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ijtimoiy-iqtisodiy, innovatsion texnik, fan va ta'limga oid ilmiy-amaliy jurnal

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05.01.03 – Informatikaning nazariy asoslari
05.01.04 – Hisoblash mashinalari, majmualari va kompyuter tarmoqlarining matematik va dasturiy ta'minoti
05.01.05 – Axborotlarni himoyalash usullari va tizimlari. Axborot xavfsizligi
05.01.06 – Hisoblash texnikasi va boshqaruv tizimlarining elementlari va qurilmalari
05.01.07 – Matematik modellashtirish
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05.06.01 – To'qimachilik va yengil sanoat ishlab chiqarishlari materialshunosligi
05.08.03 – Temir yo'l transportini ishlatish
05.08.06 – "G'ildirakli va gusenisali mashinalar va ularni ishlatish" (texnika fanlari)
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08.00.13 – Menejment
08.00.14 – Iqtisodiyotda axborot tizimlari va texnologiyalari
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08.00.16 – Raqamli iqtisodiyot va xalqaro raqamli integratsiya
08.00.17 – Turizm va mehmonxona faoliyati

Ma'lumot uchun, OAK Rayosatining 2024-yil 28-avgustdagi 360/5-son qarori bilan "Dissertatsiyalar asosiy ilmiy natijalarini chop etishga tavsiya etilgan milliy ilmiy nashrlar ro'yxati"ga texnika va iqtisodiyot fanlari bo'yicha "Muhandislik va iqtisodiyot" jurnali ro'yxatga kiritilgan.

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A HYBRID ADAPTIVE LARGE NEIGHBOURHOOD SEARCH ALGORITHM FOR ROUTING LESS-THAN-TRUCKLOAD PICKUPS WITH TIME WINDOWS AND TWO-DIMENSIONAL CAPACITY

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Annotatsiya. Kichik partiyali yuk tashish (LTL) operatorlari turli yuk jo‘natuvchilardan ko‘plab kichik hajmdagi yuklarni yig‘ib, ularni kross-dok terminalida birlashtiradi. Shu sababli mahalliy yig‘ish yo‘nalishlarining samaradorligi transport xarajatlari va yuk avtomobillaridan foydalanish darajasini bevosita belgilaydi. Maqolada vaqt oynalari, yuk og‘irligi va hajmi bo‘yicha sig‘im cheklovlari hamda har bir yuk avtomobili uchun doimiy xarajatni hisobga oluvchi LTL yuklarni yig‘ish yo‘nalishlarini rejalashtirish masalasi shakllantiriladi va gibrid adaptiv katta qo‘shnichilik qidiruvi (H-ALNS) algoritmi taklif etiladi. Algoritm regret-2 konstruktiv evristikasini, adaptiv vaznlar asosida tanlanadigan to‘rtta buzish va uchta tiklash operatorini, simulyatsion tavlanish orqali yechimlarni qabul qilish mexanizmini hamda keshda saqlanadigan joylashtirish xarajatlari yordamida vaqt oynalari bo‘yicha cheklovlarni O(1) vaqt murakkabligida tekshirish usulini birlashtiradi. 50, 100 va 200 ta buyurtmani o‘z ichiga olgan 15 ta sun’iy yaratilgan test misolida o‘tkazilgan hisoblash tajribalari natijalariga ko‘ra, H-ALNS eng yaxshi konstruktiv evristikaga nisbatan maqsad funksiyasi qiymatini 18,1–24,0 foizga, bosib o‘tiladigan masofani esa 24,8–35,1 foizga kamaytiradi. Shuningdek, algoritm adaptiv bo‘lmagan katta qo‘shnichilik qidiruvi usulidan 2,3–5,2 foizga yaxshiroq natija ko‘rsatib, 1,1–8,6 soniya ichida hisoblashni yakunlaydi.

