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A simulation-optimization approach to solve the first and last mile of mass rapid transit via feeder services

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Abstract

This paper focuses on the design of optimal feeder bus routes aimed at serving the commuting demand of suburban areas and increasing the ridership of a mass rapid transit system. The optimization problem presents a multi-objective nature. The transit operator is interested in maximizing the number of users served with the lowest vehicle kilometres travelled (i.e., maximizing profits), whereas passengers seek a high quality of service (i.e., minimizing travel times). An Ant Colony Optimization algorithm is here implemented into an agent-based modelling environment to find the optimal set of routes connecting the service area to multiple transfer stations. The potential demand at a feeder bus stop is estimated according to accessibility indicators, derived from GIS-based demographic data. The model is applied to the case study of Catania (a medium-sized city in Italy) to enhance the accessibility of urban railway stations via public transport. The proposed methodology can be used as a decision-making tool for transport operators and public administrations to understand how to design feeder bus routes to improve the accessibility of public transport.

Keywords: Feeder-bus route design; Public transport; Ant Colony Optimization; Accessibility measures; Agent based modelling.

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1. Introduction

Sustainable mobility is one of the main challenges of our century. It implies the joint planning of land use and transport systems in order to guarantee a better accessibility to a wide range of opportunities, e.g., workplace, education, healthcare, leisure, and reduce the carbon footprint of human activities. Most cities have been witnessing the uncontrolled expansion of low-density, single-use suburban development (La Greca et al., 2011), which is, almost always, characterized by low accessibility levels. While remaining the most sustainable way to provide high transport capacity in dense urban settlements, conventional public transport (PT) shows its inefficiency in low-demand areas, where mobility needs are spatially and temporally diverse, and the need of private vehicles becomes endemic. Accessibility-oriented transport planning pays particular attention on active mobility, public transport and promotes multi-modal integration, i.e., combining of various transport modes throughout a trip from an origin to a destination. Low-demand areas would benefit from a hierarchical transit network model (i.e., “feeder-trunk” scheme) having the mass rapid transit (MRT) as “backbone” of the travellers’ trip chain and bus feeder services covering the first and last mile leg of transport. The latter can consist of fixed-route microtransit, performed by buses with a schedule known in advance, or demand-responsive flexible services (Calabrò et al., 2022), which often deploy smaller vehicles (minibuses, vans, etc.) and offer a tailored alternative to private mobility. Multimodal integration along a trunk-feeder transit corridor is crucial to expand the service coverage of PT without exceeding in operational cost (e.g., vehicle-kilometres travelled) and still guaranteeing an accessibility level competitive with that of the private automobile.

1.1. State of the art

In medium and large cities, where an MRT system operates, an effective planning and design of feeder routes can be identified as a solution to the first and last mile transport problem related to suburban and low-density zones. Kuah and Perl (1989) defined the feeder bus network design problem (FBNDP), which solution consists of a set of feeder-bus routes (and the related service frequency) able to minimize the sum of user and operator costs. Since this seminal paper, many authors have proposed analytical (Chang and Schonfeld, 1991) and heuristic (Wang, 2019) models aimed at supporting the design of feeder services, either in the network perspective (Kuan et al., 2006; Mohaymany and Gholami, 2010; Almasi et al., 2018) or in the optimal routing (Xiong et al., 2013) and scheduling (Lu et al., 2015) of such services. However, none of the previous studies adopts accessibility measures obtained, e.g., from socio-demographic and mobility datasets (Giuffrida et al., 2017).

It is well-known that FBNDP is a NP-hard, non-convex optimization problem, therefore it often requires a complex mathematical modelling and innovative solution methods, including exact (analytical) methods, heuristics and metaheuristics. The latter have acquired an ever-increasing importance in the various phases of planning, management and monitoring of transport systems. Among the different metaheuristics, Ant Colony Optimization (ACO) algorithms are particularly suitable for route optimization problems (Dorigo and Stützle, 2004), even when used in hybrid approaches together with other heuristics (Kuan et al., 2006).

