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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Innovative tram-based methodology for Last-Mile Delivery: preliminary technical analysis of a Two-level Mixed Logistics System

TESI DI LAUREA MAGISTRALE IN
MECHANICAL ENGINEERING-INGEGNERIA MECCANICA

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Academic Year:	2021-22

Abstract

The thesis work is focused on the presentation and description of an innovative freight delivery method, which integrates the multimodal framework typical of Last-Mile Delivery with the utilization of a tram vehicle. The method proposed is called Two-Level Mixed Logistics System (2L-MLS) and involves the presence of two echelons of operations for performing freight delivery: the first level is characterized by a tram network able to connect several zones of the city, while the second one is composed by a capillary system of vehicles optimized for the transportation of freight from the tramway network to the final customers. The thesis is based on some European cases of tram applications for freight delivery and from the technical-scientific analysis of the international literature. The research addresses the advantages and main characteristics of tram systems, providing the reasons behind their utilization for the first level of the system presented. The work focuses on the first level of 2L-MLS, describing the analytical model used for the preliminary technical assessment of the adaptability of an existent tramway line. The model proposes a comparative analysis between different cities in which tramway lines are installed, considering some technical characteristics of the infrastructure and service. The methodology proposed enables to identify, among the stations of the tramway line, the ones that are most suitable for freight management activities. Within the parameters considered for the evaluation of the adaptability of the stations, the following ones are exploited: the possibility of installing secondary rails for cargo wagons, the proximity to points of interest (shopping malls, restaurants, hospitals, …) and the localization of the stations in which potentially perform freight service, in order to distribute them optimally along the line. Successively, the model proposed is applied to an Italian context to identify on one hand the predisposition of the tram cities towards the 2L-MLS implementation and on the other hand its validity and efficacy. Thanks to the utilization of data-analysis software, among which GIS (Geographical Information System) instruments, it emerges that Milan represents the best alternative, for which a detailed inspection of a specific tramway line is computed. The obtained results confirm the validity and the applicability of the model as instrument for decision-making support for the assessment of different case-studies.

Key-words: transportation planning, city logistics, public transportation, Last-Mile Delivery, tram-based freight transport, mixed logistics system.

Abstract in lingua italiana

Il lavoro di tesi presenta e descrive un metodo innovativo e di facile applicazione per la consegna delle merci, integrando la struttura multimodale caratteristica della Consegna all'Ultimo Miglio con l'utilizzo di un veicolo tramviario. Il metodo proposto è detto Sistema di Logistica Misto su 2 Livelli (2L-MLS) e richiede la presenza di due gradi operativi per la distribuzione delle merci: il primo livello è caratterizzato da una rete tramviaria capace di connettere tra loro più zone della città, mentre il secondo è composto da un sistema di mobilità capillare composto da veicoli ottimizzati per il trasporto della merce dalla rete tramviaria al destinatario. La tesi nasce dallo studio di alcune principali applicazioni europee di tram per la consegna di merci e dalla analisi della letteratura tecnico-scientifica internazionale. La ricerca tratta i vantaggi e le principali caratteristiche dei sistemi tramviari, riportando le ragioni che giustificano l'utilizzo di questi ultimi nel primo livello del sistema analizzato. Il lavoro si concentra sul primo livello, descrivendo il modello analitico utilizzato per la valutazione preliminare di adattabilità di una linea tramviaria esistente. Il modello propone una analisi comparativa tra diverse città in cui è presente una linea tramviaria, considerando successivamente alcune caratteristiche tecniche dell'infrastruttura e del servizio. Il metodo proposto permette di identificare tra le attuali stazioni della linea tramviaria, quelle che si prestano maggiormente anche ad attività di gestione delle merci. Tra i parametri considerati per la valutazione della adattabilità delle stazioni, si annoverano la possibilità di istituire binari secondari per la fermata dei tram cargo, la vicinanza rispetto a punti di interesse (centri commerciali, ristoranti, ospedali, …) e la localizzazione delle stazioni potenzialmente utilizzabili per il servizio merci, al fine di distribuirle in maniera ottimale lungo la linea. Successivamente, il modello proposto viene applicato a un contesto italiano per identificare da un lato la predisposizione delle città tramviarie al progetto di adattabilità e dall'altro la sua validità ed efficacia. Tramite l'utilizzo di software per l'analisi di dati, tra cui strumenti GIS (Geographic Information System), emerge che la città Milano rappresenta la migliore alternativa, per la quale viene effettuata una analisi di dettaglio su una specifica linea tramviaria.

I risultati ottenuti confermano la validità e l'applicabilità del modello quale strumento di supporto alle decisioni per ulteriori casi studio.

Parole chiave: pianificazione dei trasporti, logistica urbana, trasporto pubblico, Consegna all'Ultimo Miglio, trasporto merci via tram, sistema di logistica misto.

Acknowledgements - Ringraziamenti

Prima di trattare i temi affrontati nella tesi ci tengo a ringraziare tutte le persone che mi hanno accompagnato durante questo percorso, a partire dal Professor Fabio Borghetti, relatore della tesi, la cui sapiente guida ha reso possibile la stesura del lavoro. Ringrazio allo stesso modo la Dott.ssa Beatrice Bianchini, co-relatrice della tesi, che si è mostrata un valido supporto grazie alla sua competenza e disponibilità.

Successivamente ringrazio tutta la mia famiglia per il sostegno datomi senza mai chiedere niente in cambio. In particolare, ringrazio i miei genitori Mario e Maria per avermi sempre messo al centro dei loro pensieri e fornito preziosi consigli per il mio percorso di vita. Ringrazio allo stesso modo mio fratello Matteo, ingegnere aerospaziale laureatosi al Politecnico di Milano, il quale è sempre stato il mio esempio e modello, e non solo dal punto di vista formativo. Non potrò mai ringraziare abbastanza i miei nonni Tonino ed Angela, ai quali questa tesi è particolarmente dedicata, che mi hanno sempre fatto sentire una persona speciale, con l'affetto che solo i nonni sanno dare ai propri nipoti.

Ringrazio tutti i miei amici di vecchia data con cui condivido bellissimi ricordi e mi permettono di crearne di nuovi ogni giorno. Ringrazio inoltre tutti i miei colleghi conosciuti durante il percorso universitario, i quali hanno reso la vita da studente molto più leggera e spensierata, e che sono felice di poter chiamare amici.

A tutti voi, che mi avete sempre mostrato affetto e stima come studente e persona, riempiendo le mie giornate di gratitudine e orgoglio, dedico questo lavoro.