Kalit so‘zlar: kichik partiyali yuk tashish (LTL), transport vositalari yo‘nalishlarini rejalashtirish, vaqt oynalari, ikki o‘lchovli sig‘im, adaptiv katta qo‘shnichilik qidiruvi, gibrid algoritm, simulyatsion tavlanish.

Аннотация. Перевозчики сборных грузов (LTL) собирают многочисленные небольшие отправления от разных грузоотправителей и консолидируют их на кросс-докинговом терминале. Поэтому эффективность локальных маршрутов сбора грузов непосредственно влияет на транспортные затраты и степень использования грузовых автомобилей. В статье формализуется задача маршрутизации транспортных средств для сбора сборных грузов с учётом временных окон, ограничений по грузоподъёмности и объёму, а также фиксированных затрат на использование каждого грузового автомобиля. Предлагается гибридный алгоритм адаптивного поиска по большому району (H-ALNS). Алгоритм объединяет конструктивную эвристику regret-2, четыре оператора разрушения и три оператора восстановления, выбираемых на основе адаптивных весов, механизм принятия решений на основе имитации отжига и проверку допустимости временных окон за O(1) с использованием кэшированных затрат на вставку. Вычислительные эксперименты на 15 синтетически сгенерированных тестовых экземплярах, содержащих 50, 100 и 200 заявок, показали, что H-ALNS снижает значение целевой функции на 18,1–24,0 %, а пройденное расстояние — на 24,8–35,1 % по сравнению с лучшей конструктивной эвристикой. Кроме того, алгоритм превосходит неадаптивный поиск по большому району на 2,3–5,2 %, при времени вычислений от 1,1 до 8,6 секунды.

Ключевые слова: перевозки сборных грузов, маршрутизация транспортных средств, временные окна, двумерная вместимость, адаптивный поиск по большому району, гибридный алгоритм, имитация отжига.

Abstract. Less-than-truckload (LTL) carriers collect numerous small shipments from different shippers and consolidate them at a cross-dock terminal. Consequently, the efficiency of local pickup routes directly affects transportation costs and truck utilisation. This paper formulates the LTL pickup routing problem with time windows, weight and volume capacity constraints, and a fixed cost per truck, and proposes a hybrid adaptive large neighbourhood search (H-ALNS) algorithm. The algorithm integrates a regret-2 construction heuristic, four destroy and three repair operators selected using adaptive weights, a simulated annealing acceptance mechanism, and an O(1)-time time-window feasibility check based on cached insertion costs. Computational experiments conducted on 15 synthetically generated instances with 50, 100, and 200 requests show that H-ALNS reduces the objective value by 18.1–24.0% and the total travel distance by 24.8–35.1% compared with the best constructive heuristic. Furthermore, it outperforms a non-adaptive large neighbourhood search by 2.3–5.2%, with computation times ranging from 1.1 to 8.6 seconds.

Keywords: less-than-truckload (LTL), vehicle routing, time windows, two-dimensional capacity, adaptive large neighbourhood search, hybrid algorithm, simulated annealing.

INTRODUCTION

In less-than-truckload (LTL) transportation a carrier serves many shippers whose shipments are too small to fill a truck. Shipments are picked up in the city by local trucks, brought to a cross-dock terminal, consolidated and sent on line-haul routes. The local pickup operation accounts for a large share of total LTL costs, and its quality depends on how well routes combine geographically close requests while respecting customer time windows and truck capacity. In practice both the weight and the volume of a shipment matter: light but bulky freight can fill a truck by volume long before its weight limit is reached.

The resulting problem is a variant of the vehicle routing problem with time windows (VRPTW) [1, 2, 8]. For tight computational budgets, exact methods may be difficult to apply to large constrained instances, motivating heuristic search without implying that all such instances are intractable in practice. Among them, adaptive large neighbourhood search (ALNS) [4, 5], which develops the large neighbourhood search of Shaw [3], is one of the most effective for routing problems with side constraints. This paper adapts ALNS to LTL pickup routing and combines it with several acceleration techniques, resulting in a hybrid algorithm referred to as H-ALNS.

