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Title: Tactical service design and vehicle allocation optimization

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Setting the frequencies of service lines constitutes the main activity in the tactical planning of public transport operations. A typical frequency settings problem requires the allocation of vehicles to a pre-determined set of service lines in order to achieve a trade-off between the coverage of passenger demand and the operational costs. However, allocating the optimal amount of resources (i.e., buses) to each service line of a broader transport network does not guarantee the optimal utilization of vehicles. The reason is that buses are allocated to different lines according to the observed passenger demand at each line without taking more detailed measures for adjusting to the demand variation along each of these lines. For instance, at some segments of a service line the bus occupancy levels might be high because of the significant passenger demand while in other segments they might be running under-utilized. In addition to the demand variations among the different segments of a service line, there can also be a significant demand variation between the different directions of the line (for instance, the inbound direction of a bus line might have significant passenger demand while the outbound might have low demand levels). Those spatiotemporal demand variations on different segments and/or directions of a service line cannot be tackled by setting the frequencies of buses at the line-level; and therefore, the optimality at the network level cannot be ensured.

For addressing those specific inefficiencies in frequency settings and vehicle allocation, this work proposes a tactical planning with flexible vehicle allocation and service design (where service frequencies are not set per line, but per line segment). This work introduces a method with a sequence of steps for performing the flexible service design and vehicle allocation at the tactical planning stage. First, the observed O/D demand variations at the level of each bus line are utilized for generating a list of control points where short-turn and interlining operations are allowed. Allowing short-turns and interlinings at control points leads to the generation of new (sub-)lines which serve different segments compared to the original service lines. The generated candidate short-turn and interlining lines form a group of virtual lines on which a number of buses can be allocated. By doing so, we introduce an additional flexibility in allocating buses to lines because apart from the original service lines, buses can also be allocated to the set of virtual lines for matching the passenger demand variation at different segments of one line without unnecessarily serving all the stops of that line.

The generation of a vast set of virtual short-turn and interlining lines enables to allocate vehicles at specific line segments with significant passenger demand, but -at the same time- increases dramatically the number of lines where buses can be allocated. Therefore, the optimal allocation of vehicles to original and virtual service lines becomes a computational intractable problem given the large number of potential virtual lines at a city-wide network. In more detail, setting the frequencies of original and virtual lines is a discrete optimization problem where the objective function attempts to match the demand at the segments of each line while also reducing the operational costs. The form of the objective function is fractional because the demand matching and the operational costs are contradictory objectives that are combined using weight factors. Given the fractional form of the objective function, setting the frequencies at each original and virtual line is a nonlinear constrained optimization problem and its computational complexity is exponential.

For this reason, the constraints of the problem are relaxed with the use of an exterior point penalization function which is structured in a way that its minimization favors the satisfaction of constraints.

In addition, three heuristic algorithms are introduced for optimizing this problem. Those heuristic algorithms belong to the category of evolutionary optimization and converge rapidly to an optimal solution, which cannot be guaranteed that is the global optimum due to the non-convexity of the objective function. Those three algorithms are a purpose-built Sequential Genetic Algorithm (S-GA), a Greedy Genetic Algorithm (GGA) and a Particle Swarming Optimization method which is defined in such a way that can tackle discrete optimization problems (DPSO). The initialization and the iteration steps of those algorithms are described in the following figures.

