Logistic Modeling of the Last Mile: Case Study Santiago, Chile

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Abstract: This research proposes a new distribution system of goods in the historical center of the city of Santiago, Chile. For the design of the urban logistic system, the methodology city logistics and last mile are used. This design incorporates to the freight transport flexible solutions that improve the efficiency of the distribution process and trade supply, minimizing the environmental impact of the atmospheric pollution (AP). The proposal was made through the data collection, the characterization of the sector and the diagnosis of the urban logistics processes. The analysis of the factors allowed to evaluate the costs of the AP negative externalities. The causes were used as design criteria for the proposals, with the aim of improving the quality of life of the city users. The physical location selection of the Cross-Docking was made through an optimization model of maximum coverage. The optimization algorithm of the nearest neighbor was proposed for vehicle routing. The analytic hierarchy process (AHP) was used to generate a ranking of the best non-polluting vehicles to be used in the zone. Finally, the results obtained allowed a 53 ton decrease in carbon dioxide in the square kilometer and reduced 1103 h of interruptions per year in the vehicular congestion of the sector.

Keywords: atmospheric pollution; city logistics; historical center; last mile; urban logistics

1. Introduction

The historical centers play an important role in cities. These spaces represent the oldest parts of a city, being these the urban nucleolus of the original planning and construction of an urban area. Today, the sectors configure with the highest demand of space in urban zones, generated by the offer of commercial, political, economic, social and cultural services. In summary, great part of the city's history, starting from the culture that originated it. The offer and demand relation among the actors that take part in the historical centers entails a rigorous coordination and planning of all their activities (public transport, merchandise, waste, information, and private transport). These different actors share a public territory of citizen law, regulated by government institutions.

According to Ranieri et al. [1] sometimes, social or economic activities of a group of people have an impact in other groups (pedestrian concentration, vehicles, trucks, and bicycles) with different

interests; the concentration of these agents generates indirect costs or negative externalities. On the other hand, authors such as [2] supported by the economic theory, state that the costs of the activities fall on individuals other than the agents that generate them. This implies that the costs generated on third parties are not compensated by those responsible for their generation; being of social interest generating mechanisms that allow achieving compensations.

For Su et al. [3] the study of agent relations corresponds to urban logistic (UL). Cities depend to a large degree on an efficient UL to guarantee their attractiveness, quality of life and economic development [4]. In the 21st century, with the objective of improving competitiveness and sustainability of urban zones; in some European metropolitan regions UL models are generated in order to have the most important cities of the region work as business units, applying elements of accident prevention and road safety [5]. The model essentially includes the movements related to the commercial activity; including goods transport, with its associated operations: delivery, collection, transfers, load, unload, points of sales, Cross-Docking (CD) and urban inverse logistic [6].

Any transformation of space in the urban renovation process takes part in the analysis of the joint actions developed by UL agents (public administration, manufacturing and service companies, real estate promoters, owner of the lands, owner of the homes and citizens). These agents have more logistic complexity in the centers of the cities due to the amount of users that demand the use of the space [7]. This characteristic of agent density is recurring in Latin and Asiatic cities, where most of the population is concentrated in mega cities [8]. Research on UL took place during the 80s and 90s in Japan and the Netherlands focusing on the optimization of vehicles routing problems (VRP), location of logistic terminals, and cooperative loading systems based advanced technological information [8].

From a sustainable perspective, UL is focused in the analysis of the environmental component (green logistic) [9], this component is included in the UL frame through the carbon footprint quantification; emitted by internal combustion engines (ICE) diesel-gasoline in the logistic operations [10]. For the first time, in the 70s in Germany, investigations about the goods flow in the urban transport were made, focusing mainly in the cooperative distribution in urban zones [8]. The cities and their main meeting points incorporate the environmental perspective to the set of UL perspectives (economic, social and urban) establishing a complete sustainability vision [11].

The logistic externalities are an important topic especially in the urban areas. The sensitivity of the citizens to the environmental problems generated by the transport sector has led the political leaders to develop long term strategies to reduce their negative externalities [1]. In this context, the negative externality that tributes to the environmental variable due to the processes caused by UL is the atmospheric pollution; product of the emissions generated by ICEs that circulate in the historical centers.

Literature Review

The model proposed in [1] specifies the costs of negative externalities, which are related directly with the variables, transport speed, and technology of motor force. The main technologies of force are ICE, hybrid and electrical.

Galván et al. [12] pose solutions oriented to UL problems in the city of Barcelona, Spain; these authors use the continuous approach method, determining the principal indicators of the demand of the system (volume and amount of orders, time and space distribution, etc.) and supplies (number and type of vehicles, service rate, etc.) to finally make an analysis based on the tail theory. Other optimization tools use extensions of the VRP model. Muñoz-Villamizar et al. [13], they used the metaheuristic multi-depot vehicle routing problem (MDVRP), together with horizontal collaboration (HC) and the use of alternative vehicles to reduce general cost, social and environmental impact in the city of Bogota, Colombia. An example of HC occurs when different companies decide to cooperate, sharing storage capacity and vehicles in order to perform final delivery to its clients. MDVRP is a NP-hard problem, therefore as the problem grows (that is to say, the number of spots that must be

serviced by the vehicles) approaches to exact solutions present calculation difficulties in order to explore the feasible region of the problem efficiently.