LITERATURE REVIEW

The vehicle-routing formulation of Dantzig and Ramser [1] established the connection between dispatch decisions and transport cost. Solomon [2] studied routing and scheduling with customer time windows, where geographic proximity alone does not determine whether two requests can share a route. For local LTL collection, these constraints are supplemented by two independent load resources: the maximum mass and the maximum occupied volume. The resulting model concerns additive capacities, rather than geometric pallet placement or two-dimensional bin packing.

Shaw's large neighbourhood search [3] removes a group of visits and reconstructs the affected solution, permitting changes beyond a single relocation. Ropke and Pisinger [4] developed adaptive selection among competing neighbourhood operators, while Pisinger and Ropke [5] demonstrated the broader applicability of the framework to vehicle-routing variants. These works motivate an operator portfolio, but they do not imply that every added operator or adaptation rule improves every instance.

Simulated annealing [6] provides a mechanism for accepting some deteriorating candidates and thereby diversifying the search. Efficient route-time calculations, including propagation of feasible service times, are connected to the work of Savelsbergh [7]. The present contribution combines these established components for a depot-return pickup setting. Its effectiveness should be assessed through the reported comparison and targeted ablation experiments rather than attributed to an individual component solely from a comparison with a simpler operator portfolio.

RESEARCH METHODOLOGY

Problem formulation. Let 0 denote the terminal and N = {1, …, n} the set of pickup requests. Each request i has a weight w_i (kg), a volume v_i (m^3), a service time s_i and a time window $[a_i, b_i]$. A homogeneous fleet of m trucks with weight capacity Q_w and volume capacity Q_v performs one tour per shift of length T, starting and ending at the terminal. Travel distances d_{ij} and times t_{ij} are given. A tour $k = (0, i_1, \ldots, i_L, 0)$ is feasible if

$$\Sigma(i \in route\ k) w_i \le Q_w; \quad \Sigma(i \in route\ k) v_i \le Q_v. \tag{1}$$

$$a_i \le E_i \le b_i; E_j = max(a_j, E_i + s_i + t_{ij}). \tag{2}$$

and the truck returns to the terminal no later than T, where E_i is the service start time. The objective combines travel distance, the fixed cost F of each truck used and a penalty P for each unserved request U:

$$Z = \Sigma(k \in K)\, \Sigma((i,j) \in route\ k) d_{ij} + F|K| + P|U| \to min. \tag{3}$$

The fixed cost rewards consolidation, which is the main economic goal of LTL operations. In this study F = 50 km-equivalents and P = 1000 km-equivalents.

Model assumptions and interpretation. All requests are pickups for one terminal, all trucks are homogeneous, and each truck performs at most one tour in the shift. Because collected load is nonnegative and no intermediate unloading is modelled, cumulative weight and volume increase along a route. Checking the total route demand is therefore sufficient for these two capacity constraints. This simplification would not hold unchanged for mixed deliveries, intermediate unloading, multi-trip operation or load-dependent resource limits.

Time windows constrain service start, and waiting is permitted when a truck arrives before the opening time. Travel times are deterministic in the reported experiment. The terminal return is treated as a final node with latest arrival T, so return feasibility is included in route-time calculations. Loading geometry, axle limits, driver breaks and terminal handling schedules are outside this model and should not be inferred from the two-resource capacity test.

Distances and fixed truck costs are expressed in kilometre-equivalents. Thus the objective is a normalized planning cost rather than a monetary invoice. The unserved-request penalty discourages omissions but does not mathematically guarantee complete service for every possible instance. Report the number of unserved requests separately, and examine a service-first lexicographic objective if complete service is mandatory. A finite penalty should not conceal the trade-off between an expensive route and a rejected order.

Solution representation and verification. A solution consists of an ordered list of visits for each activated truck and an explicit set of unserved requests. Every request must occur either once in a route or once in that set. Depot departure and return are represented explicitly, and unused trucks are distinguished from empty routes produced temporarily by a destroy operator. This prevents a repair step from charging the fixed cost twice or treating a truck as available after it has already been used.

