in S_0}\sum_{j\in S_0}\sum_{t=t'_{i,j}+1}^{T'}\sum_{k\in K}e_{i,j,t-t'_{i,j},k}+$$

$$\left(\sum_{i\in S_0}\sum_{j\in S_0}\sum_{t=t'_{i,j}+1}^{T'}\sum_{k\in K}\left(t^{v}_{i,j}\cdot x^{v}_{i,j,t-t'_{i,j},k}\right)+\sum_{i\in S_0}\sum_{t=t'_{i,j}+1}^{T'}\sum_{k\in K}t^{load}\cdot\left(y^{u^+}_{i,t,k}+y^{u^-}_{i,t,k}+y^{b^+}_{i,t,k}+y^{b^-}_{i,t,k}\right)+\right.$$

6. HGSDAC-SBC Algorithm

Hybrid Genetic Search with Adaptive Diversity Control + **Station Budget Constraint**

Algorithm 1: HGSADC-SBC

Initialization: Generate a population Pop consisting of a feasible subpopulation Pop_f and an infeasible subpopulation Pop_i
Set $iter\_no\_imp = 0$ and $current\_best\_value = +\infty$
while $iter\_no\_imp < It_{NI}$ and $cpu\_time < T_{max}$ **do**
Randomly select two individuals Ind_1 and Ind_2 from Pop
Generate the routes of offspring C_1 and C_2 using ordered crossover on the routes of Ind_1 and Ind_2, then apply the SBC heuristic on the routes to determine the (un)loading and repairing quantities for C_1 and C_2
Educate on both C_1 and C_2 by applying local search procedures to generate new routes and using the SBC heuristic to determine the (un)loading and repairing quantities
if C_i $(i = 1, 2)$ is feasible **then**
  Add C_i to the feasible subpopulation Pop_f
else
  Add C_i to the infeasible subpopulation Pop_i and repair C_i with the probability P_{repair} using local search procedures and the SBC heuristic
end if
if the individuals become feasible after repairs **then**
  The repaired individuals are added to the feasible subpopulation Pop_f
else
  The repaired individuals are discarded, and the original infeasible solution is kept in the infeasible subpopulation Pop_i
end if
if the size of Pop_f or Pop_i reaches the maximum subpopulation size **then**
  Select survivors from the corresponding subpopulation
end if
Set bs = the solution with the best fitness value from Pop_f and set bv = the fitness value of bs
if $bv \geq current\_best\_value$ **then**
  Set $iter\_no\_imp = iter\_no\_imp + 1$
Else
  Set $current\_best\_value = bv$, $current\_best\_sol = bs$, and $iter\_no\_imp = 0$
end if
if $iter\_no\_imp \geq It_{div}$ **then**
  Diversify the population consisting of Pop_f and Pop_i and adjust the penalty parameter
end if
end while
return $current\_best\_sol$, $current\_best\_value$

7. Station Budget Concept (SBC)

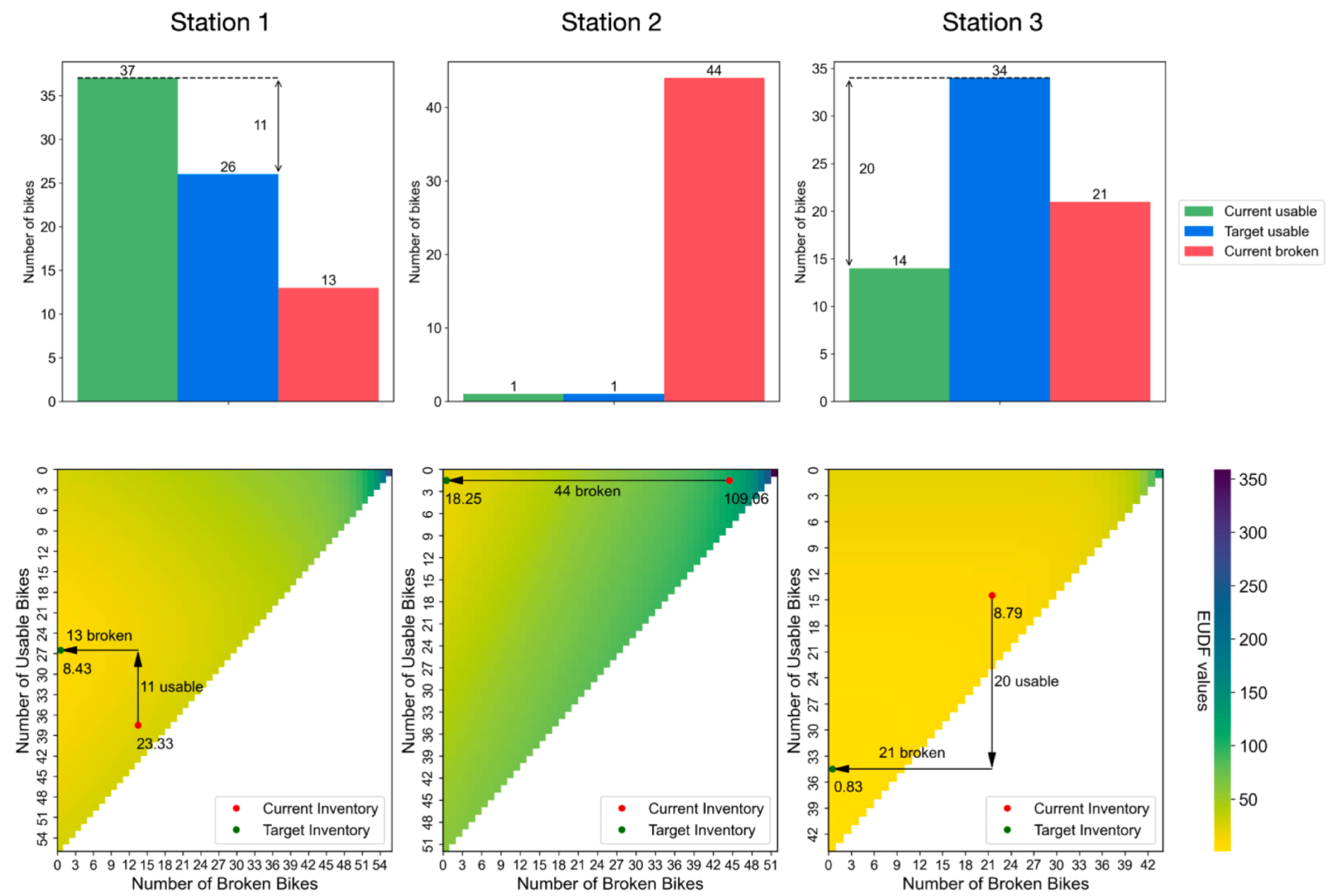
Key Innovation: Prevents over-allocation of service time to early stations