At present, the rapid growth and development of cities forces the optimization of the distribution processes of goods; through last mile (LM) efficient models. Researchers and the automotive industries have to develop urban logistic vehicles (ULV) of low fuel consumption and high efficiency. Authors such as Wu et al. [14] propose a design of a model for the optimization of the administration of energy efficiency and dimensioning of components ULV with plug-in fuel cell. These types of solutions along with the utilization of drones [15] aim at minimizing logistic distribution cost. For example, in Europe, the increase of diesel fuel vehicles was of 15% in the 90s until 2003 [15]. To mitigate the environmental impact and the operational cost of these diesel vehicles dimensioning of ULV with less tonnage and high energy efficiency is proposed.

The growth of cities without urban planning has generated negative atmospheric effects. Searching for solutions, authors such as Faccio et al. [16] they develop an eco-logistic model through electrical vehicles to promote deliveries in urban areas of the province of Vicenza (north of Italy). Those distributions (green deliveries) were created to fight pollution problems through sustainable logistic models, achieving savings of carbon dioxide (CO_2) emissions of 84% with respect to the same distribution made by ICE. These authors state that freight transport causes around the 25% of the total emission of CO_2.

For Gatta et al. [17] the internet purchases have direct relation with the increase of vehicular traffic; the electronic commerce generates more deliveries and in consequence more cargo vans in residential areas. According to Visser et al. [18], the increasing number of cargo vehicles in residential areas translates into environmental pollution problems. To face this problem, caused by the considerable increase on internet purchases, the authors propose to modify the vehicles and adjust of speeds to make driving more energy efficient. The options are: low fuel combustion engines, lightweight vehicles, and electric vehicles. The sustainable vehicles such as bicycles, electric, and hybrids are technological innovations that are able to reduce the negative externalities, particularly environmental pollution.

De Oliveira et al. [19] they develop a study called simulation of a urban logistic space for the distribution of goods in Belo Horizonte, Brazil. The objective of the authors is to provide UL solutions through the modeling and the mathematical simulation, providing several advantages to those who participate in the urban distribution of goods, such as; reduction of the number of trips, wait time, number of vehicles, CO_2, noise and LM costs.

Authors such as Awasthi et al. [20] designed a multi-objective model for the decision making focused in the location planning of the urban distribution centers in a diffuse environment. The investigation established the location criteria: accessibility, safety, connectivity to multimodal transport, costs, environmental impact, proximity to customers, proximity to suppliers, resource availability, compliance with the regulations of sustainable load, possibility of expansion, and quality of service. The correct location of the urban distribution centers, are feasible solutions and efficient to decrease the AP indexes restricting the entrance of large vehicles.

The investigation of Kin et al. [21] allowed to improve the management of the use of the space of the cargo trucks, to reduce the unnecessary movements during the supply of urban zones in Belgium. The synchronization model for Belgian inland transport (SYMBIT) is a model based on agents simulating grouping scenarios. The objective of the model is to measure and reduce the mileage of the set of vehicles to serve an urban area. The diagnosis identified the companies that make daily delivery trips and/or service where the load optimization is not a priority. The companies are required by contract to run specific delivery routes, regardless of the load level of the vehicles. The model established new load protocols to increase the additional capacity of the vehicles without decreasing the level of service for the regular customers of the companies. The benefit is double, the vehicles improve their load capacity and the sustainability of the zone through the reduction of the kilometers traveled on the reduction of CO_2 emissions.

In the study of Staniek and Sierpiński [22] through a routing algorithm the s-mile project for the planning and organization of the transport on UL was developed. The main objective of the authors is the creation of a platform (tool integrated system) for the traceability of the distribution processes of goods achieving as results of the platform operation the optimization of the routes reducing negative impacts in the environment, time and costs. The application S-mile is developed through the mobile devices that allow company-conveyor-client integration, identifying green and red routes. The mobile application represents a fundamental support in the dispatch route planning, boosting recognition of a sustainable logistic in the urban zones.

Authors such as Faccio et al. [23] designed a multi-objective model with traceability data in real time for solid waste collection UL in Italy. These authors integrated different technologies within its model: radiofrequency identification (RFID) [24–26], general service of packages via radio (GPRS) [27] and the global positioning system (GPS) [28] for the optimization of the routes of the collection trucks. In its operation, the technologic application recognizes the volume of the containers and specify according to the established criteria, the route that a collecting vehicle must follow; managing to optimize the number and load capacity, kilometers traveled and the amount of CO_2 emissions. Recently, Okude and Taniguchi [29] they developed a model VRP on a large scale highway network. This algorithm uses a hierarchical traffic network model composed of two layers according to the frequency of highway use. The algorithm is based on the taboo search and the hierarchical traffic network. In the study of Bu et al. [30] a method of preference to select optimal locations of spots to reload goods for later distribution in the city. The optimization is centered on the trucks that enter the urbanized area, where the truck can choose among at least two locations with similar distances determined by a specific whole value generated randomly by a given interval. The investigation of Leonardi et al. [31] addresses the reduction of cargo traffic and its environmental impact on London, where a stationary and office supply company replaced its diesel vans with clean vehicles (tricycles, electric vans) that operate from an urban consolidations center located in the delivery area. The results show that the total distance traveled and the CO_2 emissions by package delivered dropped by 14% and 55% respectively.