A verification routine should reconstruct all route loads and service times from the original request and travel matrices, independently of cached values. It should check unique service, the fleet limit, both capacities, every service-start window and the terminal deadline. Verification of the final solution establishes model feasibility; it does not establish global optimality or the accuracy of a real road-network model.

ANALYSIS AND RESULTS

Hybrid ALNS algorithm. The algorithm (Fig. 1) starts from a solution built by regret-2 insertion and iteratively destroys and repairs it. At each iteration q requests are removed, where q is drawn uniformly between 5% and 25% of the requests (at most 30) (Fig. 1.).

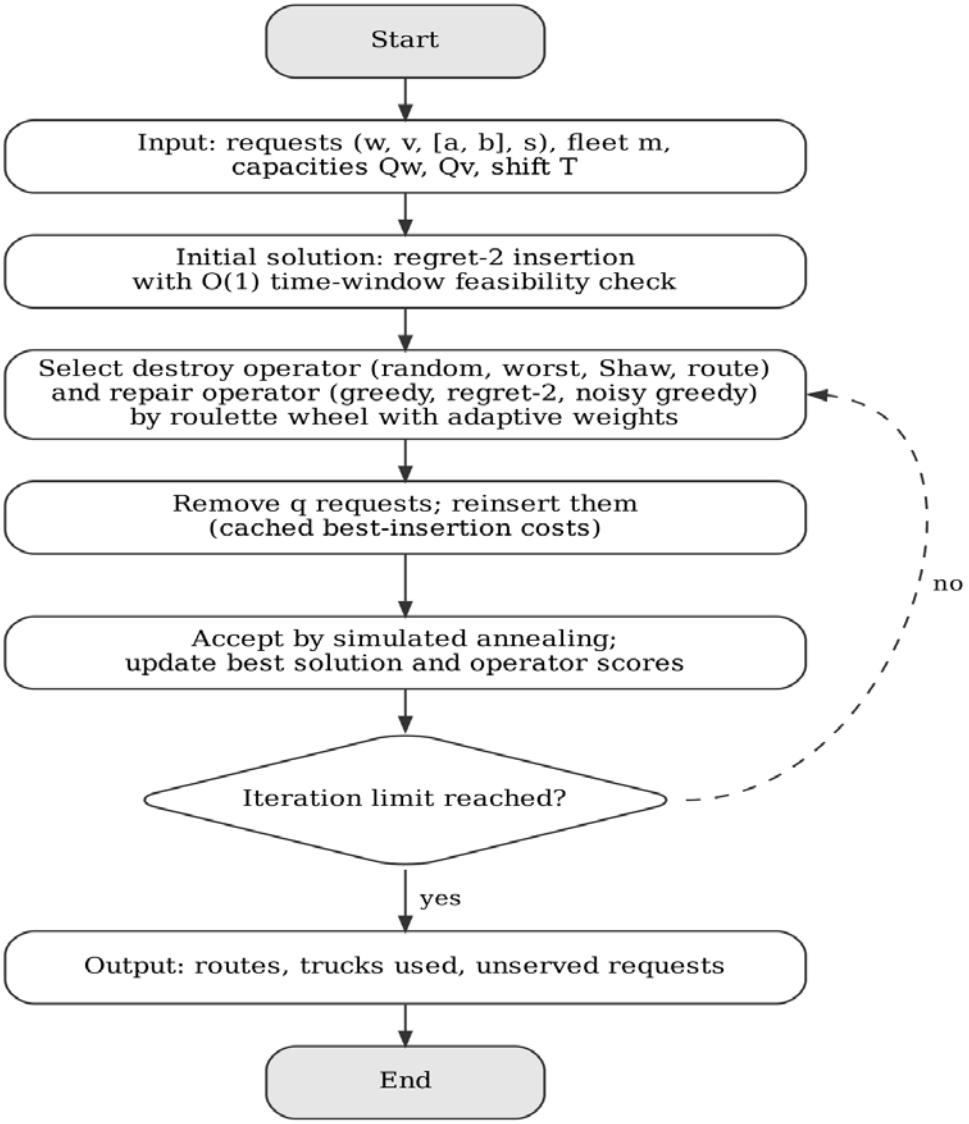


Fig. 1. Flowchart of the hybrid ALNS algorithm[1]

