Integrated Passenger-Freight Transportation Model: Metro of Quito (Ecuador) as a Case Study

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Abstract. This paper explores the potential of a collaborative passenger and freight transportation system as a sustainable option for urban logistics. A novel multi-objective optimization model is proposed for packages delivery services using the capacity of a mass public passenger transport network, considering the Quito Metro (Ecuador) as a study case, in which metro stations are used to pick up and deliver packages. This would be a new efficient model for mixed distribution for last mile delivery. The model considers several objectives linked to the interests of different stakeholders: cargo transport costs, delivery times and the passenger service level. The integration of freight and passenger transportation will promote greater efficiency in the passenger transport network, reducing the number of commercial fossil fuel vehicles that circulate exclusively for freight transport within the city limits, and will improve life conditions in metropolitan areas. In this study, a mixed linear integer multi-objective programming model is proposed to represent this problem of joint transportation of passengers and packages, including some criteria and restrictions that represent real rules of operation and business. Finally, to solve the proposed model, a genetic algorithm based on the well-known NSGA-II is implemented for a real world case study of the metro of Quito for validation.

Keywords: Freight on public transport · Urban Logistics · Integrated Passenger Freight Transportation · Multi-objective optimization

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1 Introduction

While the COVID-19 crisis brought passenger traffic to a standstill, freight traffic by air, sea and truck continued to run to keep the world's economies going and to deliver vital goods. Car trips to crowded city centers and shopping malls were replaced by an explosion of online shopping and doorstep deliveries. Cargo boxes stuffed between the seats of passenger planes replaced tourists and conference attendees flying to distant lands. The crisis also caused severe disruptions in the movement of goods, and the world saw the consequences of the system's weaknesses: delays and empty shelves.

Demand for freight transportation will undoubtedly plummet in the economic aftermath of COVID-19, but the balance between passenger and freight transportation has shifted, perhaps forever [1]. The crisis is an opportunity for a mobility transformation that considers an approach that addresses both passenger and freight transport. Such an approach could channel resources into building an efficient system that also addresses the climate crisis that has already begun. In this context, this work emphasizes the urgent need for better integration of passenger and freight transportation to make our entire mobility system more resilient and sustainable.

Urban planners often consider ridership when allocating road and building space. This fact is clearly reflected in the growing interest in 'tactical urbanism' (a term coined for the action-oriented approach involving short-term, low-cost and scalable interventions in existing road infrastructure). On the one hand, cities such as Brussels or Hong Kong are creating more space for pedestrians and cyclists and prioritizing access for electric vehicles [2,3]. These changes help improve the quality of life in urban areas and make the transport system work better for people. However, such urban planning often does not include freight or urban freight transport, even though, a quarter of the world's population shops online. In the U.S., online purchases are up 44.0% in 2020 compared to 2019 [4]. That's the highest annual e-commerce growth in at least two decades. It's also nearly triple the 15.1% increase in 2019 [5].

The transportation of freight has a major impact on the economy; both large and small businesses rely on the collection and transportation of goods on a daily basis. Ecuador cities are no exception. For example, due to the topology of the city of Quito, the vast majority of goods are delivered from the south to the north and vice versa, traveling more than 70 km from their point of origin. Industrial areas are located at the extreme ends of the city, but consumption points are located in the center.

There have been some studies on the potential impact of using rail systems such as inner-city subways and trams to transport goods within urban areas. Very few of these studies are conducted in Latin America and there is no study in Ecuador. Jansen et al. [6], Ghilas et al. [7], and Li et al. [8] show how the entire freight transportation sector (manufacturers, shippers and carriers, as well as receivers) generally derives economic benefits from transporting goods by public transportation. They consistently find that public transportation agencies realise economic benefits when they make their spare transportation capacity available

to transport parcels and/or small units of goods. In addition, public agencies can benefit financially from greater sustainability of transit operations. There are also benefits in the social sphere. Less burdensome transportation operations pave the way for delivery and passenger services. This new paradigm in the Ecuadorian context implies a significant change in the current operational and theoretical approach to mobility. Another point is the need to make both public and private investments and adjustments. At a minimum, a consolidation facility and pick-up and delivery points must be made available at selected transit hubs to initiate an integration process. An acceptance model (targeting public administrations, private and public companies, actors of the transport and logistics systems in general) needs to be merged with an integrated business model that should take into account all stages of the innovation process: from concept and planning to implementation, monitoring and evaluation.