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1. Introduction

1.1 The link between pollution and mobility

The rising of the global temperature of the planet is one of the most concerning megatrends regarding the modern society, afflicting the present and the future of the world. Global warming is strictly connected to the social and economical development of the countries in the last centuries, since in the most advanced continents, the main states had to resort to carbon-based resources to strongly affirm their economical growth, emitting pollutants that are no longer sustainable for the health of the planet. Notwithstanding the emerging problem of global warming, nowadays some developing countries, are still pursuing the objective of economical growth in order to increase their financial status and tackle poverty, consequently producing an enormous quantity of pollutant in the atmosphere [1]. As a result of these actions, the global temperature is expected to rise by 7°C within the end of the century if no actions are undertaken [2]. The reported scenario would be catastrophic for the planet and could affect permanently the lives of all the living creatures of the world. Since the temperature will increase, glacial environments will eventually disappear with the consequence of increased level of the oceans that, combined with the constant increase of the temperature of the oceans, will strongly impact maritime ecosystems and could endanger some maritime creatures which are not able to withstand such warm environments. The European Commission is currently pushing towards a scenario for zero net emission of greenhouse gases within 2050. This ambitious projection is part of the "Green Deal", which is an agreement between European countries aimed at ensuring a modern, resource-efficient and competitive economy to all the members of European Union [3]. Many progresses are still to be made for reaching the final objective, due to the intensive development of carbon-based economy and abuse of fossil-fuel source of energy which contributed to a great economical and social development on one side, but with considerable drawbacks on the environment, since the pollution of the air has reached values far beyond the tolerable. That is the reason why, in the XXI century, many companies had the opportunity to shine in the market thanks to their green economies.

Transportation is currently one of the most polluting activities, responsible for over 24% of global CO_2 emissions and over 14% of annual Greenhouse Gases (GHG) emissions [4]. Hence, the rising interest of modern society in decarbonisation and green alternatives for energy production has grown exponentially and companies working in the transport sector are currently strain themselves to develop new technologies in order to meet the global climate targets for 2050. However, while for other sectors green economies and policies are pushing producers and consumers to consider environmental-friendly solutions, for the transport sector the emissions are continuously increasing due to the intensification of freight transport demand pushed not only by long-distance deliveries but also by e-commerce and Last-Mile-Delivery (LMD) based transport. Figure 1.1 depicts an in-depth analysis of CO_2 emissions in transport sector, in which it can be observed that the most pollutant vehicles are the ones based on wheel transport, not only because of the fuel by which their motor is propelled, but also because of their greater number of units with respect to vehicles moving by rail or by air.

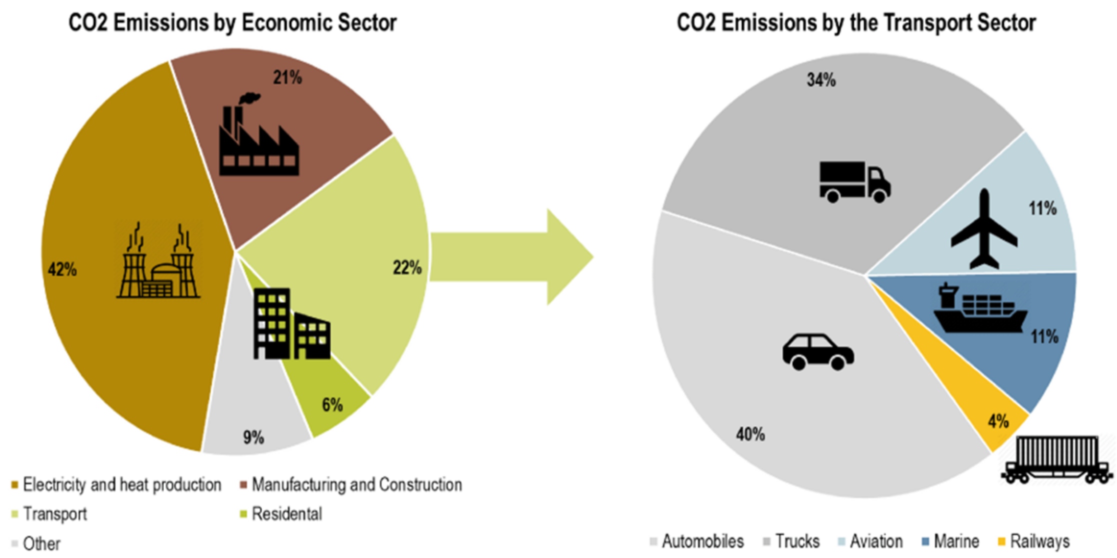


Figure 1.1: Global CO_2 emissions distribution by economic and transport sector

Source: Transportgeography.org

Based on the pollution analysis undergone in recent years, the European Commission decided to set rigid standards for transportation sector to be fulfilled within year 2050. Among the others, there is the complete ban of traditionally fuelled cars in urban areas, the reduction of 40% of pollutions derived by maritime transport and the transfer of 50% of the total freight transport over distances higher than 300 kilometres from wheels to rails and sea [5]. In order to achieve the goals defined, each country belonging to the European Union must go through radical changes in their definition of mobility. This is related to their citizens as well: nowadays, several people are struggling to intend the movement from origin to destination as an integrated multimodal activity, preferring to move by private cars instead of taking collective transport systems. This well-established conviction is difficult to eradicate, especially for elder people, making difficult for countries to follow the European guidelines.

New technologies are currently being studied to reduce the global pollution generated by vehicles, and some of them are already well-integrated in the ordinary lives of people. Electric and hybrid vehicles few decades ago were innovative concepts with little possibility to have success in the market, yet they currently are the pillars of the future mobility thanks to their high energy efficiency and low emissions. It has to be considered, though, that from the production point of view the technology still must undergo many developments, since electric energy generation continues to rely mainly on carbon and fossil fuels, far from being net-zero sources of energy. In recent years the advantages provided by the use of hydrogen as a fuel are being exploited and thus the technology is starting to spread in the market. Figure 1.2 reports the definitions of the different typologies of hydrogen used as fuel, based on their origin and modality of conversion. The main obstacle to overcome for the diffusion of hydrogen vehicles is the elevated cost of what is called "green hydrogen", which is the one obtained from the process of electrolysis, powered by renewable resources like water or wind without emission of CO_2. Electrolysis is a process which consists in obtaining pure hydrogen from the disruption of a water molecule into hydrogen and oxygen ions thanks to electricity [6]. Green hydrogen currently represents less than 1% of hydrogen produced in the world and therefore its price is still too high to allow a deep penetration in the transport market. It is stated that the cost of production of H_2 via electrolysis is 5 times higher than the conventional technologies [7]. Although the high production costs, thanks to future development of technology, researchers remain confidant about future positive development of green hydrogen technologies and its consequent reduction of price along the years, following the same trend of other renewable energy sources like solar and wind.