Destroy operators: random removal; worst removal, which removes requests with the largest distance savings with a randomised choice; Shaw (related) removal [3], which removes requests close to a random seed request in space and time; and route removal, which empties a short route and so helps reduce the number of trucks.

Repair operators: greedy insertion at the cheapest position; regret-2 insertion, which first inserts the request with the largest difference between its best and second-best route; and greedy insertion with ±10% noise on insertion costs.

Adaptive selection and acceptance. Operators are chosen by roulette wheel. Every 100 iterations the weight of each operator is updated as $w \leftarrow 0.9 \cdot w + 0.1 \cdot \pi/\theta$, where π is the score collected by the operator (33 for a new best solution, 9 for an improvement, 13 for an accepted worse solution) and θ is the number of times it was used [4]. A new solution is accepted by the simulated annealing rule [6] with probability $\exp(-\Delta Z/\tau)$, where τ decreases geometrically to 0.2% of its initial value.

Acceleration (hybrid components). Two techniques make the search fast. First, for every route the earliest start times E_i and the latest feasible start times L_i are stored, so the feasibility of inserting request u between i and j is checked in O(1) time [7]:

$$e_u = max(a_u, E_i + s_i + t_{iu}) \leq b_u; e_u + s_u + t_{uj} \leq L_j. \quad (4)$$

1 Author's Original Contribution Based on the Research Findings

Second, during repair the best insertion cost of every removed request into every route is cached, and after an insertion only the costs for the modified route are recomputed. Identical empty trucks are represented by a single candidate route.

Construction and insertion cost. For request u, enumerate feasible positions in each route and retain the cheapest position per route. Regret-2 compares the best and second-best route alternatives, encouraging early insertion of requests that have few attractive options. If only one feasible route exists, give that request priority under an explicit tie rule; if no feasible route exists, keep it unserved. An unused truck supplies an additional alternative only while the fleet limit permits activation.

Insertion cost includes the change in travel distance and the fixed cost if a new truck is opened. Because serving a previously unserved order also removes its penalty, the complete objective change is evaluated before acceptance. Emptying a route may remove a fixed cost, which helps explain why route removal can improve consolidation. The amount removed must be interpreted consistently for each operator: the route-removal operator removes a whole selected route, whereas the sampled q controls request-level removals.

Adaptive weights and stopping configuration. Destroy and repair operators use separate positive weight vectors. The probability of selecting an operator is its weight divided by the sum in its own portfolio. Scores are accumulated by outcome category, and the highest applicable category is used once per iteration. If an operator was not used during a 100-iteration segment, its weight should be retained rather than dividing by zero. Initial weights, any minimum weight and the treatment of accepted equal-cost moves must be recorded for replication.

For a worsening move with objective difference $\Delta Z>0$, the acceptance probability is $\exp(-\Delta Z/\tau)$; an improving move is accepted. For H iterations and a terminal temperature ratio of 0.002, a reproducible cooling specification is $\tau_h=\tau_0\times0.002^{(h/H)}$. The initial temperature τ_0 is an essential tuning parameter and must be supplied with the implementation. Preserve the best feasible solution separately, since the current annealing state can be worse than the best-so-far state.

Scope of constant-time feasibility checks. The local insertion inequalities assume valid forward earliest-start and backward latest-start labels for the unchanged route, deterministic travel times, permitted waiting and a fixed anchor. At the terminal, the backward recursion starts with $L_{terminal}=T$; at an earlier customer i followed by j, $L_i=\min(b_i,L_j-s_i-t_{ij})$. Checking one chosen position is then constant-time, including two scalar capacity totals.