Many cities in Latin America have special geographical conditions, in the Andean region cities embedded in valleys between mountains, or on the coast cities follow the flow of a river. Many times, the main characteristic of these cities is an elongated design, longer than wide, which makes them suitable to having a main line of mass public transportation, for example, with a single metro line that allows to go quickly from the top to the bottom of the city, managing to significantly minimize costs, time and negative externalities in passengers' transportation. In other cases, establishing a single line for mass passenger may be a cheaper option for some Latin American countries, within the reach of the state budget, instead of a complex and expensive network. Examples of cities where this type of transportation system has been established in Latin America are Guayaquil (Ecuador), Quito (Ecuador), Panama City (Panama), Caracas (Venezuela), Medellín (Colombia), Santo Domingo (Dominican Republic), among others. It can be seen in Fig. 1 that a single line runs through the entire city or at least sectors of the city with high traffic congestion.

Fig. 1. Mass transit system that crosses the Metropolitan Area of several Latin-American cities

All these systems have some similarities. In Guayaquil (Ecuador) the Aerovía is a suspended aero public transportation system that connects the economic center of the metropolitan area of Guayaquil, usually overcrowded, and the neighboring industrial city of Durán with 5 km in length. The project entered into

operations in 2020 [9], allowing a safe and fast crossing, from one side of the river to the other in 15 min, as an alternative crossing to the bridge through which, to travel the same stretch, would take 40 to 60 min [10]. Panama Metro is the only Central American Metro System, inaugurated in 2014. It has 30 stations, with a total length of 37 km [11]. Medellin Metro transportation system (Colombia) began operations in 1995 with a single line 25.8 km long [12]. Santo Domingo Metro is the public road transport system, or metro, that helps the city of Santo Domingo, capital of the Dominican Republic. It is the largest metropolitan rail system in the Caribbean with a 15 km route on its line 1 [13].

The present research aims to contribute with the development of a multiobjective optimization model [14] and its corresponding solution method based on simulations and metaheuristics for the integrated passenger and urban freight transportation problem applied to a public transportation system. A mathematical model is proposed and solved using evolutionary algorithms. Due to the nature of the studied system, algorithms for the treatment of multiobjective optimization problems can be identified. It is proposed to computationally solve the model using algorithms specifically designed for this task it, validating this innovative proposal by carrying out experiments considering real instances, using the new metro of Quito as a case study.

2 Related Work

Ranieri et al. [15] explore innovative approaches to last-mile freight transportation and also look at collaborative and cooperative logistics. Cleophas et al. [16] analyze vertical and horizontal approaches to collaboration in urban transport. They classify public freight transportation as a form of vertical collaboration. Another innovative approach is the so-called underground logistics system (ULS) [17]. These underground systems, which are mostly for freight transport, can relieve urban logistics by reducing the use of road infrastructure. As a result, freight traffic does not have to interact with existing passenger traffic, and public transportation is not used. Moreover, there exist works investigating how ULS systems can be built [17].

There are several ways in which freight can share public transportation with passengers, with varying degrees of integration:

1. *Shared track*: freight is transported in a separate vehicle that only shares infrastructure with public transport vehicles. This is particularly the case for light rail, where freight is carried in separate wagons without passengers and with its own traction unit. It is necessary to ensure that freight vehicles do not interfere with the timetable of passenger vehicles. Examples of this least integrated type of shared transport can be found in Dresden, Frankfurt or Zurich [18].
2. *Shared vehicle*: freight is transported in a separate wagon (light railways) or an attached trailer (e.g. bus). People and freight share the same travel route, time and distance. Dependencies exist mainly in loading, unloading and transhipment. For examples, see Shen et al. [19] and Behiri et al. [20].

3. *Shared Wagon*: freight is transported in the same wagon or compartment as passengers. Passengers and freight do not only share the travel route, time and distance, but also the space. In particular, peak periods of transport demand for both passengers and freight must be taken into account, as the available space must be divided between the two. In addition, design and safety considerations must be taken into account [21].