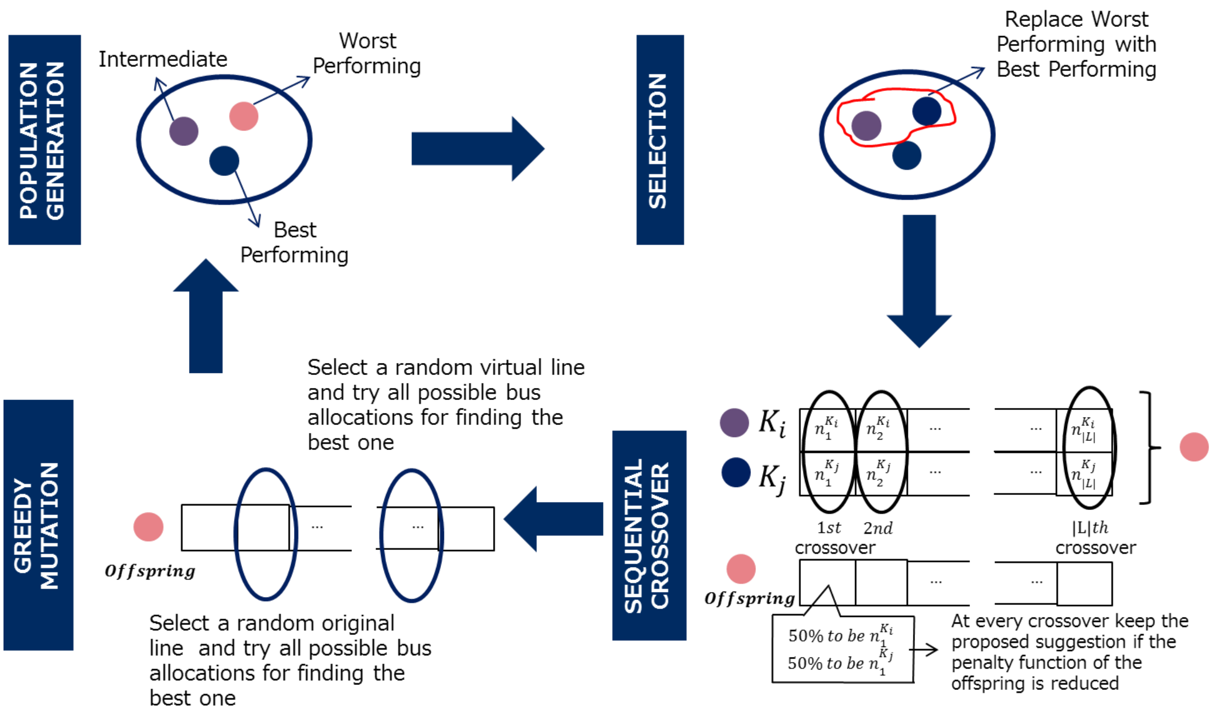

Fig.1: Sequential Genetic Algorithm (S-GA)