Authors such as Buhrkal et al. [32] propose an adaptive large neighborhood search algorithm to solve a waste collection vehicle routing problem with time windows in a Danish company. This algorithm is used to find routes of optimal cost for garbage trucks thus all the containers are emptied and the residues transported to disposal sites, respecting the customer's time widows and guaranteeing that the drivers have the rest time required by law. Many urban areas are experimenting an increase in the number of trucks and vans ICE/diesel-gasoline that deliver goods to retailers as well as a reduction in the use of clean vehicle delivery. The urban distribution systems are typically characterized by vendors that operate their own vehicle fleet, distributing only their products to their clients. As regularly solution methodology to this problem authors such as Thompson and Hassall [33] evaluate the benefits of a collaborative distribution network that involves vendors that share the use of vehicles and storage areas.

For this, these authors use a hypothetical urban distribution system to estimate the performance of the HC distribution system. The process used to transform independent distribution systems to collaborative networks is also presented.

For this study the main objective is to design and evaluate UL prospective scenarios through the design of a new UL model for the city of Santiago, whose purpose is the optimization of the carbon footprint through a new distribution model and an optimization model of the minimum distance traveled. The methodologies used correspond to LM to establish the area of study and city logistics (CL) for the diagnosis and determination of the main factors that influence the UL model of the city. The purpose of this model is to improve the quality of life of the customers and to establish sustainable alternatives to decrease the emissions generated by ICE that participate in the UL processes.

2. Data and Research Methods

2.1. Research Framework

The methodology is based on the most significant works in CL [34] and LM proposed by the Massachusetts Institute of Technology (MIT) square mile project [35–39]. MIT Center for Transportation and Logistics creates the LM methodology as a UL atlas in mega cities focusing on the relevant data collection in the logistic processes in the urban zones. The objective of the methodology is to observe and measure the dynamics of the logistic processes and make a UL analysis. The methodology has been implemented successfully in the Latin American cities of Bogota [40,41], Sao Paulo [42,43], and Rio de Janeiro [11,44].

On the other hand, the CL methodology designs a systematic procedure to analyze the goods transport problems and establishes a procedure to present solutions. The stages of the methodology are: (1) problem description, (2) data collection, (3) definition of alternatives, (4) model approach, and (5) selection and review. Recent case studies on CL establish different objectives to improve functioning of logistics in cities: collaborative strategies for goods delivery [45], zero emission CL and electromobility [46], low-carbon distribution network [47], transportation system with mixed passengers and goods [48], location selection of CL centers [49] and on-demand rapid transit system [50]. All of these case studies provide solutions by means of CL, principally with the use of discrete optimization to establish feasible solutions.

The delivery vehicles in big cities for the LM are the following: bicycles, electric vehicles, tricycles, small diesel vehicles and electric bicycles.

The methodology of this investigation is constituted in four stages: (1) characterization of the square kilometer (km^2) based on the LM methodology, (2) diagnosis of the determinant factors, (3) prospective scenarios techniques developed by CL and (4) analysis of results. Section 2.2 describes in detail the development of each of the stages and sub-stages that make up Figure 1.
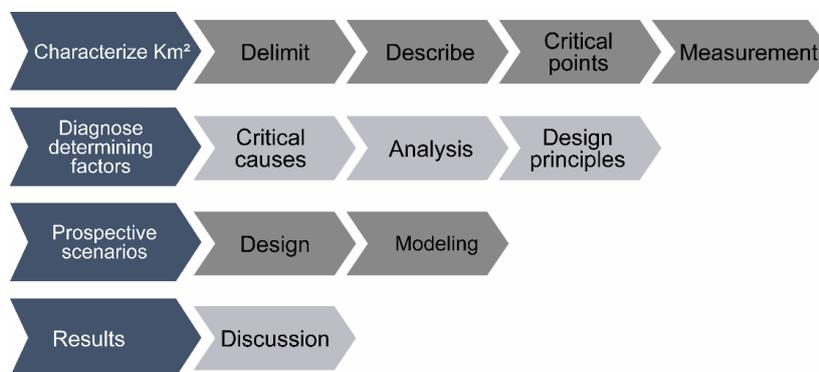

Figure 1. Stages and sub-stages of the methodological structure.

2.2. Methods and Data

2.2.1. Characterization of the Square Kilometer

The characterization process breaks up into four sub stages that must be developed in a systematical way: delimit, describe, and determine critical spots and measurement.

1. Delimitation of the km^2: it is important to collect historical background of the zone to understand its functioning. In second place, the factors that give value to the place must be recognized in order to determine the importance of counting with sustainable UL in the historical center of the city.

2. Description of the km^2: the demand of the agents is studied, in order to specify the resources that comply with the needs that they demand of the UL of the zone, such as: avenues and their

orientation, exclusive public transportation lanes, pedestrian ways, bike paths, and loading and unloading zones.

3. Critical spots of the km^2: with the delimitation of the square kilometer and its respective description, the logistic needs of the zone are analyzed, for this, the spots of the sector that have the greatest levels of user and vehicle concentration are determined. With the aforementioned, the critical logistics spots will be selected, and these will be the strategic locations for the gathering of information in the field.