Ji et al. [22] envision a multimodal passenger-and-package sharing (PPS) network for urban logistics that integrates subways, taxis, and trucks. A "hub-and-spoke" structure is designed that includes nodes at subway stations and service shops connected to the hubs. Packages are transported by subway on the backbone links between the hubs and carried by taxis or trucks between the service shops and the hubs, depending on the unit cost of these two modes and the capacity constraint of taxis. A mixed integer linear programming model for hub location problems - a combination of the multi-assignment p-hub median problem without capacity constraints and the capacitated multi-assignment p-hub covering problem - is formulated to optimize the multimodal PPS network. They propose a modified genetic algorithm (GA) to solve the large hub location problem (HLP). The HLP model consists of binary variables indicating hub locations and non-negative continuous variables indicating package flows. A modified GA considers the set of binary variables as individuals.

Romano-Alho et al. [23] introduced a concept called cargo hitching. The solution is to use spare capacity in passenger traffic. This paper contributes to the existing literature on cargo hitching in the following dimensions: a) Application of an agent-based simulation framework to systematically study the impact of cargo hitching from the perspective of travellers, carriers, and regulators. The simulation framework includes detailed modelling of mobility-on-demand services on the supply and demand side, explicitly capturing the interactions between supply and demand; b) Conduct extensive simulations to cover different freight demand allocation strategies to special vehicles using a city-wide model of Singapore in 2030 and gain insights into the potential impacts of cargo hitching. The authors used SimMobility, a high-resolution agent and activity-based simulation platform for flows of people and goods.

Zheng et al. [24] proposed a framework for integrating metro for urban logistics delivery to avoid conflicts with ground transportation and reduce delivery costs, transportation distance, and vehicle delivery times. By integrating a metro-based underground logistics system with ground-based delivery vehicles (GDVs), an optimization model for urban logistics delivery route based on a single metro line was developed to improve delivery efficiency. In the processing of this model, the total transportation cost was used as objective function, considering the capacity constraints of GDVs and a soft customer time window. In addition, the vehicle routing problem with time windows was considered.

Villa et al. [25] investigated the potential of a metro system in a large city like Madrid to offer delivery services by using existing transportation capacity

and using the metro stations to collect parcels in lockers. This would be a new mixed distribution model for last mile e-commerce delivery. To this end, the paper assesses the costs and impacts of two alternative scenarios for managing unused rolling stock space (shared trains) or dedicated enforcement services (dedicated trains) on existing routes. The external costs of the proposed scenarios are compared with the current scenario for e-commerce delivery (parcel delivery by road). This study presents the quantification of the economic, environmental and social cost analysis of a new model for e-commerce parcel delivery using the public transportation network in a large city. The study focuses on evaluating and comparing the total estimated costs for the two proposed alternatives. The results show that underground transportation of parcels could significantly reduce the costs of congestion, accidents, noise, greenhouse gas emissions, as well as air pollution.

In Sun et al. [26], a metro prototype is developed that integrates retrofitted metro stations and newly built capsule pipelines to support automated delivery from urban logistic, gateways to inner-city destinations. Based on four indicators (i.e., freight flow unit, regional accessibility, environmental cost savings, and order priority), an entropy-based fuzzy TOPSIS evaluation model is proposed to select appropriate origin/destination flows for underground freight transportation. Then, a mixed-integer programming (MIP) model with a well-tuned solution framework combining a multi-objective Particle Swarm Optimization (PSO) algorithm and the location-allocation routing (LAR) of the M-ULS network is developed. The simulations are based on Nanjing metro for validation. Results confirm that the proposed algorithm is able to make high-quality Pareto-optimal [14] LAR decisions. Moreover, the Nanjing M-ULS project demonstrates strong economic feasibility and benefits to society and the environment.

3 Mathematical Formulation

The linear scheme of the transport system is represented in Fig. 2, with the stations and travel time tt_s from the departure station for demand i, d_i to the arrival station a_i. Demands are a set of goods that suppliers send to final customers. These demands must be packed at the departure station in load units, which we denote as boxes. Once these demands are delivered by the supplier, they are temporarily stored in departure stations with a cost, until they can be shipped in a train to their destination station, where each cargo is picked up by the final customer. We assume that the demands must be transported integrally, that is, the same demand cannot be divided to be sent in different trains.

Bearing in mind the aforementioned, in order to formulate a multi-objective model for the integrated passenger and freight transport, the following expressions are derived, with model sets in Table 1, parameters in Table 2 and decision variables in Table 3:

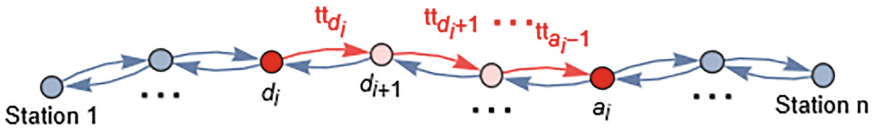

Fig. 2. Conceptual model for the integrated passenger-freight transportation of Quito Metro

Table 1. Model Sets.