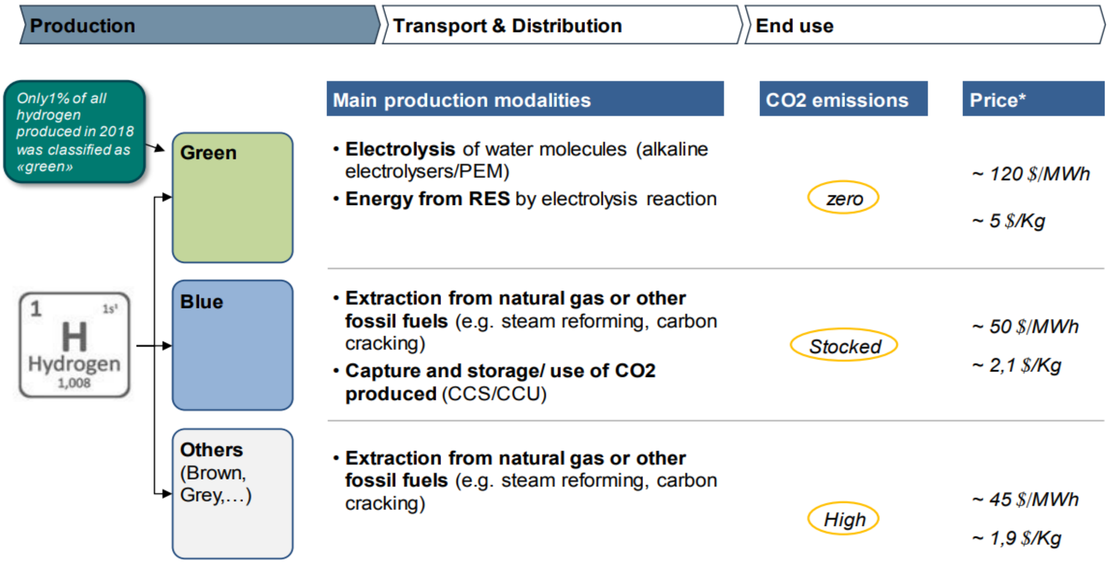


Figure 1.2: Insights on hydrogen production

Source: *course "Mobility Infrastructure and Services" provided by Politecnico di Milano, held by Mazzoncini R.*

In the modern society ruled by advanced megatrends like urbanization, smart cities and digital solutions, a growing interest in efficient methods to organize and arrange travel of people is rising towards the scientific community. Thus, the basis for new passenger-tailored systems were established revolving on the concept of placing the customers' needs under the spotlights. In this perspective, the individual is considered as a part of an intricated and widespread network, accessible via smartphone applications in any moment of the day. These connections are provided by perpetual communications between people and utilities, known also as Internet of Things (IoT), which will represent one of the pillars of smart cities, directly related to the idea of smart mobility. In fact, through IoT the customer is able to decide which means of transportation is best suited for the travel is going to accomplish, depending on the specific situation. Of course, the more advanced the technology, the more efficient needs to be the exchange of information, so it derives that the success of smart mobility cannot be possible without a proper network for the storage and exchange of data. Some issues regarding IoT still prevent it from the implementation and are related mainly to the privacy of sensible data of the users, which must be guaranteed by the network [8]. Being IoT a new instrument, also rights and regulatory frameworks concerning its operability and responsibilities are at the moment not clear enough. The process of integrated systems between users of mobility services and the acquisition of digital data is fundamental to ensure the citizens' inclusion in smart cities, which will be the cornerstone of future society. The main features of IoT are reported in Figure 1.3.

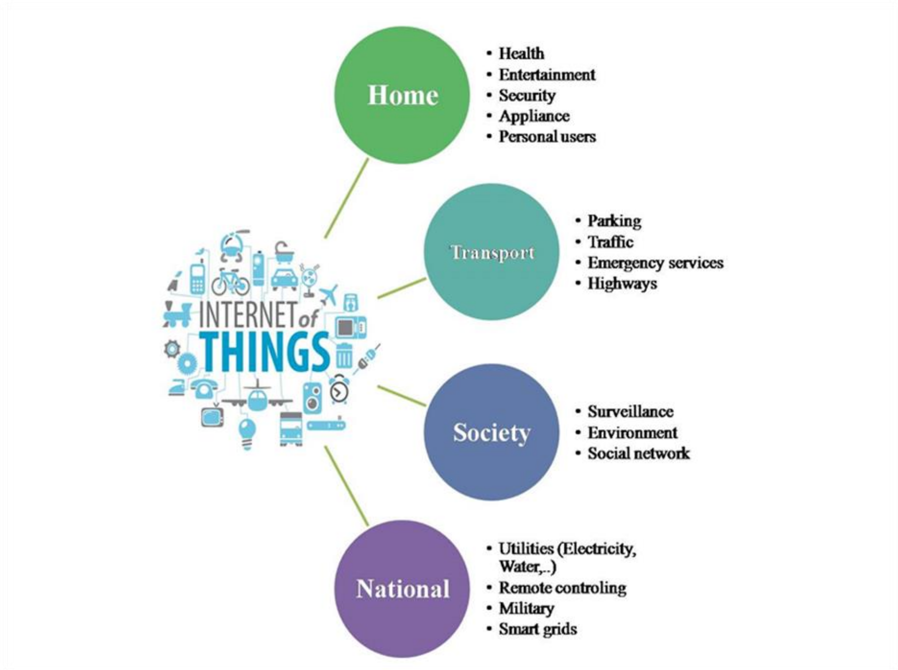


Figure 1.3: Internet of Things (IoT) framework

Source: [9]

Another trend topic for passengers' transport is the so-called Mobility-as-a-Service (MaaS). This modality combines services from different transport modes and provide customised mobility solutions through a single interface. MaaS can be offered to users based either on a monthly payment package or on a single-journey payment, similar to mobile phone services. In the northern countries of Europe, the development of MaaS has raised the interest of scholars and many applications has been successfully implemented [10]. On the other side, is not easy for MaaS to establish in the transport system market and the reason is that there are several barriers that this modality of passengers' transport needs to overcome to appeal to the most of customers. Firstly, the technology is rather new, so the knowledge about the topic is at the moment not developed enough to support a MaaS project and give it credibility in front of stakeholders. Moreover, the service is completely digital, with issues like the management and security of data to take into account, without considering that the accessibility to the platform could be difficult to people which are not familiar with online platforms. For these reasons, the cornerstone for the success of MaaS is represented by IoT, which is related to the connection between physical objects and virtual data, fundamental for the development of future smart cities. Since the transport sector is heavily regulated, national policies need to support MaaS and implement facilitative legislation. It is crucial to find the right level of regulation, whereby public interest is served, and private actors find it easy enough to participate and innovate [11]. In practice, this includes for instance changes in national tax legislations, thus inducing demand for alternative mobility solutions. The main characteristics of MaaS are resumed in Figure 1.4.

