Optimizing a demand-responsive feeder system for low-demand areas

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SHORT SUMMARY

Efficient public transport systems are essential for the dynamism of medium and large cities. With the growth of urban areas around large centers, new neighborhoods emerge in the suburbs and pressure the public transport system. A limited solution is to extend the system with feeder lines. However, in the last decades, demand-responsive systems emerged, complementing traditional systems and providing efficient transportation services for users and operators. We introduce a demand-responsive public bus system that considers shortcuts and detours and modifies the departure times of a feeder system, based on the current demand. This system contains a recognizable backbone, but it is not fixed. The operation is optimized, using a memetic algorithm, for each operation period in order to reduce passenger travel time. The optimized system in our experiments reduces passenger travel time with 18 to 38% compared to a traditional system operating the same network with fixed routes and timetables.

Keywords: demand-responsive transportation; dynamic offline optimization; memetic algorithm; transportation network modeling

1. INTRODUCTION

Over decades, the primary mode of public transportation has remained fixed-route bus systems. These traditional systems offer a scheduled service along predefined routes, where users must adapt to service availability (Sanchez, 2008). In order to offer this service in suburban regions, feeder lines are often available, connecting low-demand areas to a hub station where a high-frequency service operates, taking passengers further along the main network. However, both demand and service frequency in a suburban area are still relatively low to obtain a profitable operation, especially during off-peak hours. Over the years, there has been an increase in real-time demand-responsive systems where users indicate their preferred departure times and locations for a private or shared trip (Schofer et al., 2003). However, these services are expensive, and costs are sensitive to traveled distances.

Several types of demand-responsive systems have been designed to address different challenges. For instance, Nourbakhsh and Ouyang (2012) explore a demand-responsive system for low-demand areas but focus on a door-to-door service following routes structured in a grid system with transfers at the intersections. The idea of combining demand-responsive systems with the operability of traditional systems is also explored by Quadrifoglio *et al.* (2008), where the vehicle in operation follows fixed routes with mandatory bus stops with the possibility to deviate according to logic detours, serving other points inside the operation area. Wei *et al.* (2020) develop a demand-responsive feeder system coordinating routing and frequency-setting of the buses with other services at the hub station, which is the common destination for passengers in feeder systems. Vansteenwegen et al. (2022) present a recent and comprehensive survey on demand-responsive public bus systems.

In this research, a demand-responsive feeder system is developed to offer some characteristics of a traditional system merged with some features of flexible systems. This results in a regular frequency of operation, predefined routes, and bus stops along the way. However, the departure times of each bus will be optimized, together with its route. To be more specific, limited detours and shortcuts are considered for each predefined route. This results in a set of possible routes that each bus can follow. A fixed number of buses run for consecutive operation periods. A bus that departs in a given period must arrive at the hub station in the same period. For each period, there is a list of passengers that request to use the system and the time they will arrive at the desired bus stop to wait for the buses. The optimization of the route and the timetable of the demand-responsive system occurs just before the operation period starts. As much as possible, requests will be accepted, so passengers are picked up at their bus stop as soon as possible after their arrival. However, some passenger requests will have to be rejected, and then the passenger will be included in the optimization of the following period. A memetic algorithm is introduced to optimize this demand-responsive feeder system. The objective is to minimize the sum of the travel times for all passengers, from the moment they arrive at the bus stop until they arrive at the hub station. In the experiments, the system performance is compared with the performance of the traditional feeder system, where bus routes and departure times are fixed.

2. METHODOLOGY

The service is optimized with a memetic algorithm (MA) for each period of operation. It combines a genetic algorithm that explores the search space with local search to improve the current solutions of a given generation. One route from the list of possible routes and an appropriate departure time is assigned to each bus in the current period. For the initial generation, a given number of random solutions are created. For the following generations, crossover techniques merge the solutions of the previous generation, selecting routes and departure times for each bus in operation, in order to generate a new solution. Since each passenger's preferred departure stop and time is known during the optimization process, the solution's fitness value is assessed by the sum of all passenger travel times. A penalty is included for rejected passengers.

The local search techniques correspond to a repair and an improvement operator. In the repair operator, routes are modified, and departure times are adjusted to avoid rejected requests. For each solution in a generation, a rejected request is selected, and the operator tries to include it in any of the buses. This can be done in two ways. First, the bus departure time is delayed if a passenger arrives at the bus stop after the bus passes. If no bus is assigned for that bus stop, a detour tries to include that bus stop in one of the bus routes. In the improvement operator, the current solution is optimized by trying to find a better route for one of the buses. This new route should still serve all passengers assigned to that bus. Moreover, the bus departure time can be advanced in order to reduce passenger waiting times at bus stops.