Based on this premise, this paper focuses on the first and last mile problem of passenger trips, identifying the provision of feeder bus routes for mass rapid transit as main solution. This work intends to provide a methodological approach for the design of a feeder bus system in multimodal transport networks. With respect to the existing literature, the main contribution of this paper is the integration of GIS socio-demographic and transport data, accessibility measures and a tailored route optimization algorithm in a multi-agent simulation platform. The work also extends the model of Calabrò et al. (2020), with the possibility of finding the best set of bus stops to be served by multiple feeder bus lines, which are connected to different MRT stations. Moreover, this improved model allows for a more detailed spatial representation of the transport demand, which is geocoded at the single building level.

The remainder of this paper will outline the methodology (Section 2) with the details of the agent-based model (ABM) and the optimization algorithm used. Then, the model is applied to a real case study (Section 3) and results are discussed. Finally, some considerations for further research (Section 4) are provided.

2. Methodology

The optimization model is implemented in the *NetLogo* agent-based programming and modelling environment (Wilensky, 1999). The model is set up by following three steps: (i) the creation of the network graph; (ii) the estimation of the accessibility level associated to bus stops, as an indicator of the potential transport demand; (iii) the implementation of the ACO algorithm. These steps are explained in the following subsections.

2.1. Network graph

The network graph is created starting from the identification of possible bus stops and streets where the feeder service can operate. It is a directed graph, consisting of "stop-nodes" and links connecting them. Stop-nodes are characterized by an accessibility indicator, based on the potential transport demand gravitating around them and a distance-related impedance function. Given a couple of stop-nodes $i, j \in S$, the link ij is characterized by the road distance attribute L_{ij}, namely, the link length. Each feeder route $r \in R$ starts and ends in a special stop-node (terminal-node) $k \in S^*$, where R is the set of feeder routes and $S^* \in S$ is the set of the MRT stations to be served by the routes.

2.2. Transport demand and accessibility measures

In this model, it is assumed that a high percentage of ridership is directed to or come from the MRT stations (i.e., many-to-one / one-to-many demand pattern) as in peak-hours commuting trips. Therefore, the following five hypotheses are made:

- Passengers travel from a stop-node i to a stop-node j ($i \neq j$), where $i \in S^* \vee j \in S^*$.
- Each bus route is linked to exactly one rail station, i.e., a one-to-one correspondence exists between R and S^*.
- Each stop-node can be part at most of one feeder route.
- Vehicles have no passenger capacity constraints.
- Vehicles have the same commercial speed, since the travel time variability due to traffic conditions is neglected.

Moreover, the following four assumptions are related to the potential demand for the feeder service:

- The transport demand is associated to the stop-nodes, based on the circular "catchment area" of given radius d_{walk}, i.e., the assumed maximum distance users would walk.
- The transport demand depends on socio-demographic data, i.e., the number of residents and employees in the catchment area.
- The more is the walking distance from a stop-node, the lower is the users' willingness to use the feeder service.
- The more is the distance from a the nearest MRT station, the higher is the users' willingness to use the feeder service.

To express the potential transport demand of a stop-node, accessibility indicators are used. More in detail, a "gravity-based" accessibility model (Hansen, 1959) is assumed, with spatial modified Gaussian impedance functions (Kwan, 1998). Two types of accessibility, namely "active" and "passive" accessibility (Cascetta, 2009) are considered. In the present model, the active accessibility measures the potential of stop-node i to attract users whose origins are in the catchment area of i, while the passive accessibility measures the potential to attract users whose destinations are in the catchment area of i.

$$A_{act,i} = \sum_{h \in Z_i} M_h \cdot f_b(d_{i,h}) \cdot f_t(d_{k,h}) \tag{1}$$

$$A_{pas,i} = \sum_{h \in Z_i} W_h \cdot f_b(d_{i,h}) \cdot f_t(d_{k,h}) \tag{2}$$

where M_h and W_h are the number of residents and the number of employees, respectively, of the building h. We indicate with Z_i the set of traffic zones inside the catchment area of i. As regards the two impedance functions, f_b and f_t, the former takes into account the negative effect of increasing walking distance $d_{i,h}$ from the stop-node i to the building h, while the latter assumes that the attractiveness of the feeder service increases with the distance $d_{k,h}$ from the nearest MRT station (terminal). The two functions are expressed as follows:

$$f_b(d_{i,h}) = e^{\frac{{d_{i,h}}^2}{2\gamma_b^2}}, \quad if\ d_{i,h} < d_{walk} \tag{3}$$

$$f_t(d_{t,h}) = 1 - e^{\frac{(d_{t,h}-d_{walk})^2}{2\gamma_t^2}}, \text{if } d_{t,h} > d_{walk}; \quad 0, \text{otherwise} \tag{4}$$

where γ_s and γ_t are weights governing the rate of decline of the impedance functions, and d_{walk} is the maximum distance users are willing to walk. Finally, the accessibility of stop-node i is expressed as the weighted sum of active and passive accessibility:

$$A_i = w_{act} \cdot A_{act,i} + w_{pas} \cdot A_{pas,i} \tag{5}$$

where w_{act} and w_{pas} weigh the relative importance of active vs. passive accessibility.

2.3. Optimization algorithm

The problem of finding routes connecting a set of vertices of a directed graph, with the objective of maximizing (or minimizing) a given objective function is a NP-hard problem in the field of operations research, deriving from the well-known Travelling Salesman Problem (TSP). More in detail, the proposed model aims at finding the optimal set of feeder bus routes connecting the service area with a given number of MRT stations, considering that the transit operator is interested in widening the catchment area (i.e., maximizing the potential demand of the service) with the lowest vehicle kilometres travelled (i.e., minimizing costs), whereas passengers seek a high quality of service (i.e., minimizing the travel time and the detours from the shortest path). In other words, the transit agency should find a trade-off between prioritizing the service coverage and favouring the PT ridership.

The model resorts to an ACO algorithm to solve the optimization problem. ACO algorithms (Dorigo and Stützle, 2004) are inspired by the social behaviour of certain ant species and their ability to find shortest paths between their nest and a food source exploiting a communication based on pheromone trails. This process can be applied by a population of artificial (programmed) ants to find minimum cost paths jointly and iteratively, feasible with respect to a set of constraints. In fact, ACO algorithms have been proved to be effective in solving TSPs. Each link ij of the graph G has two attributes: (a) the pheromone trail τ_{ij}, encoding the long-term memory about the whole collective search process, and (b) the heuristic information η_{ij}, which represents a cost-related information known a priori. The former is updated iteration by iteration, while the latter does not change and is set equal to the ratio between the accessibility of stop-node j and the link length, $\eta_{ij} = A_j / L_{ij}$. The algorithm proposed in this paper is based on the MAX-MIN Ant System (Stützle and Hoos, 2000), involving three main differences with respect to the first versions of ACO: (i) to better exploit the best solutions found, after each iteration only the best ant is allowed to reinforce the pheromone trail; (ii) to avoid stagnation of the search the range of pheromone values is limited to an interval [τ_{min} τ_{max}]; (iii) to achieve a higher exploration of solutions at the start of the algorithm, the pheromone trails are initialized to τ_{max}. A single simulation consists in an iterative process described as follows. Before the simulation starts, the GIS data and the network graph are imported, the model parameters are initialized, the Accessibility A of stop-nodes and the Heuristic values η of links are computed, and a number N_{col} (equal to the number of terminal-nodes) of ant colonies, each one consisting of a number N_{ants} of ants, is generated on each of the terminal-nodes. At each simulation step, each ant k has to choose the next stop-node to visit. Denoting with $\mathcal{N}_i^k$ the feasible neighbourhood of ant k being at stop-node i, i.e., the set of stop-nodes linked to i and not visited yet, the probability of visiting the stop-node $j \in \mathcal{N}_i^k$ is given by the following random proportional rule:

$$p_{ij}^{k} = \frac{[\tau_{ij}(t)]^{\alpha} \cdot [\eta_{ij}]^{\beta}}{\sum_{l \in \mathcal{N}_i^k} [\tau_{il}(t)]^{\alpha} \cdot [\eta_{il}]^{\beta}} \quad \text{if } j \in \mathcal{N}_i^k \tag{6}$$