4. Measurement of the km^2: once the three previous points are accomplished, the last stage of the characterization process proceeds to be implemented, that consists on the gathering of information required by the LM methodology. The information will be used to diagnose the current situation of the UL. The variables to be measured are the following: store inventory, highways, traffic count, violations by interruption and delivery monitoring.

2.2.2. Diagnosis of Determining Factors

The information collected in the chapter of the square kilometer in the historical center allows knowing the main AP causes associated to UL. Later, the impact of the main causes in the UL process is analyzed and finally, the criteria are specified to develop the proposal (reduction of pollution) with the CL methodology.

2.2.3. Prospective Scenarios

Through the established criteria in the diagnosis chapter the different proposals are designed; focused on improvement of the UL operations of the historical center of Santiago, specifically in components that diminish the CO_2 emissions. The proposals designed are improved using the recent contributions on innovative UL strategies [51]. The modeling allows to value quantitatively the effect of the design proposed for the reduction of the atmospheric pollution. The selection of the transport systems will be through the technique of the relative weights using the methodology AHP.

2.3. Objective Function to Define the Location of the Cross-Docking

The implementation of a distribution center CD in the outskirts of the km^2 studied, is proposed. The value of the square meter was calculated over each possible location for the installation of a CD, taking Santiago center as reference, the square meter is worth 55.2 UF. The demand established itself over the amount of deliveries measured during a day in a period of two hours in each critical location (78 daily), with a homogeneous distribution over each spot. The maximum cargo to be delivered must not surpass 200 kg. the distribution center must have superior capacity than the established daily demand. The capacity is equal to 23,400 kg per day.

The coverage was done analyzing the four possible peripheral areas of the km^2 where the installation of a CD is feasible, and the places denominated critical logistic spots of the sector, which is where great part of the delivery takes place, a radius of 1000 m of coverage starting from each possible CD was taken into account, analyzing if the selected spots were able to reach the critical demand locations. The cost matrix is done through costs variables that have CD (cost of making a trip upon the distribution of products).

The objective function looks to (1) maximize demand with facilities opened in the area defined as LM. Restriction (2) ensures the assignation of a facility to each node of demand. Restriction (3) restricts the maximum number of facilities (*k*). Restriction (4) sets the maximum budget for the opening cost and the service cost for each demand node of the facility *j*. Restriction (5) defines the capacity required to cover the demand. The total demand of the clients *i* cannot surpass the capacity of the facility *j*. Additionally, to a client *i* only one facility is assigned *j* if it is within the coverage rank, the restrictions (6) and (7) define the binary variables.

Model Formulation

Max:

$$\sum_i \sum_j Di \times Yj,i \times Nj,i \tag{1}$$

Subject to:

$$Xj \geq Yj,i \ \forall i \ \forall j \tag{2}$$

$$\sum_j Xj = Kj \tag{3}$$

$$\sum_i \sum_j Yj,i \times Nj,i \times Cj,i + \sum_j Sj \times Xj \leq P \tag{4}$$

$$\sum_I Di \times Yj \leq Fj \times Xj \ \forall j \tag{5}$$

$$Xj \in \{0,1\} \ \forall j \tag{6}$$

$$Y\,j,i \in \{0,1\} \ \forall i \ \forall j \tag{7}$$

where I and i set and index of the nodes of demand, J and j set and index of potential locations for the installations, D_i is demand of the point i, F_j is capacity of an installation in the point j kg, K_j is number of installations to be open, P is budget, S_j is opening cost of each possible center, $C_{j,i}$ is transport cost, $N_{j,i}$ is the coverage radio from point j to point i (meters), X_j is binary variable, 1 if the installation opens in the node j. 0 on the contrary, $Y_{j,i}$ is binary variable $\{0,1\}$, with value 1 if installation j it opening to cover the demand of i.

3. Results and Discussions

3.1. Characterization of the Square Mile

The first three stages of the characterization process delimit, describe and determine critical locations established for the historical center of the city of Santiago. The process established the historical limits of the city of Santiago (Figure S1). The analysis of the agents of the zone allowed defining the limits of the square mile (Figure S2).

The description of the main roads, degree of congestion, interaction of agents, and the UL transport systems established the main characteristic of this mile (Figures S3–S5).

Finally, the critical points of the city correspond to the intersection points of the most congested avenues of the historical center. The six avenues, four in north-south orientation and two east-west, allow six critical intersection points.

Table 1 summarizes the information of the first three points of the characterization of the square kilometer. Column one describes the development of the model variables, column two details the stage of the process (delimit, describe, or critical locations) of the characterization of the square kilometer and column three details the number of figure/table to which the variables belong in the supplementary materials.

Table 1. Characterization of the variables.