Benefit-Cost Ratio Function (BCRF):

$$BCRF^t_s(p,b) = \frac{F_s(p,b) - F_s(q,0)}{t^{load}\cdot(|q-p|+b)}$$

- Quantifies dissatisfaction reduction per unit service time
- Higher BCRF stations receive larger time budgets
- Unused time redistributed dynamically to later stations

8. BCRF Illustration



$$BCRF^1_1 = \frac{23.33 - 8.43}{(11+13)\times 60} = 0.0103 \qquad BCRF^1_2 = \frac{109.06 - 18.25}{44\times 60} = 0.0344 \qquad BCRF^1_3 = \frac{8.79 - 0.83}{(20+21)\times 60} = 0.0032$$

Fig. 4.1: BCRF calculation for 3 stations. Top: inventory status; Bottom: EUDF heatmaps.

9. Computational Results

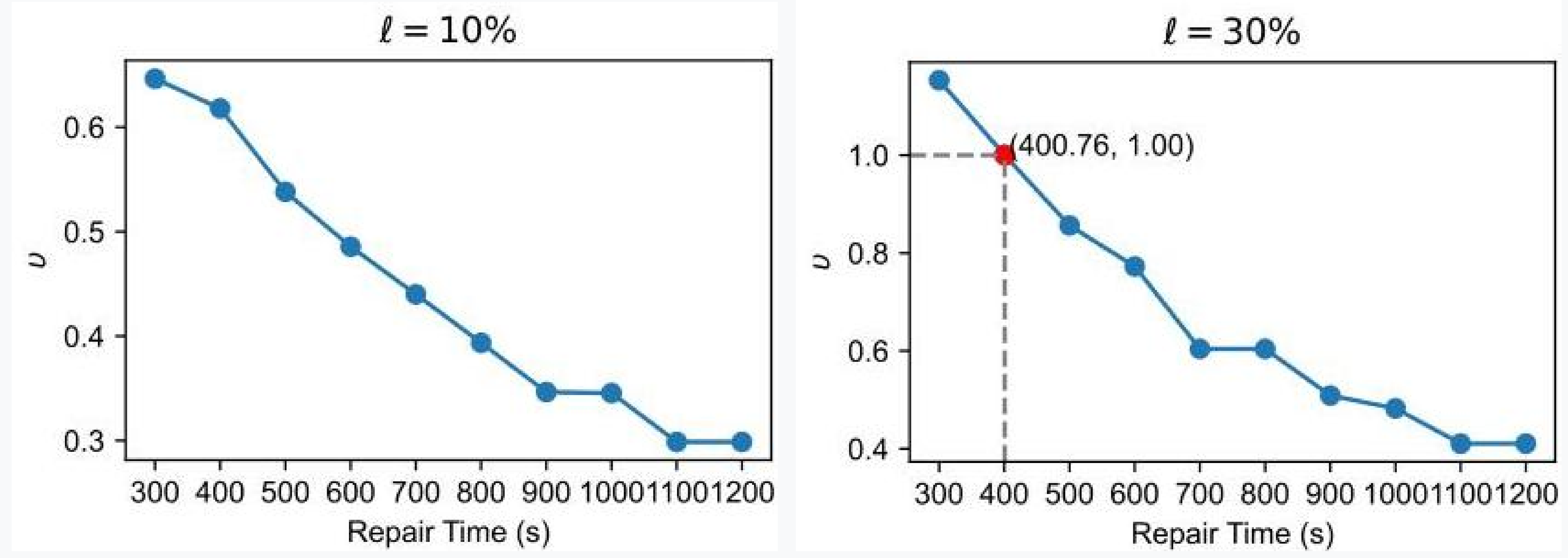
Comparison vs Gurobi (T=2h, τ=600s, 20 runs)