Set	Description
$i : 1, ..., I$	Demands
$j : 1, ..., J$	Vehicles (Trains)
$s : 1, ..., S$	Stations
$f : 1, ..., F$	Transportation Fares

Objective functions

$$Minimize\ f_1 = \sum_{i=1}^{I}\sum_{j=1}^{J}(R_i - r_i\ x_{ijd_i}) \tag{1}$$

$$Minimize\ f_2 = \sum_{s=1}^{S}\sum_{i\in II_s}\sum_{j=1}^{J} h_j\ Q_i x_{ijs} \tag{2}$$

$$Minimize\ f_3 = \sum_{i=1}^{I} UC_1 Q_i\,(R_i - r_i\ ) + \sum_{i=1}^{I}\sum_{f=1}^{F}\sum_{j\in F_f}^{J} UC_{2j} Q_i \left(E_i - \sum_{s\in I_s} tt_s\right) \tag{3}$$

Equation (1), (2) and (3) give the three objective functions namely:

- Minimization of total time of demand permanence in the stations waiting to be loaded (1).
- Minimization of total time during the loading, unloading and transport operations of the boxes (2). It should be noted that the time required by the boxes during their movement from the train are the same regardless of the way in which the loads are assigned to the trains, therefore, only the loading or unloading time differ according to the schedule in which the loads are assigned.
- Minimization of total transport and storage cost incurred from the time the demands arrive at their departure stations until they are transported and delivered to their destination stations (3).

The aim of this multi-objective model is to determine a set of time in which the demands are loaded without violating the constraints (4) to (18). i.e., subject to

Table 2. Parameters.

Parameter	Description
r_i	Time at which the demand i is ready to be transported
d_i	Departure station for demand i
a_i	Arrival station for demand i
End_i	Time expected for the delivery of demand i
UC_1	Unitary cost involved in storing a box /
	unit of time in a station ($ /box/unit of time)
$UC_{2,j}$	Unitary cost involved in send a box on train j ($ /box)
F_f	Set of trains in which the f fare is applied
l_j	Train j's departure time from the station 1
SC_s	Storage capacity at station s
tt_s	Travel time from station s to the next one
I_s	Set of demands needing to pass by station s on their way
II_s	Set of demands departing from or arriving at station s
D_i	Set of demands departing from the same station as demand i
	and ready for departure earlier than i: $D_i = \{\ k\ / r_k \leq r_i \& \ d_k = d_i\}$
Vol_i	Volume of demand i
We_i	Weight of demand i
CVB	Boxes volume capacity
CWB	Boxes weight capacity
Q_i	Number of boxes containing demand i
cap_j	Boxes transport capacity of train j
W_{max}	Maximum waiting time of trains at any station s
W_{min}	Minimum waiting time of trains at any station s
h_j	Time needed for handling (loading/unloading) a single box at train j
M	Big positive real number

$$\sum_{j=1}^{J} x_{i,j,d_i} = 1, \quad i = 1,\ 2, \ldots,\ I \tag{4}$$

Constraint (4) assures that each demand is loaded onto a single train exactly once.

$$x_{i,j,s} - x_{i,j,s+1} = 0, \quad \forall\ s \in [d_i, a_j - 1], i = 1,\ 2, \ldots,\ I \tag{5}$$

Constraint (5) enforces that the demand, once a train is assigned, goes through all stations from its departure station to its arrival station.

$$\sum_{i \in I_s}^{J} x_{i,j,s}\ Q_i \leq cap_j, \quad j = 1, \ldots, J,\ s = 1, \ldots, S \tag{6}$$

Constraint (6) forces the transport capacity of each train.

$$x_{i,j,d_i}\ r_i \leq\ l_j + \sum_{s=1}^{d_i - 1} \left(C_{j,s} + tt_s\right), \quad i = 1, \ldots, I,\ j = 1, \ldots, J \tag{7}$$

Table 3. Decision variables.