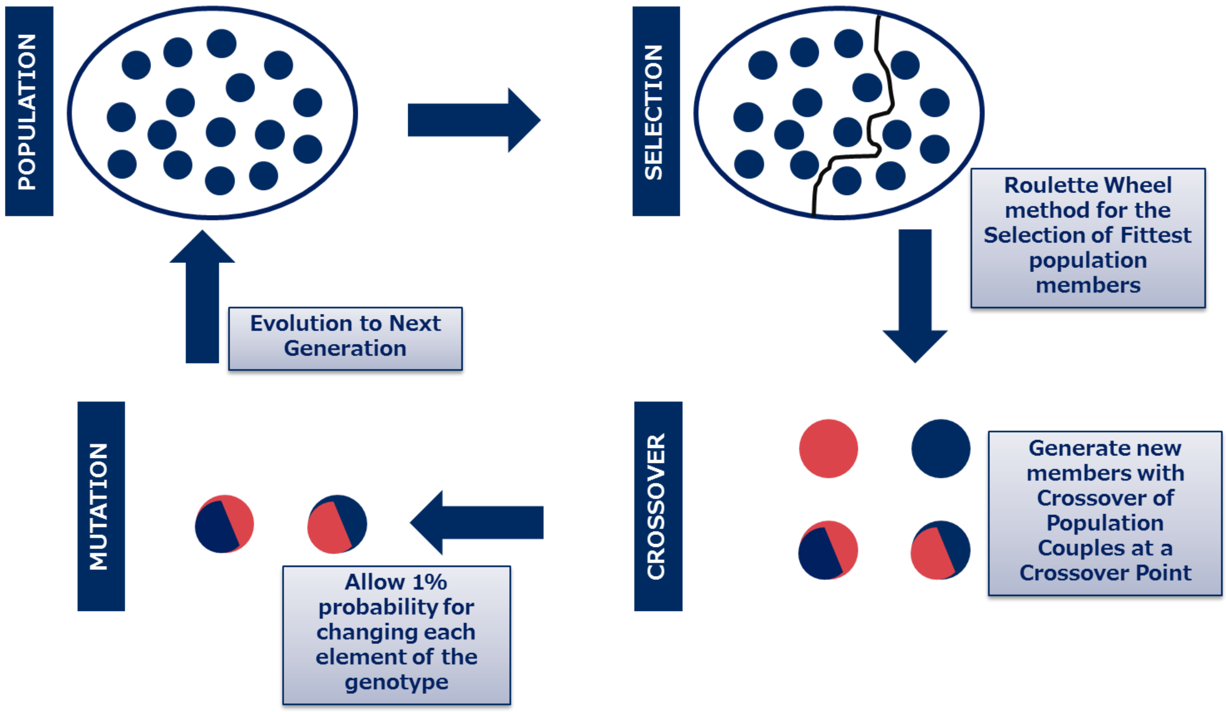

Fig.2: Greedy Genetic Algorithm

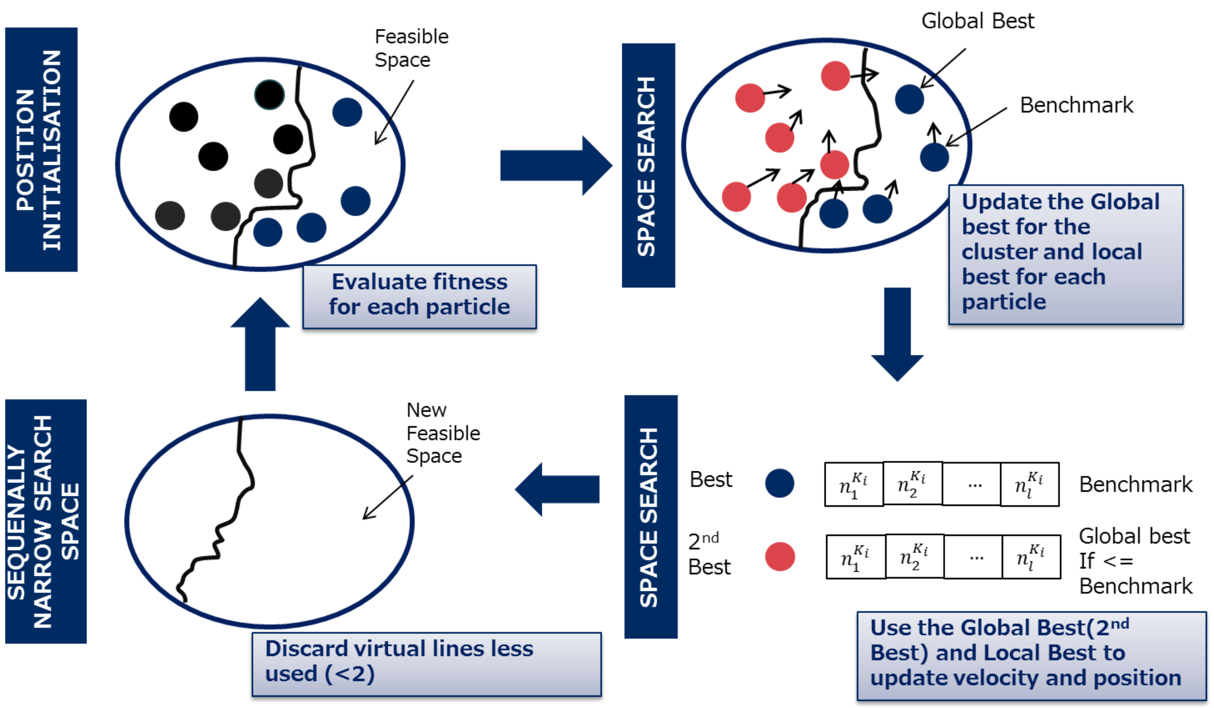

Fig.3: Discrete Particle Swarm Optimization (DPSO)

The performance of those algorithms is tested in the bus network of a city in central Europe that contains eight (8) central bus lines. For deriving the OD demand per line, we utilized as data input the smartcard logs of passengers after processing them to derive the aggregated travel demand between different bus stops at each line. The DPSO solution method was not able to satisfy the entire set of problem constraints and could not provide a feasible solution. The other two algorithms were able to improve the exterior point penalty function score below the threshold level of constraints' satisfaction as presented in Fig.4. In Fig.4, both algorithms (GGA and S-GA) start from an initial solution guess of the number of buses allocated to 93 short-turn and interlining virtual lines and try to improve this allocation at each iteration step.