2.1. Problem Formulation

The demand-responsive feeder system (DRFS) runs in an area represented by a graph $G = \{V, L\}$, where V is the set of hub station and bus stops ($i = 0, 1, \dots, n$) and L indicate links between bus stops $i \in V$ and $j \in V$ at a travel cost of $c_{i,j}$. The objective of the DRFS is to minimize, for each operation period, the total travel time of the passengers (p_{tt}), including waiting and in-vehicle time and a penalty for unserved demand. A fixed number of lines connecting all the bus stops to the hub station is available. For each line, a set of feasible routes can be determined, considering limited detours, stop skipping and a route length limited to the duration of the operation period.

3. RESULTS AND DISCUSSION

The results of the demand-responsive feeder (DRFS) system are compared with the results of the traditional feeder system based on a simulation of both services. After optimizing the routes and departure times of the buses for the DRFS, passengers travel time are measured based on the timetable of the buses and the desired departure time of passengers. The same simulation occurs for the traditional feeder system (TFS), where routes and departure times of buses are fixed.

The parameters of the MA were determined based on preliminary tests. The good performance of the MA was confirmed in comparison with optimal results obtained by solving a mathematical model of the optimization problem using the CPLEX solver. For a set of 20 instances, the routes obtained with the MA for the DRFS are the same as for the optimal solution in 70% of the simulated operation periods, with an average travel time for passengers of 29 minutes, 0,6% above the optimal solution. In the TFS, the average travel time for these instances is 31.5 minutes

Here, we will focus on evaluating the efficiency of the DRFS based on five experiments. In every experiment, the passenger travel time in the DRFS is compared with the travel time in the TFS. Therefore, both operations are simulated over all operation periods, with a fixed number of buses and serving the same list of passengers. For a given network composed of 25 bus stops connected with three lines to a hub station, 100 passengers randomly send a request for a five-hour operation horizon, divided into operation periods of one hour. Therefore, each bus is operated five times, with a (possibly) slightly different route every time. There are several instances for optimization in which the requests are assigned randomly for variation. These instances are clustered according to the number of bus stops without any request during a given period. There are 30%, 50%, or 70% of empty bus stops on each instance.

The first three experiments evaluate the impact of the number of buses available. Each experiment considers 60 instances, 20 for each percentage of empty stops. In the first experiment, two buses are available during each operation period. The number of buses available is three in the second experiment and four in the third experiment. In the fourth and fifth experiments, three buses per operation period are available, but the detours considered are no longer limited in the fourth experiment. Buses can perform any movement in the network going from terminal to hub station, as long as there are no cycles and they arrive before the end of the period. In the fifth experiment, a different network is used with 70 bus stops and 300 requests in the operation period. The average waiting, in-vehicle, and total travel times for the TFS and the DRFS are presented in Table 1.

When analyzing the waiting times in all experiments, it can be noticed that in the TFS passengers have to wait around 30 minutes for a bus. This is obviously related to the randomly assigned desired departure times, which will on average be around half of the operation period duration. Moreover, since the routes are always the same in the TFS, as well as the demand at bus stops in all instances, the average in-vehicle time is the same for different percentages of empty stops. Increasing the number of buses in the TFS reduces the number of bus stops covered by each bus, and thus the length of pp. the route. With two buses per hour, it's possible to serve the whole area with the traditional feeder system with an average travel time per passenger of 56.1 min. By including one extra bus per hour, this average travel time reduces 18%, to 46.2 min. By including the fourth bus in the hourly operation, the extra gain was only 3%, reducing the average travel time of passengers to 44.7 min. It is clear that including the fourth vehicle does not generate a significant improvement for the passengers in this network.

When comparing the DRFS with the TFS in the first three experiments, it can be seen that the average waiting time is reduced with 31%, 48%, and 58% for two, three, and four buses respectively. This is a significant improvement due to the flexibility in the routes and timetable, which increases with the number of buses. However, the average in-vehicle times are only reduced for two buses, with 29%. For three and four buses, the in-vehicle time even increases slightly, with 1%. When only two buses are available, the relatively longer routes allow more useful shortcuts. With three and four buses, routes are already shorter and detours become equally useful as shortcuts. Summing both times in the total travel time, the DRFS reduces the passenger travel time by 30%, 31%, and 38%, respectively.

In the fourth experiment, with unrestricted movements for buses, the waiting time was even better than in the initial experiment with three buses, with 54% improvement. However, there was also an increase in the in-vehicle time due to the longer detours to better serve the passengers. In the end, the total travel time was only slightly better than in the initial experiment with three buses, with now 32% of improvement compared to the TFS, instead of 31% with the predefined rules that limit the possible detours. Therefore, we conclude that these limited detours are a good tradeoff between maintaining recognizable routes and gaining total travel time.