Development of Variables in the Model	Stage of the Characterization Process	Supplementary Materials
City Specifications		
Historical city limits of 12 km². These are the following: to the north - Mapocho river, east - Santa Lucia hill, south - municipality of San Miguel and west - municipality of Estación Central.	Delimit	Figure S1
Delimitation of the km² based on the interaction and concentration of the UL agents that participate in the city. The limits are as follow: North - Rosas Avenue, south - Libertador Bernardo O'Higgins Avenue, east - Miraflores Avenue and west - Hermanos Amunategui Avenue	Delimit	Figure S2
Traffic orientation of the main avenues of the delimited areas. The Avenues and its characteristics are the main, free logistic resource available for all the agents of the city.	Describe	Table S1
Schedule with the most amount of movements. Definition of three schedules with the most agglomeration: (1) Morning rush hour-users transit to the beginning of their work day, additionally, all major business' are open (example, main retail stores open at 11am), (2) midday rush hour- with the lunch activities and (3) evening rush hour - people return home at the end of their work days. Additionally, a flow of buyers and visitors exist all throughout the day.	Describe	Table S2
Congestion scale of main avenues during the morning rush hour. Scale of colors of the congestion most to least congestion; colors, burgundy, red, orange and green.	Describe	Figure S3
Congestion scale of the main avenues during the afternoon rush hour. Scale of colors of the congestion, most to least congestion; colors, burgundy, red, orange and green.	Describe	Figure S4
Congestion scale of the main avenues during the evening rush hour. Scale of colors of the congestion,-most to least congestion; colors, burgundy, red, orange, and green.	Describe	Figure S5
Score scale according to the level of congestion of the Figures S4–S6. The lowest green color score corresponds to value 1 and it is the least quantification of transit in the area. The congestion was classified in four categories in the table.	Describe	Table S3
Level of congestion of the six main avenues from monday to friday. Considering that these days are the ones of greater use of space in the zone. The averages are obtained by avenues according to time and day.	Describe	Table S4
Store inventory in the selected area. The avenues with the most amounts of stores are: Estado, San Antonio, Mac-Iver, Huerfanos and Compañia.	Describe	Table S5
Distribution of stores per avenue in percentage.	Describe	Figure S6
Information of the roads and regulations of the main avenues of the delimited area. It could be observed that, Agustinas is a one way street with two lanes, there is no bicycle path, one lane may be used to park, and there is no public transportation lane.	Describe	Table S6
Distribution of possible critical points based on the intersection of the avenues with the highest scores from north to south, and the highest scores from east to west.	Critical locations	Figure S7
Selection of the six critical information collection points. Estado and Ahumada avenues have the same characteristics and allow diminishing the intersection in two points.	Critical locations	Table S7
Concentration of vehicles during the working day (7:30 am to 7:30 pm) in the six critical points. In total, eighteen measurements were made, with duration of 45 min each, which 18 were divided into three sub measurements of 15 min. For this study a day was considered as 12 h, thus is the time considered for most user concentration.	Critical locations	Table S8

Table 1. *Cont.*

Development of Variables in the Model	Stage of the Characterization Process	Supplementary Materials
Seconds of interruptions in the vehicular critical points per interruption source. The violation of the vehicular flow happens with stops greater than 5 s. To measure the interruptions the point that intersects the pedestrian avenues was eliminated. The interruptions were carried out in the three established schedules (AM rush hour, mid-day rush hour and evening rush hour) for each strategic point, that is, 15 measurements. The amount of interruptions was 292.	Critical locations	Table S9
Amount of agents affected by the interruptions. The 292 interruptions with time greater than 5 s affected 601 agents.	Critical locations	Table S10
Percentage distribution of the deliveries per schedule. Sampling were taken in five critical points during two hours.	Critical locations	Figure S8
Amount of deliveries per schedule. The sampling considered five critical points during two hours. In total, 78 deliveries were detected.	Critical locations	Table S11
Percentage distribution of the deliveries per amount in the five critical points of the historic center. A homogeneous distribution is presented, where the least percentage is 17 and the grater is 24%.	Critical locations	Figure S9
Amount of deliveries per critical point during the two hours of sampling. The spot that generated the most quantities of deliveries was the intersection of San Antonio with Huerfanos, with a total of 19 deliveries.	Critical locations	Table S12
Percentage distribution of the deliveries per type of vehicles. The sampling considered five critical points during two hours. It is noted that more than 80% of the deliveries are carried out by trucks or vans.	Critical locations	Figure S10
Amount of deliveries per type of vehicle. The sampling considered five critical points during two hours. Trucks obtained most of the deliveries, totaling 41.	Critical locations	Table S13
Percentage distribution of the deliveries per type of equipment. The sampling considered five critical spots during two hours; 60% of deliveries were made by a person without a shopping cart.	Critical locations	Figure S11
Amount of deliveries according to the type of logistic element used for the delivery of the goods. The "people" element considers an individual using a tray, bag, or his own hands. The sampling considered five critical spots during two hours.	Critical locations	Table S14
Table of distance frequencies between the load vehicle and the store. For example, 35 deliveries made a displacement between 2 and 51.75 m. At the same time, the table showed that two deliveries generated a displacement of over 350 m. The sampling considered five critical points during two hours.	Critical locations	Table S15
Determinants Factors		
The average of the ten most sold cars of the passenger segment in the month of february 2018, is considered.	Determinants factors	Table S16
The average of the ten most sold cars of the SUVs segment in the month of february 2018, is considered.	Determinants factors	Table S17
The average of the ten most sold cars of the commercial segment in the month of february 2018, is considered.	Determinants factors	Table S18
The average of the ten most sold cars of the pickup segment in the month of february 2018, is considered.	Determinants factors	Table S19
The average of the ten most sold truck in the month of february 2018, is considered.	Determinants factors	Table S20
The average of the ten most sold buses in the month of february 2018, is considered.	Determinants factors	Table S21
Amount of CO_2 emitted per agent during the day. The buses, trucks and pickups are the ones that generate the most amount of CO_2 in grams per kilometer.	Determinants factors	Table S22