Variable	Description
$x_{i,j,s}$	1 if demand i is in train j at station s, 0 otherwise
$y_{k,i}$	1 if $k \in D_i$ and k is not yet loaded when i becomes ready for departure
$C_{j,s}$	Waiting time of train j at station s
R_i	Time at which demand i is loaded (at station d_i)
E_i	Time at which demand i arrives at its destination station (at station a_i)

Constraint (7) assures the arrival time of demands, so that a demand can only be assigned to a train that arrives later than the demand's departure station.

$$C_{j,s} \geq W_{min}, \quad j = 1, \ldots, J, \ s = 1, \ldots, S \tag{8}$$

$$C_{j,s} \leq W_{max}, \quad j = 1, \ldots, J, \ s = 1, \ldots, S \tag{9}$$

Constraints (8) and (9) ensure that the minimum and maximum waiting times are satisfied at each station.

$$C_{j,s} \geq \sum_{i \in II_s} h_j \ x_{i,j,s} \ Q_i, \quad j = 1, \ldots, J, \ s = 1, \ldots, S \tag{10}$$

Constraint (10) determines the feasibility of the waiting time of each train at each station.

$$Q_i = Max \left\{ \left\lceil \frac{Vol_i}{CVB} \right\rceil, \left\lceil \frac{We_i}{CWB} \right\rceil \right\} i = 1, \ldots, I \tag{11}$$

Equation (11) is designed to represent the number of boxes needed to pack each demand.

$$R_i \geq l_j + \sum_{s=1}^{d_i - 1} (C_{j,s} + tt_s) - M(1 - x_{i,j,d_i}), \quad i = 1, \ldots, I, \ j = 1, \ldots, J \tag{12}$$

Constraint (12) determines the earliest time at which each demand is loaded into a train.

$$R_k \leq r_i + M \ y_{k,i}, \ k \in D_i, \ i = 1, \ldots, I \tag{13}$$

Constraint (13) forces the consistency of the definition of binary variables y.

$$\sum_{k \in D_i}^{J} y_{k,i} \ Q_k \leq SC_{d_i} - Q_i, \ i = 1, \ldots, I \tag{14}$$

Constraint (14) forces the storage capacity at each station.

$$x_{i,j,s} \in \{0, 1\}, i = 1, \ldots, I, \ j = 1, \ldots, J, \ s = 1, \ldots, S \tag{15}$$

$$C_{j,s} \geq 0, R_i \geq 0,\ j = 1, \ldots, J,\ s = 1, \ldots, S \tag{16}$$

$$R_i \geq 0, i = 1, \ldots, I \tag{17}$$

$$y_{ki} \in \{0, 1\},\ k \in\ D_i, i = 1, \ldots, I \tag{18}$$

The last block of constraints (15) to (18) define the binary decision variables $x_{i,j,s}$ and $y_{k,i}$ in addition to the no negative real variables R_i and $C_{j,s}$.

4 Case Study

The Metro of Quito city, capital of Ecuador, will be the underground public transport network of the city. The system's first line, which will include 15 stations, extends from Quitumbe (south of the city) to El Labrador (north of the city) with a length of 22.6 km (see Fig. 3). Its operation is expected to start in December 2022, according to its promoters. It will allow to cross almost the entire city in 33 min, a section that normally takes between 90 to 120 min through the current congested roads of the city [27].

Fig. 3. Metro of Quito line

The presented model for integrated passenger and freight transport is applicable in environments such as the Metro of Quito transport system, whose first Metro Line is based on a linear system of mass transportation, with stations where merchandise may be loaded and unloaded. In this type of transport system, trains may be thought as doing a circular route, i.e. they start from station 1 (Quitumbre), go through all the stations located on the line, arriving at station 15 (El Labrador) and returning back to station 1 in the opposite direction using a parallel line.

The studied model represents this situation and considers simultaneously several objective functions, each of them representing the interests of different stakeholders: cargo owners, customers, passengers, and government. Several constraints that reflect possible real situations may also be considered: system operation rules and business conditions for load management.

The following Schedule Table (see Table 4) reflects the behavior assumed for the operation of the Quito metro. Table 4 presents an unique *ID*, with the corresponding *Station name*. The table also presents the *Station stay at regular time*, and the *Station stay at rush hour*, both of this waits inside the station are for the loading and unloading of merchandise or passengers, (times are defined in minutes) and finally the *Schedule Table* indicates a *Traveling time to the next station* (also in minutes).

Table 4. Schedule Table.