Figure 1.4: Main features of MaaS

Source: www.drivinginside.com

Although MaaS represents an interesting way of interconnecting multiple services for customers, the behaviour of people could heavily affect its successfulness. When dealing with habits of people, estimations based on surveys and queries are frequently adopted to identify their willingness and intentions. The major problem of behavioural analysis is that people can change opinion during time, making the process of estimation of the impacts of new services and infrastructures on people really complicated, considering also that in general humans are rather attached to their habits. Many people, indeed, prefer not to change vehicle during their ride from origin to destination and they generally tend to use private cars, which are pollutant and vulnerable to traffic congestion. Consequently, many people would repel the idea of using multiple services to get to their final destination. To conclude, addressing people's behaviour is one of the most difficult activities to do when implementing new transportation projects and, unluckily, it is also the most crucial one, since whichever project that has no customer to serve is doomed to failure.

1.2 Insights on freight transport: environmental impacts and modality choices

The word "mobility" is not only related to the transportation of people from origin (O) to destination (D), but also to the transportation of freight. Freight transport is an important branch of the world of mobility. It refers to all actions regarding the movement of any type of goods and represents a focal point of the supply and production chain of the products available in the market. In some cases, the transportation of raw material to be refined or final products to be delivered to retailers and shops represent the most time-consuming activity of the production process. Hence, it is fundamental to address the problem of mobility of goods in order to shorten the time needed to perform this action, considering also the high costs which are involved in the transportation operation, especially for what concerns maritime and aviation freight transport.

The transport chain of a product can be built-up as a single or multi-step process. In the first case, only one mean of transportation is needed between the supplier and the receiver, while in the second case a change of transport vector is needed to perform the delivery action [12]. In general, multi-step processes involve long-distance deliveries, but these are not the only cases. If suppliers or retailers are not well-connected to the commercial links, it is possible that more than one vehicle is needed to complete the delivery, even if the distance is short. It is straightforward that a multi-step process, requiring more than one vehicle to perform the delivery, is not only more expensive but also more pollutant with respect to single-step processes. Since the most used vehicles for long distances are cargo ships and air cargo (while for short distances diesel trucks are preferred), freight transport is a highly pollutant activity and therefore needs to be regulated. As a matter of fact, for wheel-based transport, the European Union regulates the emissions from diesel vehicles since 1991, both for Light-Duty Vehicles (LDVs) and for Heavy-Duty Vehicles (HDVs). The difference between LDVs and HDVs is the weight of the vehicles. Under 3.5 tonnes of weight, the vehicle is classified as LDV, otherwise is considered HDV. The first ones are generally used for short-distance deliveries as e-commerce or LMD, while for long-distance deliveries HDVs are often preferred. The newest HDVs are equipped with after-treatment systems such as Selective Catalytic Reduction (SCR) systems and Diesel Particulate Filters (DPFs), to reduce exhaust NOx emissions [13].

Currently, the European market share between the different means of transportation of the goods depends highly on the monetary value of the items and their weight. It can therefore be introduced a new unit of measure to sum up the two contributions, which is the value density of the goods transported. The higher this value is, the more the market share moves from rail transport to air transport, as shown in Figure 1.5. It is interesting to analyse the market share for trucks, since they seem to be the best fitting solution for medium value density goods, thanks to their reduced cost of transport (less cost of the fuel, less distance travelled), and to the possibility to move goods directly from supplier to a customer without relying on intermediate platform of exchange of vehicles (airports or stations). When the density value of the good is rather low, the best solution is to move the goods by rail. Trains are usually preferred in long-distances application with respect to air cargoes and HDVs because of their better performances in terms of environmental pollution and delivery costs. Many of the trains in service across Europe are, indeed, electric and their elevated velocities enable quicker deliveries. The main problem of railway systems is their low penetrability due to the constrained path they run over. Moreover, in situations where the railway infrastructure is not developed enough due to the morphological configuration of the territory, the issue of low penetration becomes more emphasized. For short distances, wheel-based vehicles are still the preferred ones for performing delivery actions, thanks to the penetrability of these vehicles which allows them to reach out any zone of the cities.

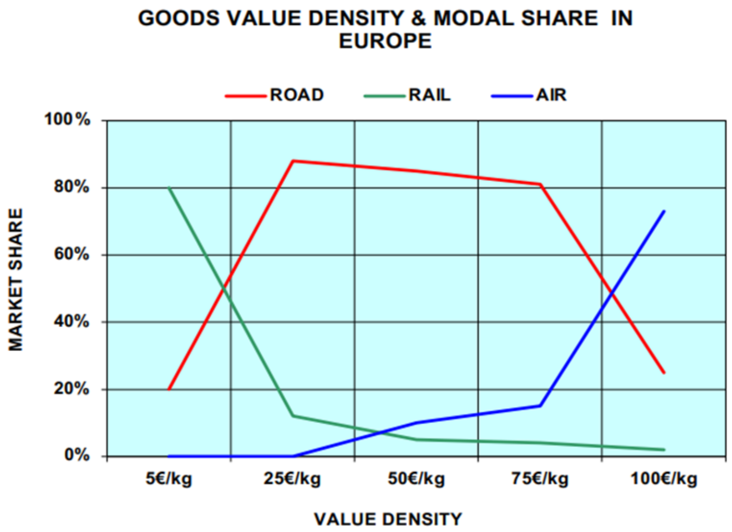


Figure 1.5: Market share distribution for freight vehicles

Source: course "Mobility Infrastructure and Services" provided by Politecnico di Milano, held by Mazzoncini R.