where α and β are parameters that control the relative weight of the pheromone trail τ_{ij} versus the heuristic information η_{ij} in the iterative search process. The graph exploration terminates, and the ants return to the terminal-stop through the shortest path, when one of the following conditions occurs: (i) the feasible neighbourhood $\mathcal{N}_i^k$ is empty; (ii) the travel time T_{route}^{k} exceeds the maximum travel time T_{max} (input value). When all the $N_{col} \cdot N_{ants}$ ants complete their route, the one of each colony maximizing the objective function (i.e., the "best ants") are allowed to update the pheromone trails along the links of their routes. With respect to Calabrò et al. (2020), the model was improved by considering the expected passenger travel time, using the feeder service, from a stop-node i to the terminal-stop ($t_{access,i}$) and vice-versa ($t_{egress,i}$), in relation with the corresponding travel times if using the shortest path ($t_{sp,access,i}$ and $t_{sp,egress,i}$). Specifically, every time the ants complete their routes, the accessibility A_i of the stop-nodes served by one feeder route is recomputed considering a penalty factor, as shown in the following equation:

$$A_i^{*} = A_i \cdot \sqrt{\frac{t_{sp,access,i}}{t_{access,i}} \cdot \frac{t_{sp,egress,i}}{t_{egress,i}}} \tag{7}$$

The computation of the objective function is affected by a penalty factor. Therefore, the optimization procedure is less likely to find "circuitous" routes instead of "direct" ones. Denoting with R^k the set of stop-nodes visited by ant k, the objective function (hereafter "efficiency") is expressed as follows:

$$E_k = \sum_{i \in R^k} A_i^{*} \cdot (1 - \delta); \quad \text{with } \delta = \frac{T_{route}^{k} - T_{max}}{T_{max}}, \text{ if } T_{route}^{k} > T_{max}; \quad 0 \text{ otherwise} \tag{8}$$

The term δ is an additional penalty given when the route travel time T_{route}^{k} exceeds T_{max}. To exploit the "experience" gained with the best solution found at the end of every iteration, the best ants reinforce the pheromone trail via the following rule:

$$\tau_{ij}(t+1) = (1 - \rho) \cdot \tau_{ij}(t) + \Delta\tau_{ij}^{best}(t) \quad \forall i, j \in G \tag{9}$$

$$\Delta\tau_{ij}^{best}(t) = Q \cdot \frac{E^{best}(t)}{E^{global-best}}, \text{ if } i, j \in R^{*}(t); \quad 0, \text{ otherwise} \tag{10}$$

where $\rho \in [0, 1]$ is the evaporation rate, $\Delta\tau_{ij}^{best}(t)$ is the amount of pheromone deposited only by the best ants on the links they crossed, R^{*} is the set of stop-nodes visited by the best ants, Q is the "diffusion rate" parameter, $E^{best}(t)$ is the value of the objective function of the best solution found at iteration t, while $E^{global\text{-}best}$ is the best value of E found from the simulation start.

3. Case study

This section presents the first results of the described ABM where multiple feeder lines are connected to different MRT stations, assuming that each station is served by one feeder line. The case study is Catania, a medium-sized city in Southern Italy (300k inhabitants) that has a metro line of about 9 km, which is currently under expansion (Calabrò et al., 2020) (Fig. 1). To test the updated version of the model, two case studies were chosen: the first one focuses on the metro stations "Nesima", "San Nullo" and "Cibali" (opened between 2017 and 2021), while the second one relates to the urban rail stations "Ognina" and "Picanello" (opened between 2017 and 2018). The MRT network of Catania currently does not have a feeder bus system complementing these stations. An overview of the geographic location of the stations is shown in Fig.1. Stop-nodes' location partially follows the actual position of bus stops in the service areas. However, the number and density of stop-nodes is studied appropriately based on two opposing needs: from one side, increasing the number of stops would reduce the users' walking time, from the other side, the higher the stop density, the slower the commercial speed V_{bus} of feeder buses would be, due to the extra time spent at each stop. The number of residents and of employees (at census zone level) used to compute the accessibility indicators of stop-nodes, is based on demographic data provided by the most recent database from the Italian National Institute of Statistics (2011).

Fig. 1. Location of the stations to serve.