This does not make a complete insertion constant-time. Searching all positions and updating labels after an accepted insertion require additional work. Cached costs are invalidated when their route changes, and an arrival-time or travel-matrix change can invalidate more than one route. Report timing for the complete repair or solver, not just the local predicate. A full route verifier should still run before a solution is returned.

Computational experiment. The following numerical results and figures describe the experiment reported in the study. The present analysis checks the displayed calculations; it does not constitute an independent rerun of the generator or solver. Per-instance data and executable logs are required for external replication.

The reported test instances were generated using fixed instance seeds (random seeds 1–5 for each size) with the parameters given in Table 1. Half of the requests are clustered around four random centres and half are uniformly distributed, which reflects a typical mix of industrial zones and scattered shippers (Tabbe 1).

Table 1.

Reported parameters of the generated test instances[2]

Parameter	Value
Service area; terminal location	40 × 40 km; centre of the area
Road distance	1.3 × Euclidean distance; speed 30 km/h
Number of requests n	50, 100, 200 (5 instances each)
Shipment weight; density	100–800 kg; 150–350 kg/m³
Service time	10 min + 1 min per 100 kg
Time window	start 0–360 min, width 90–180 min
Truck capacity Q_w; Q_v	5000 kg; 20 m³
Shift length T; fleet size m	600 min; ⌈n/6⌉ trucks

H-ALNS was compared with three constructive heuristics (nearest neighbour, cheapest insertion and regret-2 insertion) and with a plain large neighbourhood search (LNS) that uses only random removal and

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greedy insertion with fixed operators. LNS and H-ALNS performed 3000 iterations from the same regret-2 starting solution. All methods were implemented in Python 3 and run on a virtual machine with two CPU cores; every solution was verified by an independent checker of time windows, capacities and shift length. Average results over five instances are given in Table 2 (Table 2).

Table 2.
Reported average results for n = 50 (five instances)[3]

n	Method	Distance km	Trucks	Utilisation %	Objective Z	CPU s
50	Nearest neighbour	710.1	8.8	53	1550.1	0.00
50	Cheapest insertion	713.6	6.0	78	1013.6	0.01
50	Regret-2 insertion	613.1	5.6	85	893.1	0.01
50	LNS (random/greedy)	478.5	5.4	88	748.5	0.98
50	H-ALNS (proposed)	461.3	5.4	88	731.3	1.10

Table 3.
Reported average results for n = 100 (five instances)[4]

n	Method	Distance km	Trucks	Utilisation %	Objective Z	CPU s
100	Nearest neighbour	1169.4	14.8	66	1909.4	0.00
100	Cheapest insertion	1139.7	11.2	87	1699.7	0.02
100	Regret-2 insertion	1124.4	10.4	93	1644.4	0.02
100	LNS (random/greedy)	762.6	10.6	91	1292.6	3.60
100	H-ALNS (proposed)	729.4	10.4	93	1249.4	3.73

Table 4.
Reported average results for n = 200 (five instances)[5]

n	Method	Distance km	Trucks	Utilisation %	Objective Z	CPU s
200	Nearest neighbour	1932.7	25.4	75	3202.7	0.02
200	Cheapest insertion	1818.8	20.2	94	2828.8	0.08
200	Regret-2 insertion	2186.4	20.2	94	3196.4	0.09
200	LNS (random/greedy)	1345.5	20.4	93	2365.5	8.70
200	H-ALNS (proposed)	1253.5	19.8	95	2243.5	8.57

All methods except nearest neighbour served all requests. H-ALNS gave the best result for every instance size. Compared with the best constructive heuristic, it reduced the objective value by 18.1%, 24.0% and 20.7% and the travelled distance by 24.8%, 35.1% and 31.1% for n = 50, 100 and 200 respectively, while the average truck utilisation (the larger of the weight and volume load factors) reached 88–95%. The advantage of H-ALNS

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over plain LNS grows with instance size (2.3%, 3.3% and 5.2%), which supports the combined operator-and-search design in these reported instances; it does not isolate adaptation from portfolio diversity.