The optimized system performed differently in the last experiment, where a different network is applied. The average waiting time was reduced by 22%, and the in-vehicle time was reduced by 13%. Associated, the total travel time for passengers reduced by 18% compared to the TFS. Nevertheless, the achieved improvement of the best solution depends on the configuration of the network, the possibility of detours, and the distribution of the requests within the period.

Table 1: Average waiting, in-vehicle, and total travel time for passengers in the traditional and DRFS for the five experiments. Results are clustered by percentage of empty stops.

		TFS (min)			**DRFS (min)**		
		Waiting time	**In-vehicle time**	**Total time**	**Waiting time**	**In-vehicle time**	**Total time**
Two buses /hour	30%	28.1	27.7	55.8	20.3	20.7	40.9
	50%	28.4	27.7	56.1	20.2	19.8	40.0
	70%	28.8	27.7	56.5	18.1	19.0	37.1
	Average	**28.4**	**27.7**	**56.1**	**19.5**	**19.8**	**39.4**
	Imp. (%)				**-31%**	**-29%**	**-30%**
Three buses /hour	30%	29.1	16.5	45.6	15.9	16.9	32.8
	50%	29.4	16.5	45.9	15.7	16.6	32.4
	70%	30.5	16.5	47.0	14.7	16.4	31.0
	Average	**29.7**	**16.5**	**46.2**	**15.4**	**16.6**	**32.1**
	Imp. (%)				**-48%**	**+1%**	**-31%**
Four buses /hour	30%	28.4	15.5	44.0	12.9	15.8	28.7
	50%	29.1	15.5	44.7	12.1	15.7	27.9
	70%	29.8	15.5	45.3	11.7	15.3	27.0
	Average	**29.1**	**15.5**	**44.7**	**12.3**	**15.6**	**27.9**
	Imp. (%)				**-58%**	**+1%**	**-38%**
Unrestricted movements	30%	29.1	16.5	45.6	14.6	18.2	32.8
	50%	29.4	16.5	45.9	13.7	18.1	31.7
	70%	30.5	16.5	47.0	12.8	17.3	30.0
	Average	**29.7**	**16.5**	**46.2**	**13.7**	**17.9**	**31.5**
	Imp. (%)				**-54%**	**+8%**	**-32%**
Large network	30%	29.8	20.5	50.3	23.9	18.5	42.4
	50%	30.2	20.5	50.7	24.0	18.1	42.1
	70%	30.2	20.5	50.7	22.9	16.6	39.6
	Average	**30.1**	**20.5**	**50.6**	**23.6**	**17.8**	**41.4**
	Imp. (%)				**-22%**	**-13%**	**-18%**

Finally, increasing the percentage of empty bus stops reduced the total travel time in the DRFS for all experiments. It indicates that the demand-responsive feeder line benefits from larger variation in demand and is suitable for low-demand suburban areas during off-peak hours, when demand is scarce, and many bus stops are expected to be empty during operation.

The computation times to optimize the service for each operation period with two, three, and four buses are 92s, 56s, and 53s, respectively. This illustrates the relation between the computation time and the number of possible routes the buses can be assigned to. In these experiments, buses have on average 442, 159, and 73 possible routes, respectively. When unrestricted movements are allowed for three buses, the average computation time is 396s, with 2.149 possible routes. For the last experiment, the computational time is 459s with 1.561 possible routes per bus on average. Despite having less routes than in the previous experiment, the larger network and three times more requests increase the computation time.

4. CONCLUSIONS

In this project, a memetic algorithm is developed to optimize a demand-responsive feeder bus system (DRFS). The algorithm adjusts routes and departure times of buses according to passengers' desired time to initiate their trips. Since the DRFS operates the same number of buses as in the TFS and serves similar lines, it operates a system between the TFS and a fully flexible DRFS. When comparing travel times with a traditional feeder system, the average waiting time was reduced significantly, up to 58%, due to flexible routes and timetable in the DRFS. In contrast, the possibility to minimize in-vehicle time depends on the network's characteristics and the distribution of the requests. However, summing waiting and in-vehicle times always lead to a reduced travel time for passengers, up to 38%, compared to the traditional system. The results presented in this paper demonstrated the benefits of operating a DRFS to substitute a TFS during off-peak hours, when demand is typically low and shortcuts can be included in the routes. However, the presented DRFS could be further improved. The objective function value can be modified to optimize both the operation and the passengers' perspective, aiming to offer an efficient operation in terms of vehicle kilometers, as well.

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