The input parameters chosen for the case study are shown in Table 1.

Table 1. Input parameters set for the case study.

w_{act}	w_{pas}	d_{walk} (m)	γ_s	V_{bus} (km/h)	N. of ants	τ_{start}	Q	ρ	α	β
1	1	400	0.128	16.0	100	10.0	1.00	0.025	1.00	0.50

The parameters of the impedance functions (Equations 3-4) are chosen considering the suburban context of the stations under exam, thus a rapid decline of the walking accessibility with the distance from the stop. From Fig. 2 one can note that the impedance f_b is close to zero at the distance 400 m from the bus stop, which is the maximum walkable distance users are willing to cover.

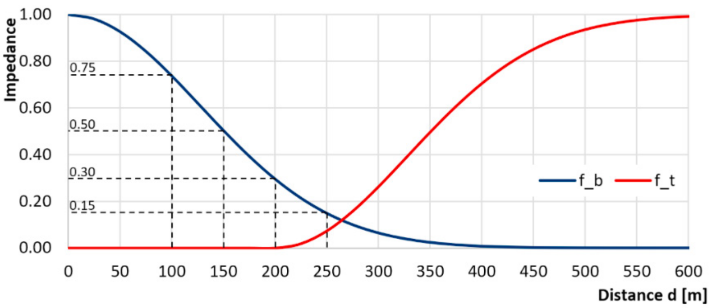

Fig. 2. Values of the impedance functions $f_b(d_{i,h})$ and $f_t(d_{i,h})$, with d_{min} = 0.2 km and $\gamma_t = \gamma_b = 0.128$.

The service area related to the three stations under exam measures 7 km^2 and includes 210 stop-nodes. Please note that not every stop-nodes have to be served by feeder bus routes, since the operator do not aim at covering the 100% of the area (it would be possible, but not cost-effective). About 41200 residents live and 11680 employees work within the study area. Fig. 3a shows the graphical output of the three optimal routes found with T_{des} equal to 30 min. Fig. 4a shows the convergence process of the objective function. In detail, the first feeder route linked to Nesima has an expected travel time (cycle time) of 29.5 min, the second route linked to San Nullo has a shorter cycle time 23.2 min, while the third route connected with Cibali station has the higher cycle time, 31.6 min. The explanation of this difference in the cycle time lies in the accessibility value of the stop-nodes. In fact, increasing too much the route coverage is detrimental for the travel time experienced by passengers, and this impact is stronger when the stop-nodes of the route have a relatively low accessibility value (e.g., few users are in their catchment area). In other words, it is better to provide a more "direct" feeder service, avoiding circuitous routes serving a sparse demand, even though this means renouncing a wider coverage. The service area of the two rail stations is smaller than the previous case: it measures 4 km^2 and includes 130 stop-nodes. Overall, 25800 residents live and 13430 employees work within the study area. The graphical output of the two optimal routes (with T_{des} = 30 min) is shown in Fig. 3b, while Fig. 4b shows the convergence process of the objective function. In detail, the first feeder route linked to Ognina station has a cycle time of 28.0 min, while the second route linked to Picanello station has a shorter cycle time 17.8 min. Also in this case, a longer route would imply more detours and higher travel times to serve a low share of additional demand. Moreover, a short route has the advantage of reducing the service headway while keeping constant the number of vehicles assigned to the feeder route.