Fig. 2 shows the routes obtained by H-ALNS for one instance with 100 requests, and Fig. 3 shows the convergence of the search on the same instance. The objective value decreased from 1712.5 to 1275.8; 95% of this improvement was achieved within the first 503 iterations. At the end of the run the normalised weights of the destroy operators were 40% (random), 28% (worst), 17% (Shaw) and 15% (route), and those of the repair operators 27% (greedy), 49% (regret-2) and 23% (noisy greedy) (Fig.2.).

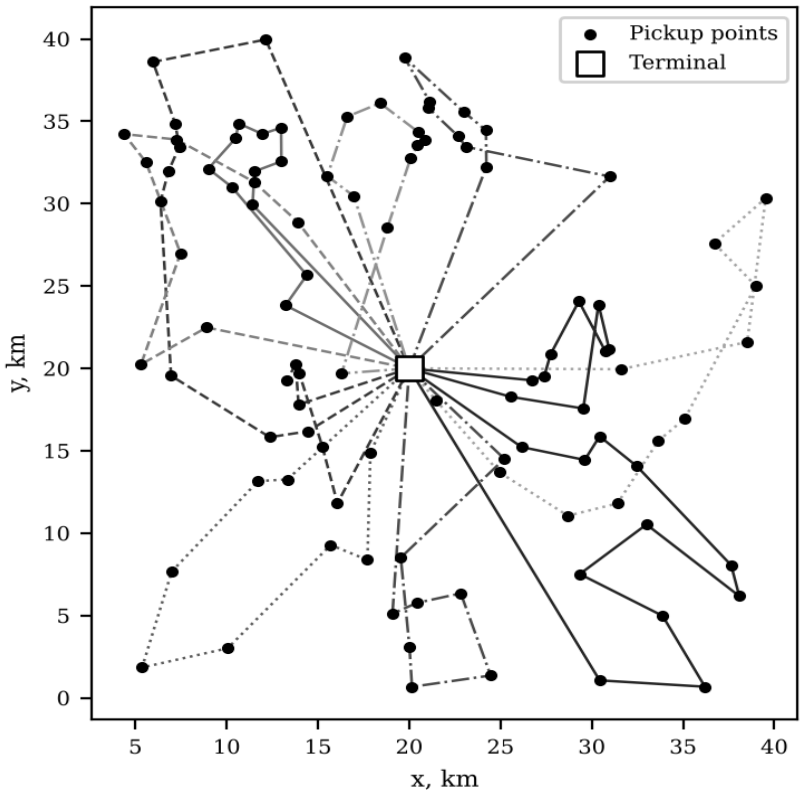


Fig. 2. Routes obtained by H-ALNS for an instance with 100 requests[6]