Table 1. *Cont.*

Development of Variables in the Model	Stage of the Characterization Process	Supplementary Materials
Results		
Alternatives as non-pollutive vehicles.	Results	Table S23
Design of cycle paths in the main avenues of the historical center. Four avenues already have bike paths (Rosas, Teatinos, and Alameda north and south) nine avenues need the creation of bike paths. There cannot be a bike path in only one Avenue, thus only public transportation transits through it and it doesn't have parking zones, this Avenue is San Antonio.	Results	Table S24
Amount of CO_2 emitted in the Km^2 per cargo vehicles a month. These vehicles are the principal logistic element of goods distribution in the zone.	Results	Table S25
Decrease of time of interruptions in the km^2. Amount of hours generated by interruptions of cargo vehicles. With the elimination of these agents by means of the CD platform, a reduction by 4.6 daily hours in interruptions is determined, what sums up to 91,93 monthly hours	Results	Table S26
Communication process of agents of the delivery process. (supply chain operations)	Results	Figure S12

The three stages of the characterization process, delimit, describe and determine measures of the last mile are between (Figures S1–S10 and Tables S1–S15).

The urban map of the city center, detailed by quantity and type of stores is presented in Figure 2. The characterizations of the type of services correspond: meal, clothes, banking institutions, drugstores, laundries, glassware, hardware stores, and sports accessory stores.

Figure 2. Concentration by type of store.

3.2. Diagnosis of the Determinant Factors

According to Austruy et al. [52], AP mainly comes from human activity, among the main atmospheric pollutants: gaseous, liquid and solid compounds are found, which are cause of major concern due to its persistence in the long term and its toxicity, even at low concentrations. The potential origin sources are the following: industrial processes, motor vehicles, domestic and industrial combustions; principally solid fuels (carbon) that produces - smoke–dust-sulfur dioxide [53,54]. Their consequences in the long term are associated to global warming, being the main concern of several scientists.

The analysis of the UL factors that determine AP directly relate CO_2 as the biggest polluting gas [55]. According to [56,57] the city of Santiago in the year 2014, presented a concentration of 8,484,628 annual tons of CO_2; 80% of this gas is generated by the transport element (6,722,356 tons) the other 18% industry (1,519,714 tons) [58].

According to the information of [59], the Tables S16–S21 show the ten best sellers ICE vehicles during the month of february 2018. To determine the CO_2 emissions of each ICE vehicles that participates in the UL of the historical center of Santiago, only the emissions informed by the Ministry of Transportation and Telecommunications in the country are considered [60]; being bus and trucks the ones that generate more deliveries and therefore the CO_2 in g/km (Table S22).

According to the analysis of the collected information through the descriptive method of observation in the field and the one provided by the data bases of the most sold vehicles; the AP product of the UL was determined as the main cause of study. As determinant causes, four principals are established: interruptions (deliveries), concentration of stores (supply), roads and regulations (low availability of cycle paths, parking possibility), and type of motor (emissions of CO_2). For all the causes ICE vehicles (trucks, van, buses and motorcycles) were taken into account.

The type of motor has a direct responsibility in the volume of CO_2 emitted to the atmosphere. Table 2 shows the average flows per day and its emission in the study area. The interruption cause is defined by the deliveries in the area; the deliveries generate detections on other agents. The detection time during the delivery is associated to the distance between retailer-client. The study establishes distances over 100 m for 50% of the deliveries.

Table 2. Amount of emissions of CO_2 by ICE during a day.

Agents	Type of Transport	Average Flow per Day	(g CO_2/km)	(g CO_2/km) Per Day
Bus	Passengers	675	336.86	227,380.5
Pickup	Freight	390	187.65	73,183.5
Truck	Freight	241	280.47	67,593.27
Total		**1306**	**804.98**	**368,153.27**

The cause concentration of stores has direct relation with others (types of motor and interruptions), which increase even more AP. For this study case, the high concentration of stores requires a constant supply where the main agent is the rigid truck. The main stores that demand this type of activity corresponds to the sector: food, clothes and drugstores; items that in the sector manage their supply chain through a model of inventory of ongoing review, causing continuous requirements to guarantee the fluidity of goods through daily requirements.

The road factor and regulations have as main cause of AP the disincentive to the use of vehicles without internal combustion such as the bicycle. In the study, only four of the fourteen avenues of the square mile have specialized paths for bicycles, additionally the use of private vehicles through the installation of parking lots in the middle of the avenues is encouraged.

3.3. Prospective Scenarios

The proposals for a solution to decrease the negative externality of the AP product of the UL operations in the sector are summarized in Table 3. The proposals are designed taking into account UL innovations and the two first sub-stages of the methodological structure: (1) characterization of the square kilometer through the LM methodology and (2) diagnosis of determinant factors through the CL methodology. The main proposals are oriented to (1) modify the normative to prohibit circulation in every schedule of load and private vehicles in the historical center; reducing the amount of CO_2 emissions and the stay time, (2) design of a terminal to prepare the CD orders on the border of the zone, to consolidate all the deliveries in only one place. The LM deliveries are made through the CD distribution system to the tenants through small vehicles without ICE and (3) design of exclusive tracks

for non-motorized transport in the current spaces intended for the private transport flow and parking on the roads.