ID	Station name	Station stay at regular time	Station stay at rush hour	Traveling time to next station
1	QUITUMBRE	4 min	2 min	3 min
2	MORáN VALVERDE	4 min	2 min	4 min
3	SOLANDA	3 min	1 min	4 min
4	CARDENAL DE LA TORRE	3 min	1 min	3 min
5	EL RECREO	3 min	1 min	3 min
6	LA MAGDALENA	3 min	1 min	3 min
7	SAN FRANCISCO	4 min	2 min	4 min
8	LA ALAMEDA	4 min	2 min	3 min
9	EL EJIDO	3 min	1 min	4 min
10	UNIVERSIDAD CENTRAL	3 min	1 min	4 min
11	LA PRADERA	3 min	1 min	3 min
12	LA CAROLINA	3 min	1 min	3 min
13	IÑAQUITO	4 min	2 min	3 min
14	JIPIJAPA	4 min	2 min	4 min
15	EL LABRADOR	4 min	2 min	-

Since the route is circular in this approach, the next station of station S_n will be the station S_{n+1} (n = 1,...,14). In the last station (El labrador) where the metro begins the returning path until the metro reaches the initial station (Quitumbre), the real next station of S_n would be S_{n-1}, but the traveling time will be assumed the same in both directions.

Table 5 presents the demand used as a didactic example. This demand is conformed by an Source Station that indicates in which station the interested party deposits his shipment (demand), a Destination Station, which represents where the shipment will be received, the number of boxes to be sent using box as unit of measure, the Time of arrival of the shipment at the source station (in minutes), which indicates at what time interval this demand was deposited at the station of origin and a desired deadline, all in minutes, indicating until what time the shipment should be received.

Table 5. Demand Table.

ID	Source Station	Destination Station	Number of Boxes	Time of arrival at the station	Desired cut-off time
1	4	8	6	604	843
2	1	6	3	840	958
3	3	8	5	592	922
4	4	7	6	520	1027
5	2	7	3	772	1005
6	1	7	6	506	1257
7	2	12	1	692	740
8	4	11	5	799	973
9	1	10	6	591	1257
10	2	4	5	624	926
11	5	10	7	632	854
12	1	7	5	782	971
13	4	1	4	646	1240
14	4	11	4	605	1173
15	2	12	3	763	1313

5 Problem Statement

To solve the proposed problem, a multi-objective genetic algorithm NSGA-II (see Algorithm 5) was implemented. This well recognized evolutionary algorithm proposes a procedure to efficiently classify the individuals of a population in several non-dominated fronts and using elitist principles, the best solutions of a population have the opportunity to be chosen for the next generation using an explicit diversity preserving mechanism called Crowding distance [28].

Algorithm 5 begins reading the Schedule and the Demand Table at step 1, the population is initialized and the restrictions are checked to make sure that population P has only feasible solutions. If no feasible solution is found, a error message is printed.

After assessing individuals of population P and using genetic operator, an offspring population Q is generated and the main loop begins at step 6. The parent and offspring population are combined in R which is sorted lexicographically according to no-dominance and crowding distance. The best individuals of R are selected to generate a new evolutionary population P. Then, a new offspring population Q is generated applying genetic operators to P.

After fulfilling a stop criterion, the loop ends and the final P is returned.

6 Case Study Results

Solving the case study with this proposed NSGA-II algorithm, Table 6 presents the obtained Pareto set.

Algorithm 1. *Non-dominated Sorting Genetic Algorithm version 2 (NSGA-II)*

```
Read demand and schedule data
t=0 //Initialize generation counter
Initialize evolutionary population P_t //set of feasible candidate solutions. If no feasible solution is found, print error message.
Assess individuals of P_t
Apply genetic operators to P_t to generate Q_t
while Stopping Criterion not met do
    R_t = P_t ∪ Q_t //combine parent and offspring populations
    if an individual (solution candidate) does not meet the constraints
        Erase it
    Sort R_t lexicographically according to no-dominance and crowding distance
    Select best elements of R_t to generate a new evolutionary population P_{t+1}
    Choose offspring population Q_{t+1} by applying genetic operators to P_{t+1}
    t=t+1
return P_t
```

Table 6. Chromosomes of each individual of the Pareto set for the Case Study.