In a perspective of reducing the intrinsic complexity of the last section of freight transport, known as Last-Mile Delivery (LMD), the possibility of splitting the logistic service into two levels is gaining increasing consensus among scholars. The main idea is an evolution of the traditional freight distribution system towards a two-level logistics framework, topic of discussion of the thesis work. The main feature of the two-level freight distribution systems is the presence of depots located at intermediate levels to store freight and exchange them between different levels. In a single-level model, depots or Consolidation Centres (CCs) are located in the outer zones of the cities and, once the freight is ready to be delivered, they are taken to their final destinations, which could be business activities, factories and households located in inner districts of municipalities. In the two-level perspective, there is a whole set of destinations and origins to be acquainted. The origins for the first level are still the CCs, but the destinations are smaller depots located internally to the city known as Distribution Centres (DCs) or satellites. Once goods arrived at the DCs, the first level of the freight distribution system is concluded and other types of vehicles, generally smaller, more efficient and environmental-friendly, deliver the goods from the DCs (which in this moment act as origin for the second level of the delivery process), to their final destinations. Figure 1.6 provides a schematic reference for a generic two-level freight distribution system.

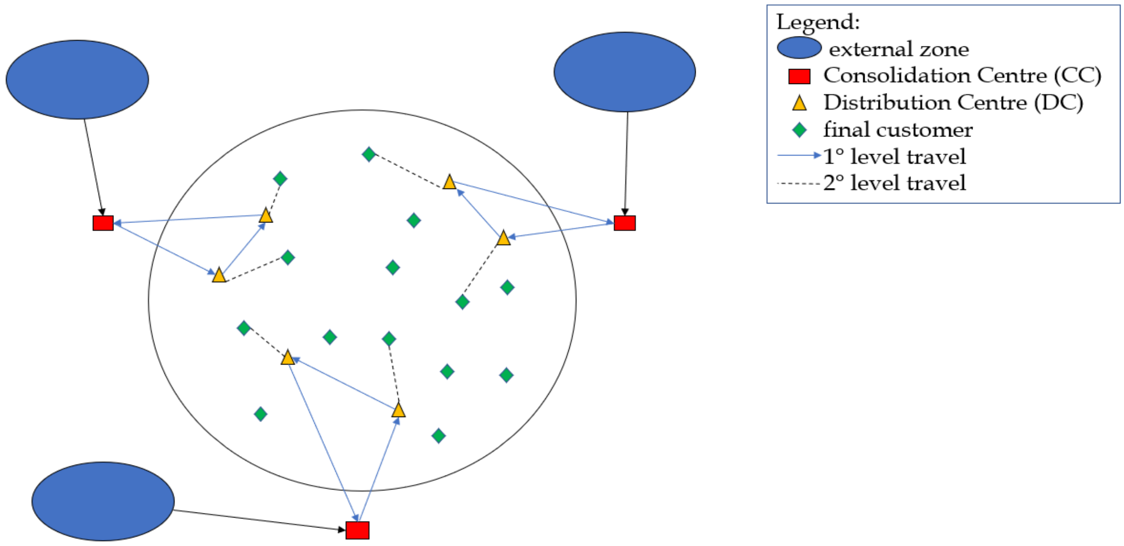


Figure 1.6: Graphical representation of a two-level freight distribution system

The idea of using Local Public Transport (LPT) vehicles to perform the 1st level travels is one of the newest trends of LMD, because it presents different advantages. For example, LPT vehicles have an outstanding capacity in terms of available space for people and, in case they will be converted partially or totally to freight service, they will serve as ideal carrier of freight for moving parcel in the inbounds of the biggest cities. Since LPT vehicles are mainly electric, they emit less pollutants with respect to LDVs and HDVs, which could also have limitations in the inner districts of the cities. Moreover, the use of LPT vehicles has minimal impact on congestion and traffic generation, since the vehicles used for moving freight are the one already performing the service, except for particular cases of dedicated vehicles only for freight movement. One of the drawbacks of using the same vehicle for passengers and freight is the creation of an adequate timetable in which fill in both the services, affecting the least the efficiency of passengers' network.

Examples of LPT vehicles that can be used are metros and trams. In order to integrate these vehicles into the logistics system, their role must be revised, converting them from a passenger-only purpose to passenger and goods operations. Some issues regarding a possible coexistence of both passenger and goods on the same network may eventually rise, such as the case of simultaneous transport of goods and people in the same cabins. For this scenario the total capacity for passenger will be inevitably reduced in order to dedicate some space for the storage on board of parcels, having a possible impact on the passengers' satisfaction of the service, especially during the peak hours of the day. Different solutions are exploited in order to avoid this occurrence, like using cargo coaches or perform freight transport operations in different times with respect to passenger service. In this way the management of people and goods would remain separated, sharing only the type of vehicles they travel by. The advantages of using metros and trams are that they move over dedicated lanes, they have a high frequency of operation, and they are electric (no CO_2 emissions). For the successful implementation of the two-level system using light-rail vehicles, also the stations need to be readjusted to the new requirements. For the stations where an exchange of goods is allowed, new facilities to drop off and pick up the goods in a simple and accessible manner must be installed.

1.3 Objective and organization of the thesis work

The thesis work aims at describing and examining the technical characteristics of a Two-level Mixed Logistics System (2L-MLS) with the objective of providing an innovative pathway for the delivery of freight throughout the use of the tram infrastructure of the city analysed. The combination of positive features of LPT vehicles and multilevel distribution systems is the key towards the implementation of a functional 2L-MLS project. As will be discussed along the course of the thesis work, trams represent one of the best alternatives in terms of LPT vehicles for performing mixed operation of passenger and freight service. The objective of the thesis work is to provide a useful instrument to decision-makers, allowing to assess whether the conditions of an existent tram line analysed are favourable for implementing the mixed logistics system. Thanks to the analysis undergone in the thesis work, readers should be able to recognize if a specific tramway line of a city is predisposed to take part in the project as first level of 2L-MLS. Thus, an operative model for the assessment is presented in terms of a preliminary technical analysis of the first level using trams. For the complete evaluation of the 2L-MLS the model presented is not enough: a similar analysis must be conducted for the second level of the delivery framework either, followed by a tailor-made Multi-Criteria Analysis (MCA) regarding different topics, from economic and political to social and environmental. The focus of the thesis work is set on the technical characteristics and performances of the tramway infrastructure as the first level of the mixed service, giving particular attention to the execution of the freight service and to its scheduling according to the passenger service, while for a similar in-depth analysis on the second level, is highly recommended to read other paper works in order to have a general knowledge about the characteristics and advantages of using different types of vehicles, like electric vans, cargo-bikes or drones. The remaining part of thesis work is organized as reported in Figure 1.7.