Table 3. Solution proposal for the reduction of AP negative externalities in the historic center of Santiago.

Innovation Proposals	Design Criteria
UL sustainable innovations	• Implementation of barriers for the entrance of load vehicles, specifically for trucks and vans. • Generation of restrictions for the operations of deliveries at the final reception place. • Increase in the displacement flow in the sector, improving the average speed of the agents and the goods. • Design of exclusive routes for non-motorized vehicles. • Elimination of exclusive routes for parking.
Logistic innovations based on vehicles	• Incorporation of the use of small vehicles in the sector. • Incorporation of use of non-polluting vehicles
Innovations based on proximity stations	• CD in the borders of the historical centers.
Logistic innovations based on management	• Prohibition of load vehicles in all schedules. • Elimination of the flow (load vehicles-privates).
Logistic innovations based on routing	• Implementation of exclusive ways for non-polluting vehicles.

The optimization model for the localization of the distribution center corresponds to the maximum coverage model. The model maximizes the demand inside the square kilometer through the study of different locations of the distribution center (Figure 3). The parameters used are the budget restrictions for construction and land purchase, number of distribution centers, location at less than 500 m of the historic center ratio. Figure 3 specifies possible selected locations to build the CD platform, where the processes of goods distribution will be made towards the historical center through small vehicles (blue stars). The green stars correspond to the critical points of the study where the most amounts of traffic, deliveries and interruptions are generated.

3.3.1. Cross-docking Location

The results of the optimization model indicate to point C as optimal for the CD installation. Figure 4 shows the layout of the zone of distribution center; this layout allows the operation of a rigid truck with a maximum of 10 m long in the unloading zone and five trucks in the waiting zone.

3.3.2. Analytic Hierarchy Process of The Delivery Equipment in The Last Mile

All the alternatives recognized in the bibliographic review will be evaluated through AHP, to generate a ranking of the best vehicles non-polluting in the logistic operations of the historical center of Santiago. The mentioned alternatives will be evaluated through recognized criteria as factors that generate AP (Table S23).

Goal: select the vehicle for the distribution of goods in the historical center of Santiago that generate minor impacts on AP.

Criteria:

1. Amount of CO_2 emissions: determination of the amount of g/km that each vehicle generates.
2. Dimensions: determination of the cubic use of space of each vehicle.
3. Weight: determination of the weight of each vehicle.

The analysis was made with a comparative matrix of weights among the selected alternatives. The weight of an alternative is defined:

Weight of the alternative *i* over the alternative j according to the criteria *k* = impact level *j*/impact level *i*.

i = {bicycle, electric vehicle, tricycle, small diesel vehicle, electric bicycle}
j = {bicycle, electric vehicle, tricycle, small diesel vehicle, electric bicycle}
k = {CO_2 emission, cubic, weight).

Through a model of normalization process and cross between weight criteria and alternatives, it was determined that the vehicle that generates greater reduction of factors of negative externalities is the bicycle (Table 4).
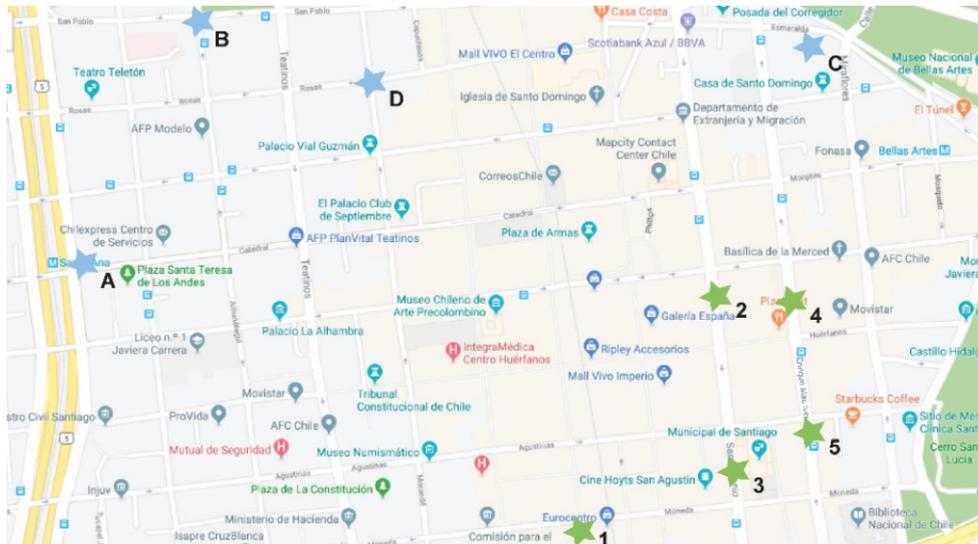
Figure 3. Possible locations for the CD distribution center.
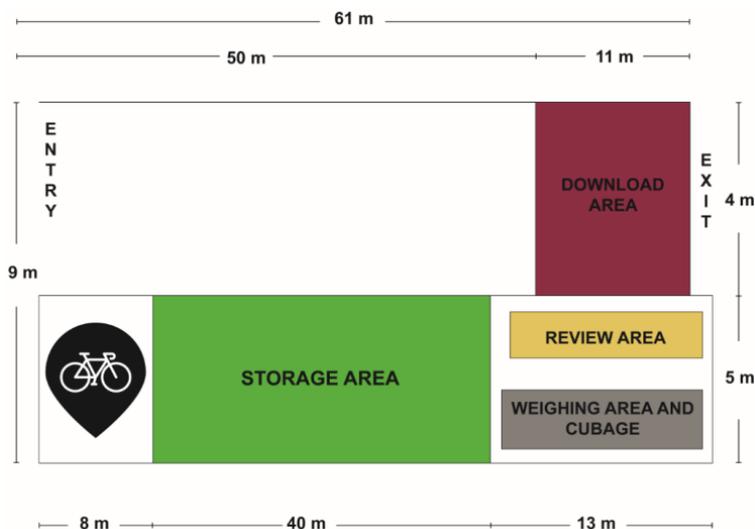
Figure 4. Layout of the proposed cross docking.