10. Cost-Effectiveness of Repairers

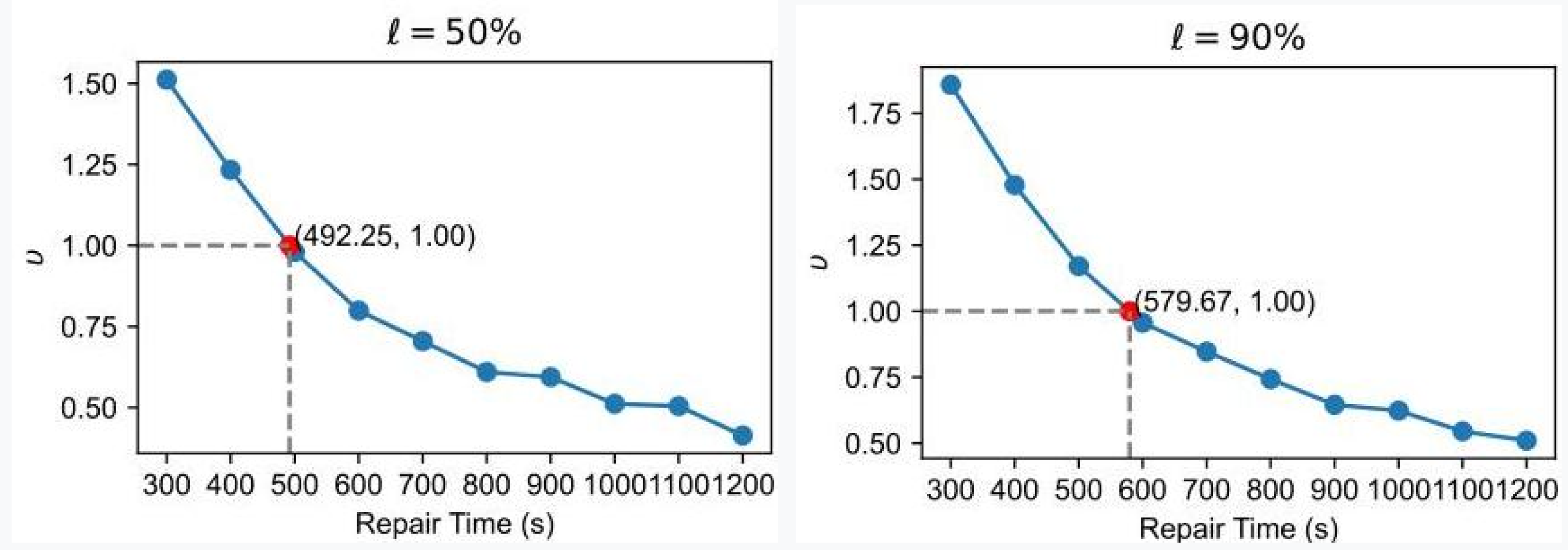
Indicator ν: Ratio of dissatisfaction reduction to repairer wage

$$\nu = \frac{c^p \sum_{i\in S}(\widehat{F}_i - \widehat{F}'_i)}{\varpi \cdot T/3600}$$

$\nu > 1$: Cost-effective $\quad$ $\nu < 1$: Not cost-effective



$\ell = 10\%$: Never effective $\quad$ $\ell = 30\%$: Threshold 401s



$\ell = 50\%$: Threshold 492s $\quad$ $\ell = 90\%$: Threshold 580s

Higher broken ratio (ℓ) → repairers effective at longer repair times

11. Key Managerial Insights

- **Critical Threshold:** Repair time > 645s ⇒ **never** cost-effective
- **Low damage ($\ell < 20\%$):** Trucks alone sufficient; repairers not justified
- **High damage ($\ell \geq 30\%$):** On-site repairers become economically justified
- **Preventive maintenance** crucial to keep repair times below threshold

12. Conclusions

1. HGSDAC-SBC is **scalable** for real-world BSS (up to 500 stations)
2. Station Budget Constraint effectively balances time allocation across route
3. Dynamic repairer deployment should adapt to daily damage levels

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References

Hu, R., Szeto, W.Y., & Ho, S.C. (2025). Repositioning in bike sharing systems with broken bikes considering on-site repairs. *Transportation Research Part E*, 104155.

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