Solution 1														
4	42	14	5	5	6	25	36	15	18	17	37	8	16	36
Solution 2														
4	42	14	5	5	6	25	37	15	18	17	36	8	16	36
Solution 3														
4	42	14	5	6	6	25	36	15	18	17	37	8	16	36
Solution 4														
4	42	14	5	6	6	25	37	15	18	17	37	8	16	36

A chromosome is a representation of a solution, in this case a vector with dimension I = 15 (see Table 6) where each position of the vector corresponds to a demand (see Table 5). An element of a chromosome represents the ID of the metro (see Table 4) where the corresponding shipment should be loaded.

For didactic purposes, consider solution 1 of Table 6, where an example could be the demand with ID 5 of 3 boxes that departs from station 2, which must be loaded on the metro with ID 5 to be sent to its destination at station 7.

Table 7. Pareto front for the Metro of Quito case study.

	F_1: Time in station	F_2: Transportation time	F_3: Total cost
solution 1	106	353.4	122.548
solution 2	90	353.4	125.428
solution 3	82	381	133.504
solution 4	82	381	133.504

Table 7 presents the corresponding *Pareto front* showing the values of the three objective function for each solution of the Pareto set. First of all, it is worth noting that even though there are 4 solutions in the Pareto set, only 3 different points will be seen in the Pareto front since solutions 3 and 4 have the same values in the objective space; therefore, we will not consider solution 4 in the following analysis.

Solution 1 is clearly non-dominated since it has the lowest value of F_3 (total cost). Similarly, solution 3 (or solution 4) is non-dominated since it has the lowest F_1 (Time in station). On the other hand, solution 2 is a compromise solution having a value for F_1 (Time in station) and for F_3 (total cost) between the values for solutions 1 and 3, while F_2 (Transportation time) is not lower than solution 1 but it is better than solution 3.

In short, the analyzed Case Study has no single best solution considering simultaneously all three objective function. Four possible non-dominated solutions were found from which a decision maker can choose the one that best fit his criterion. Any solution of the Pareto set would be a good option in a pure multi-objective context.

7 Final Considerations

Performing certain logistical activities, such as moving goods within a crowded city using available capacity in underground passenger transportation networks, is an efficient approach. However, there are very few applications in Latin America and none in Ecuador. In this context, it is worth promoting sustainable urban development that benefits the environment and improves urban logistics by diverting some freight traffic to the metro network. This paper analyzes the combined passenger and freight transport with a line network configuration, as found in some mass transportation systems in Latin American cities, using as a case study the metro system in Quito, whose stations can still be converted for the subway transport of urban delivery orders.

First, a novel multi-objective optimization model is proposed that considers three objectives to evaluate the feasibility of transporting urban delivery orders that incorporate the interests of different stakeholders: a first objective related to freight owners: the total waiting time for loading at stations; a second objective related to the level of service to passengers: the cost of loading and unloading; and a final objective related to transport network managers: the total cost of transporting the entire logistics operation.

Second, the presented mathematical model is solved using the well-known NSGA-II algorithm. The implemented algorithm was executed in a reasonable time, which proves that the algorithm can be used for practical purposes in planning the loading of goods in real transportation networks. The numerical results show that the considered objectives are in conflict; therefore, the Pareto front provides the decision maker with good quality information for further analysis and final decision making.

This work has some limitations in terms of modeling and network diversity topologies, for example, we simply specify a structure in which stations are centered around a line, rather than other types of more complex configurations, such as multiple lines with interchange stations, which are common in many metro transportation systems, left as a future work. The development of a model for combined passenger and freight transportation in an underground transportation system such as the metro of Quito also needs to consider important aspects such as the ETL (extract, transform, and load) process of several databases and the business model behind. On the one hand, the ETL approach requires a data management system with records and reports to collect, organize, present, and use the logistics data collected at all levels of the system. On the other hand, the business model requires a comparison between traditional freight transportation and the model based on an integrated passenger and freight transportation system.

In addition, an analysis of several technical requirements is needed: packaging boxes for demand response, parcel lockers, sections of metro wagons conditioned to receive goods, the coordination required between shippers, logistics companies, and crowd-shipping platform providers, as well as an analysis that examines the full range of economic, legal, social, and psychological issues involved.

Finally, among other practical considerations, the impact of uncertain demand and delays in the arrival times of goods and trains at stations should be taken into account. Of course, other objective functions and constraints could also be considered to obtain a holistic model that takes into account the interests of passengers, merchants, transit operators, and city administrators.

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