Chapter 2 provides an exhaustive description of the world of Last-Mile Delivery, describing its characteristics and the vehicle used, analysing also innovative solutions. Successively, the focus is set on LPT vehicles and trams in particular. Several examples of European tram applications for freight service are indeed reported, as well as the advantages of splitting the delivery services over multiple levels. Finally, some insights of MCA are reported, providing useful indications on the most important criteria to consider when dealing with infrastructure projects.

In Chapter 3 the two-level Mixed Logistics System (2L-MLS) implementation is described profoundly, dedicating particular attention on the infrastructure and modalities of the system proposed. An in-depth description about the storage facilities needed for 2L-MLS is then exploited. Successively, the model used for the preliminary technical analysis of the first level using trams is presented. The steps of the procedure are reported and debated using a top-down approach, from the definition of the city for the implementation of 2L-MLS to the selection of the time period for freight activities of the mixed delivery system.

Chapter 4 presents a case-study of application of the model, dealing with the situation of the Italian cities equipped with tramway infrastructures. From the application of model proposed to the case study is possible to define the most suitable conditions for the implementation of 2L-MLS. The outcome of the case-study analysis justifies the use of the model and certifies its validity. At the end of this chapter, all the consideration derived from the application of the model with reference to the case-study presented are noted down to evaluate its strengths and weaknesses and finally draw conclusions from the results obtained.

Chapter 5 resumes the main contents discussed in the thesis work and contains some proposal about future studies that can be undertaken from the consultation of the work presented.

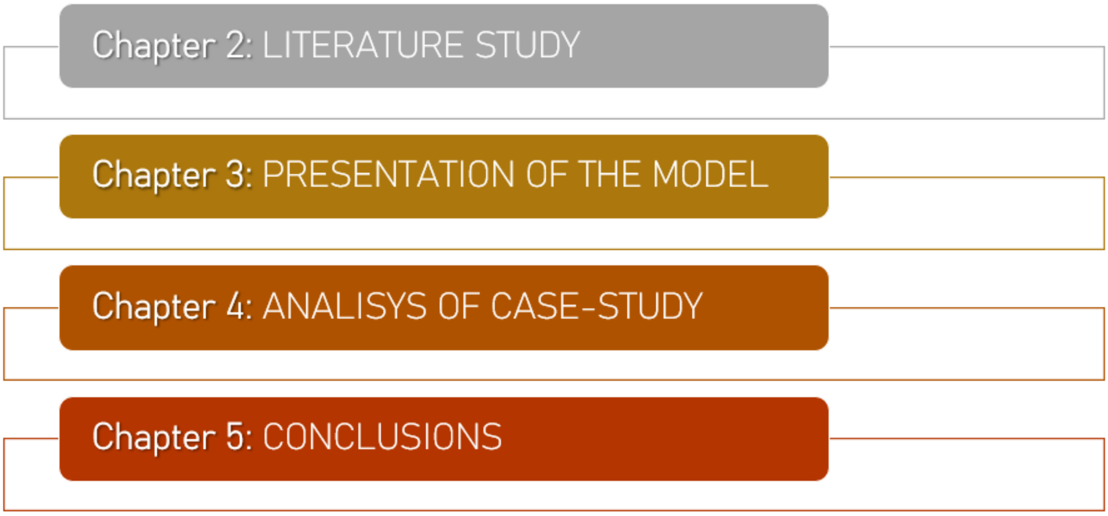


Figure 1.7: Organization of the topics dealt in the chapters of the thesis work

2. Literature study

In Chapter 2, the literature works regarding Last-Mile Delivery and freight transport combined with passengers' movement through LPT vehicles are exhaustively portrayed, together with insights of multi-levelled freight distribution systems. The main characteristics of Multi-Criteria Analysis, useful tool for the assessment of the modality of freight transport proposed by the thesis work, are also reported. The scheme presented in Figure 2.1 outlines the sequence of topics that will be discussed throughout the literature study.

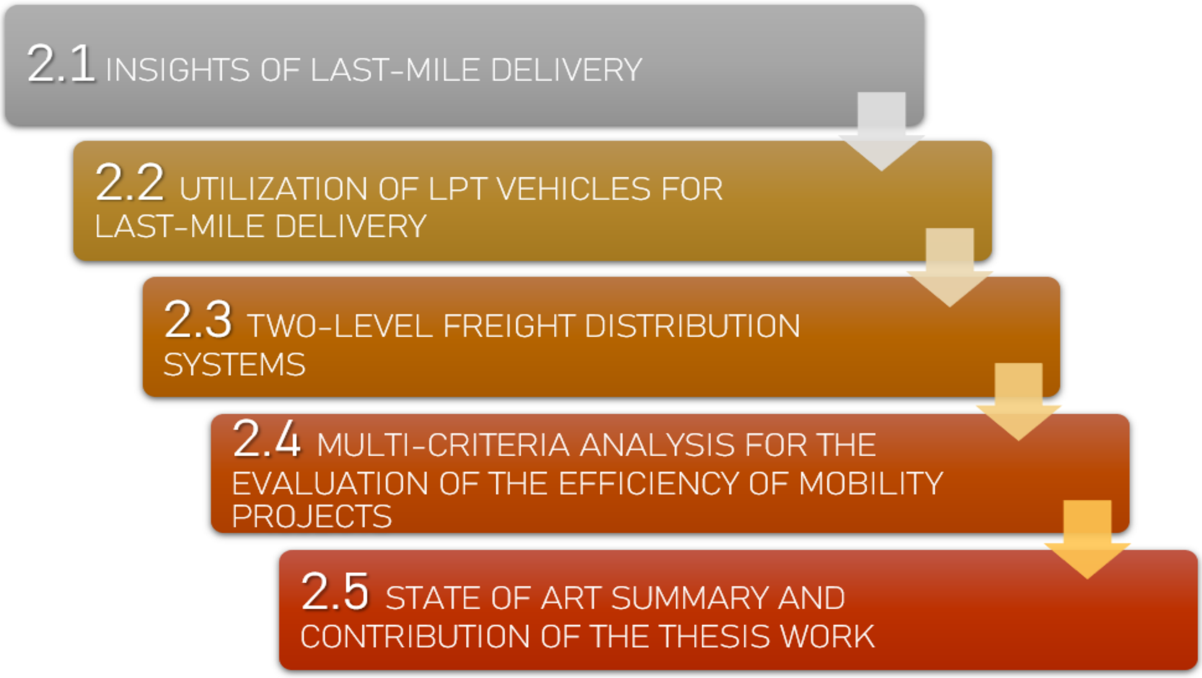


Figure 2.1: List of contents of Chapter 2

In Paragraph 2.1 the focus is set on the last section of the freight transport, define as Last-Mile Delivery (LMD). The key features of LMD are reported, together with the principal obstacles that this section of freight delivery has to overcome to complete the operations. From the analysis of the literature works about LMD, emerges the complexity of the arrangement of this delivery framework, which requires the utilization of powerful calculators for being correctly optimized. Furthermore, through the study of literature papers, the possibility of implementing new vehicles for performing LMD actions instead of using conventional ones is assessed.