Table 4. Criterion comparison emission of CO_2 over each alternative.

i/j	Bicycle	Electric Vehicle	Tricycle	Small Diesel Vehicle	Electric Bicycle
Bicycle	1	40	1	60	20
Electric Vehicle	0.025	1	0.025	1.5	0.5
Tricycle	1	40	1	60	20
Small Diesel Vehicle	0.016	0.666	0.0166	1	0.333
Electric Bicycle	0.05	2	0.05	3	1

Finally, Table S24 shows the status of the cycle paths in the avenues of the historical center of Santiago, four avenues contain cycle paths and nine avenues require the incorporation of cycle paths.

3.4. Analysis of Results

The benefits of the model are quantified with the decrease of the CO_2 emissions and by the descend of the interruption cause, reducing the permanence time of the ICE in the distribution logistics of the sector. The CD platform restricts the entrance of ICE to the historical center (Figure 4). According to Figure S11 the 60% of deliveries were made by a person without a shopping cart. Figure S12 shows the communication process of agents of the delivery process. The Table S25 details the amount of CO_2 that is emitted monthly in the zone by the load vehicles with a reduction of almost 4.5 million (g CO_2/km).

The annual benefits for the decrease of the factors that determine the costs of negative externalities in the historical center of Santiago, correspond to: (1) 53 million (g CO_2/km) less a year, diminishing the AP of the sector and (2) 1103 h less of interruptions a year in the vehicular congestion of the sector (Table S26).

4. Conclusions

In this research the methodologies CL and LM are developed for the design of a new UL model with application to the historical center of the city of Santiago. UL must articulate the running of the city; its urban mobility plans must integrate the load transport through flexible solutions that improve the efficiency of the distribution process and supply of commerce, minimizing the environmental impact.

The proposal was made through the collection of data, characterization of the sector and definition of all the logistic processes in the area of the historical center. This information allowed to model the behavior of the distribution system to generate a logistic strategy later, it is aimed at optimization the urban transport processes.

Proceeded to diagnose the conditions of the historical center through the analysis of the factors that determine the costs of the negative externalities of AP. The causes were used as criteria of design for the proposals with the aim of improving the quality of life of the customers of the city.

The main proposals of the design are: (1) reduction of the amount of CO_2 emissions and the permanence time of the ICE, setting rules of prohibition for the circulation of vehicles in the historical center, (2) design of a CD terminal in the boundaries of the area to consolidate all the deliveries and (3) maximize the use of the bicycle as UL means of transport in LM.

The CD physical location was done through a model of optimization of maximum coverage, which determined the most suitable location to maximize the reach of this location to the spots of most delivery demand. During the operation, the products arrive from the vendors and must be distributed under the FIFO model, this with the purpose of implementing a CD operation in the distribution center; this model allows reduction of time of permanence of the products.

In order to optimize the route of the carriers (bicycle), a heuristic model of the nearest neighbor was proposed. In more specific terms, the proposed system is shaped by two models: location and routing.

The methodological proposal of this investigation permits synergy, communication and coordination of all the agents that take part in the historical center of Santiago. To support these agents, it is important to consider the appropriate design criteria for each innovation proposal. For this, as future work, the development of a mobile application is proposed, that allows communication and

coordination of all the agents involved in the zone. This app allows managing the systems through mobile devices. With the purpose of keeping each stakeholder of the goods distribution process informed of the traceability of their products. At the same time, it could report enough data to allow continuous improvements to the LM management.

Finally, six critical spots of the urban center were able to be established, the total amount of stores in the km^2 is of 1419; 4 total, bike path lanes; 8 total, lanes for vehicle parking; 15 total, lanes for public transportation; sum of 7648 total, vehicles during a working day; total sum of 6.7 h per day of interruptions; total sum of 601 agents affected by interruptions; total sum of 78 deliveries per schedule, per critical spot, per vehicle, per equipment used, and frequency of deliveries; 1459.56 g/km total daily sum of CO_2 emitted by ICE and 4,419,606 g CO_2/km only cargo vehicles a month; and total sum of 91.93 h per month of decline of cargo vehicle interruption. In general terms, the results obtained allow decreasing in 53 tons CO_2/km^2 and 1103 h of interruptions a year in the vehicular congestion sector.

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