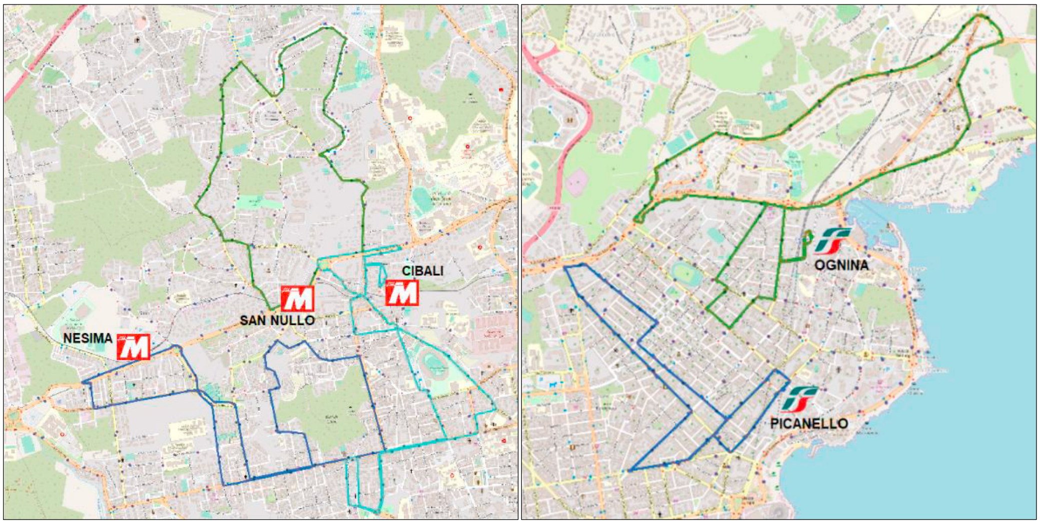

Fig. 3. (a) Feeder routes linked to the 3 metro stations (Tdes = 30 min); (b) Feeder routes linked to the 2 railway stations

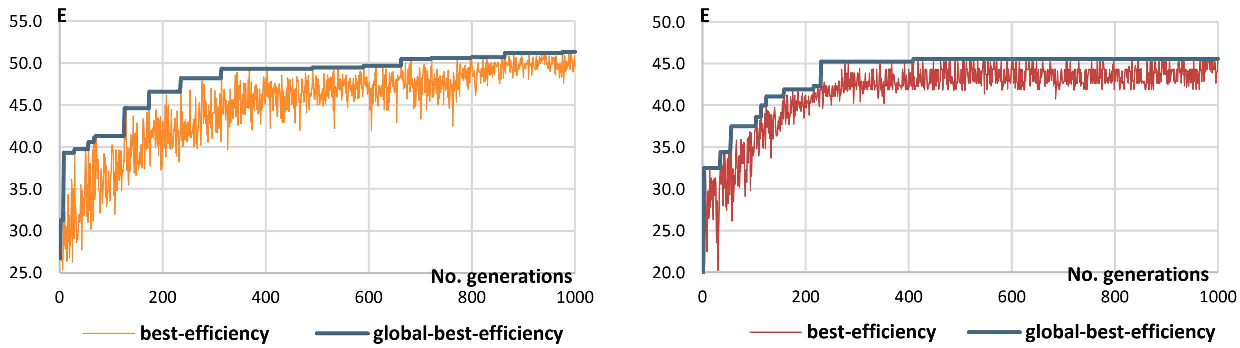

Fig. 4. Convergence process of the objective functions for (a) the first case study and (b) the second one.

4. Conclusions

This paper focused on the development of a solution model for the route optimization problem of feeder bus services, which mainly serve for the last mile leg of travellers, helping to build or reinforce a trunk-feeder scheme. An ACO algorithm has been integrated into an ABM environment to design optimal transit routes in low-demand areas, where the transport demand is biased towards MRT stations, and thus, enhancing the effectiveness of the whole transit system. The feeder route design problem with multiple stations was addressed, enabling us to find the optimal combination of routes serving different MRT stations located in Catania.

A limitation of the present model is that it is able to suggest the optimal fixed-route configuration when most of the ridership is directed to or come from a transfer station, even though this is rarely valid in mixed-use urban zones. Also, suburban areas can significantly benefit from a flexible, demand-responsive feeder service, able to vary the flexibility of route and schedule according to the period of the day. In reality, most of flexible transit services have some fixed operating schedule (Qiu et al., 2015), typically limited to departure and arrival times at checkpoints, and the uncertainty of the mobility demand in low-demand areas makes it difficult to design reliable deviation services to meet all door-to-door requests, without having a detrimental effect on passenger travel times. In fact, nowadays flexible operating policies are mostly limited to extreme low-demand areas. In this respect, the model presented can be used by public transport planners and companies as a strategic decision tool to understand which locations (e.g., potential fixed bus stops) are the most relevant to be served and which, instead, could be served only via a demand-responsive operation.

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