Paragraph 2.2 provides a description of mixed transport systems for goods and passengers, utilized for the completion of LMD. Metros and trams are the vehicles chosen to implement the technology and several worldwide applications are described. Particular attention is dedicated to tram applications, focusing on the principal case-studies. Furthermore, other examples found in literature regarding the utilization of trams are presented, to give insight about the freight fleet composition and the topic of Reverse Logistics. To conclude, the assessment of the operations to perform for converting conventional trams into mixed transport system vehicles are outlined.

Paragraph 2.3 describes the two-level freight distribution system providing examples of literature studies aimed at identifying the optimal routes for the vehicles involved, dealing with the Two-echelon Vehicle Routing Problem (2E-VRP). 2E-VRP is a modified version of the classical Vehicle Routing Problem (VRP), which represents a particular type of logistic problems. Some methodologies used to solve the 2E-VRP are reported, even though the models used are different from case to case, depending on the simplification made by the authors and by the boundary conditions of the specific problems studied. The majority of the models for solving 2E-VRP require significant computational efforts and dedicated calculators to obtain the solution, highlighting the difficulties of implementing multilevel logistics systems.

The main topic of Paragraph 2.4 is the definition of the Multi-Criteria Analysis (MCA) technique, useful instrument for the evaluation of projects throughout a multi-input methodology. The main characteristics of MCA are described in detail, as well as the most important criteria to consider for the assessment of the projects. MCA will be a fundamental part of the implementation of the 2L-MLS proposed.

Paragraph 2.5 resumes the main topics dealt in the chapter, reporting the gaps left by the literature works regarding two-level freight distribution system, to be filled with the 2L-MLS proposed in the thesis work.

2.1 Insights of Last-Mile Delivery

Last-Mile Delivery (LMD) is an activity belonging to the last section of the freight delivery service and it represents the most expensive and one of the most pollutant segments of the supply chain of a product. LMD could be defined as the group of activities required for the physical delivery of materials to the receiver's chosen final destination, from supply side to demand side [14]. In recent years, the interest on this topic rose abundantly, strongly enhanced by the affirming role of e-commerce in the last decade, which is slowly growing as one of the most competitive and profitable markets. Being one of the most crucial sections of the supply chain of a product, LMD is highly susceptible to failures [15]. It is stated that the probability of failed first-time deliveries goes from 12% to 60% in cases no delivery window was arranged by the customer in advance. Delivery failures occurs when the customer is not at home at the time of the delivery and thus the parcel has to be taken back to the depot, causing a cost to the shipping company known as "missed-delivery cost", which includes also the time taken by the deliverer to take back the order, considered as idle time because of the incapability of providing shipping services while returning the goods to the depot. The change in the planning and operation of LMD in a more sustainable way must be supported by government policies, regulations, restrictions, regional and national integrations [16]. One of the policies is to define a green network of vehicles which perform the last section of LMD which may be electric vans or cargo bicycles. The reduction of environmental impacts can be also achieved by encouraging the use of innovative technologies and initiatives such as IoT, route optimization algorithms, smart lockers and the collaboration between couriers and logistics providers [17].

Last-Mile Delivery is a process fully integrated with the framework of urban transportation network. There are many examples of supplies distributed daily in every city around the world. One widespread instance is represented by dairy products. This type of products is generally delivered at night or early morning when the road network is free of congestion. In this way the shops have full resources when they open for the workday. Differently, supplies for which travel time does not affect their quality, or products which are not dependent on their expiry dates (unlike the cases of food and beverages), can be delivered during different times of the day. Examples are technological products, deliveries of furniture or clothes and others. An accurate analysis of the traffic flows of freight from inbound and outbound the city is necessary to properly schedule the time of the deliveries, according to the typology of product.

The distribution network created by LMD is an unavoidable section of the supply chain and yet is something that must be arranged properly to interfere the least with the traffic generated by the movement of private cars and collective means of transportations. In terms of pollution and congestion, the impact of LMD is considerable: on-demand deliveries are expected to induce a 21% rise in urban traffic congestion and contribute to a 30% rise in emissions to 25 million tonnes of CO_2 per year from LMD by 2030 [4]. Regarding the issue of pollution, new solutions are currently taking place in the transportation market, e.g., electric and hybrid vehicles instead of diesel ones for completing the deliveries, while for the congestion issue there are less chances of improvement, because the parcels need to be delivered using corridors that are already saturated by other road vehicles. The idea of scheduling the deliveries in a functional manner is a subject that suppliers have to somehow resort to, as a way of avoiding the time spent by couriers in traffic and satisfy the requirements of customers in terms of promptness and quality of the delivery service. Another important characteristic that must be considered is not only the time required for completing a delivery, but also the time needed for the driver to drop-off the parcel and hand them to the customer. For some areas, especially for the historical districts of the cities where the road infrastructure is not adequately performant for the current road vehicles and the streets are aged and narrow, the driver could be forced to leave the vehicle in a position for which cause hindrance to the flow of traffic while is completing the delivery. For these situations, more adaptive vehicles could be utilized, like motorbikes or electric bikes, however, if the number and especially the weight of the parcels is not bearable for two-wheeled vehicles, congestion problems could show up, leading to idle times in the deliveries and inefficient use of the road network.

LMD has proved to be the most intricated section of the whole supply chain, especially when talking about the inner core of the biggest cities where traffic congestion makes difficult for vans and trucks to reach their final destination rapidly [18]. Researchers struggles to identify general procedures when it comes to the scheduling of delivery routes, even though impressive steps forward were made in recent years. Nowadays, therefore, difficult problems like the Vehicle Routing Problem (VRP) or its principal derivation, i.e., the Travel Salesman Problem (TSP), can be partially solved thanks to the considerable development of computer science, which enables to perform a large number of calculations simultaneously in order to obtain a satisfying result in relatively short times. VRP and TSP both regard the implementation of optimal routes in terms of time of delivery and total cost for a fleet (VRP) or a single (TSP) vehicle performing the activity. A compromise between computation time and accuracy of the final result is the basis of any simulation process, and delivery problems are not excluded from this procedure.