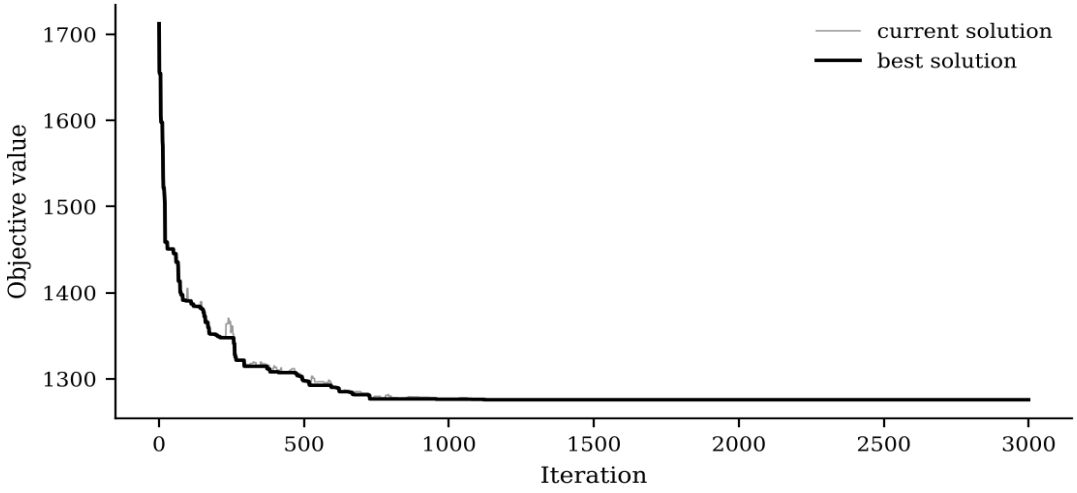


Fig. 3. Convergence of H-ALNS (n = 100)[7]

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Arithmetic checks and interpretation. The percentages in Table 5 are ratios calculated from the published group means, not the mean of instance-level percentage improvements. Those two summaries need not coincide. For n=200, cheapest insertion is the best constructive baseline by objective value, whereas regret-2 is the best constructive baseline for n=50 and n=100 (Table 5).

Table 5.
Reductions recomputed from the reported means[8]

n	Objective vs best construction	Distance vs same construction	Objective vs plain LNS
50	18.1%	24.8%	2.3%
100	24.0%	35.1%	3.3%
200	20.7%	31.1%	5.2%

The objective can be checked using distance + 50 × trucks + 1000 × unserved requests. For the 50-request nearest-neighbour row, 1550.1 − 710.1 − 50×8.8 = 400.0, corresponding to a mean of 0.4 unserved requests. The other rows have zero residual at the reported precision. Fractional truck and unserved counts are averages across five instances, not fractional vehicles or orders in an individual solution.

Utilisation is reported as the larger of the weight and volume load factors. This reflects the binding resource but should not be interpreted as simultaneous high utilisation of both capacities. Separate weight and volume statistics would provide a clearer operational picture. The repair weights reported as 27%, 49% and 23% sum to 99% because of rounding.

The reported averages favor H-ALNS across all three instance sizes, but the comparison with plain LNS changes both the operator portfolio and adaptive selection. It therefore supports the combined design rather than isolating the benefit of adaptation. A targeted ablation should compare identical portfolios with fixed and adaptive weights, followed by variants without cached insertion and without route removal. The same instances, run budgets and random seeds should be used in each comparison.

Synthetic geometry provides a controlled test, but the factor of 1.3 applied to Euclidean distance does not reproduce one-way streets, congestion or road access constraints. Reported timings are specific to the stated Python implementation and virtual environment. A two-core description alone does not identify processor frequency, memory, interpreter version or whether CPU time and wall time were distinguished. Those details, generator code and per-instance logs are needed for independent reproduction.

The five instances per size characterize only a small scenario sample. Standard deviations, best and worst outcomes and repeated solver seeds would reveal robustness that averages cannot show. A small exact or best-known-instance comparison could assess solution quality beyond constructive baselines. Sensitivity to fixed cost, unserved penalties, removal size and initial temperature should be assessed before selecting an operating configuration.

The same algorithm can act as a static optimization component in a dynamic system, but dynamic use requires additional state and commitment constraints. The present capacity model also does not solve physical loading compatibility. These limits identify the appropriate next validation steps without diminishing the observed improvements in the reported experiment.

CONCLUSIONS AND RECOMMENDATIONS

A hybrid ALNS algorithm for routing LTL pickups with time windows and two-dimensional (weight and volume) capacity has been developed. The hybrid design combines regret-based construction, an adaptive portfolio of destroy and repair operators, simulated annealing acceptance, an O(1) feasibility check and cached insertion costs. On 15 reproducible instances the algorithm reduced the objective value by 18.1–24.0% relative to the best constructive heuristic and solved instances with 200 requests in about 9 s, which supports further evaluation as an optimisation component of a dynamic LTL routing system. Further research will address dynamic requests, heterogeneous fleets and validation on real data of LTL carriers.

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