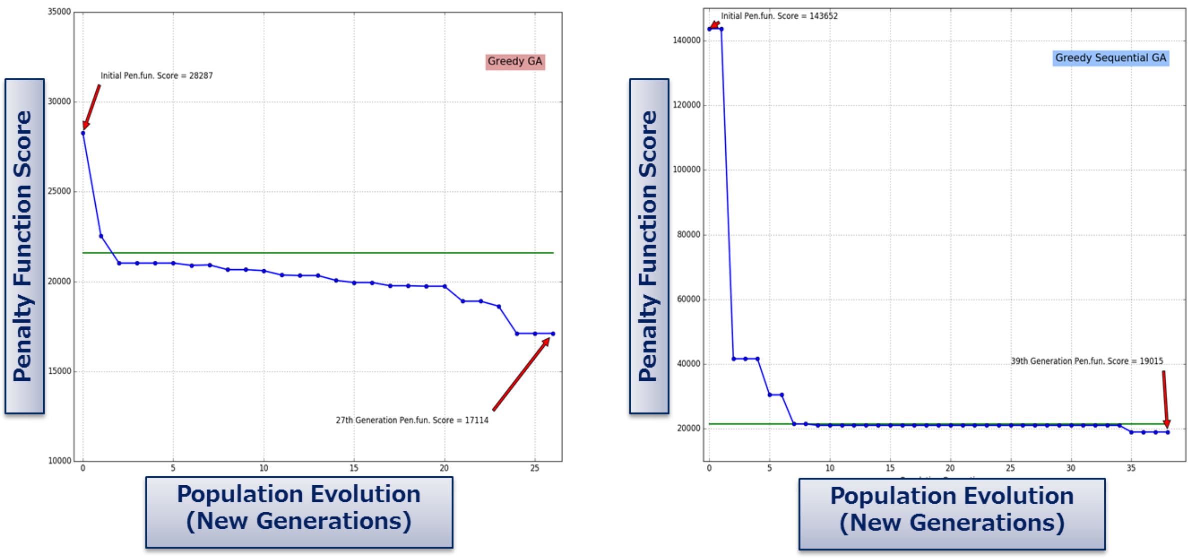

Fig.1: Improvement of the exterior point penalty function score after a number of optimization iterations with the use of the GGA (left) and the S-GA (right). The green horizontal line represents the area below which all constraints are satisfied (feasible solution space). Both the GGA and the S-GA started from initial solutions with randomly allocated vehicles to 93 virtual lines and 8 original lines and managed to improve the allocations of the vehicles in such a way that all constraints were satisfied.

The GGA reduced further the exterior point penalty function score and required less iterations that the S-GA. However, the S-GA was much faster due to the sequential crossovers and mutations that increased the probability of finding a better offspring at each iteration. In Table 1 the results from the evaluation tests are summarized.

Solution Method	Operational Costs (total travel time in min.)	Passenger Waiting Times	Computing Time
Original Lines Only	21616 min.	1.7845 min.	-
Genetic Algorithm	17114 min.	>= 1.7845 min.	66 minutes
Sequential Genetic Algorithm	19015 min.	>= 1.7845 min.	14 minutes
DPSO	17543 min.	1.853 min	56 minutes

Table 1: Comparison of the Operational Costs of the original bus allocation to the 8 central lines (Original Lines Only) against the Operational Costs after introducing virtual interlining and short-turn lines and allocating buses to those lines with the GGA, S-GA and the DPSO methods.

The segment-level vehicle allocation to original and virtual (short-turn and interlining) lines to the mid-sized European city demonstrated a potential of 20.8% operational cost reduction for the same level of demand matching compared to the scheduled operations. The GGA demonstrated the best performance and managed to satisfy all constraints while reducing significantly the operational costs by allocating buses to virtual lines. The DPSO algorithm was not able to converge to a feasible solution while the S-GA had the less computational cost (14minutes on a 2556MHz processor machine with 1024MB RAM).

Finally, an interesting discussion point is the deletion of virtual lines since the matching of passengers' demand and the operational costs were improved in cases where there was no vehicle allocation to some of the initially defined virtual lines. This means that the exhaustive generation of interlining and short-turn lines should be filtered later on from a rigorous optimization method that does not only allocate buses to lines but filters the lines which deteriorate the operational efficiency. For instance, the GGA solution filtered out 76 out of the 93 virtual lines while the S-GA filtered out 79.