An interesting topic influencing LMD researchers is the possibility to use innovative vehicles to perform the delivery. Since the market is evolving towards net-zero emission vehicles, pushed by European requirements for greener solutions and reduction of pollutants, recently many studies on this topic were published. Currently, LMD is mainly performed by diesel vans, which are not only high-emission vehicles but also rather ineffective, due to their lack of agility in deep traffic condition, thus suffering the phenomenon of heavy congestion of the roads. Moreover, their size is inadequate for operation in small city centres, campuses, or narrow streets. One way to counteract the CO_2 emissions is to use electric vans, which are also more efficient in terms of responsiveness and time delivery. However, the problem of accessibility of particular location is still an issue that needs to be overcome. For that matter, electric cargo bicycles and motorbikes are often utilized to perform LMD activities, but their limited range of operation limits their utilization and diffusion in consolidated delivery frameworks.

Amongst the innovative vehicles, drones are certainly worth a mention. Many delivery companies such as Amazon and DHL have already started to use them for parcel deliveries [19], as shown in Figure 2.2. The drones used for the deliveries are located inside the trucks' reserved space for goods, thus diminishing the total capacity of the trucks' loading. Once the trucks reach designated drop-off points, drones are released to fulfil the delivery. The advantages of using drones are the reduced time of delivery and their accessibility to any destination, as long as the minimization of CO_2 emissions, which are almost negligible. Possible drawbacks for this technology are the reduced capacity of their batteries which underlines the need for an on-ride charging infrastructure on the trucks, or at specific locations spread along the route, and possible issues concerning safety and the flight area of the drones (in certain countries drones are limited by strict rules concerning their operation and safety, especially in urban areas). Self-driving robots are also studied as solutions for LMD. In this context, self-driving robots have an advantage with respect to drones as they are designed to operate at low speed in order to share existing sidewalks and bike lanes with people. Drones, conversely, allow for unattended deliveries, which are impossible to perform in case of robots [20]. The general procedure for the utilization of autonomous robots is the following, similar to the one applied to the use of drones: the trucks load the shipments for a set of customers at a central depot where the goods to be shipped are stored; then they move into the city centre and, once a drop-off point is reached, they are loaded with shipments and launched to autonomously deliver their goods to customers [21].

Figure 2.2: DHL drone operating in China

Source: Gdoweek.it

Another innovative solution for LMD is the V-feather, an electric freight carrier composed by multiple modules of various size and type able to single-handedly manage the deliveries without the support of any other vehicle [22]. The V-Feather, reported in Figure 2.3, is a concept vehicle made of detachable modules: one voluminous cabin module is where the driver is sitting, while the other modules are detachable and arranged for handling different type of goods. Additionally, some of the modules have a refrigeration system which allows the vehicle to carry frozen food. These modules can easily be dropped off or picked up after recharging at different locations within the city. The idea of utilizing a vehicle with detachable parts has the advantage of minimizing the number missed deliveries by addressing the number of modules before the operation. Depending on the demand, the optimal number of detachable modules can be calculated, increasing the efficiency of the delivery activity. V-Feather vehicles are still concept vehicles and are intended to have considerable market penetration within 2030, but for now no further information are available about their composition and utilisation.

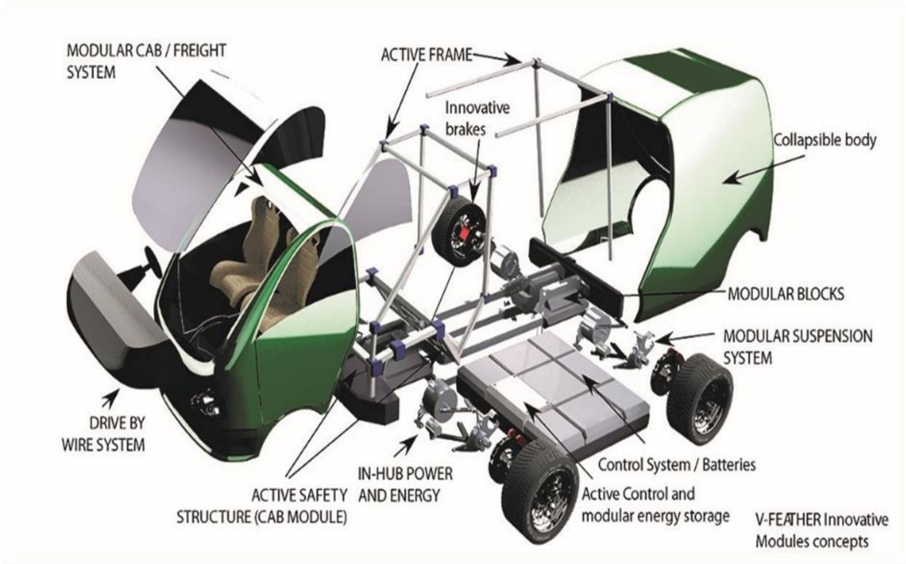


Figure 2.3: V-Feather vehicle configuration

Source: Luxembourg Institute of Science and Technology

2.2 Utilisation of Local Public Transport vehicles for Last-Mile Delivery

From the first years of XXI century, the idea of implementing shared mobility for passengers and freight started to grow rapidly. Consequently, literature works regarding the topic of mixed transport rose abundantly. There are different modalities for carrying out the mixed transport service, like the usage of dedicated vehicles for both the movement of people and freight or combining the two operations by using the same vehicles rearranged to serve delivery services together with passengers' management. The latter activity is also known as 'piggybacking' and scholars, after having considered different categories of LPT vehicles for the purpose, agreed on the usage of light rail vehicles, pushed by their short headways and capillarity, allowing them to reach the inner core of the cities starting from the outer zones. Therefore, two branches of research developed in parallel: while some authors decided to focus on the potentiality of the metro systems, others prefer to exploit the tram solutions.

2.2.1 Brief description of metro applications

Regarding the first branch, Zheng et al. exploited the feasibility of a Metro-based Underground Logistics Systems (MULS) which consists in an intermodal mechanism of mixed passenger and freight [23]. Freight is transported during off-peak periods using metro railways either through batch driving or attachment carriages. One of the biggest concerns for the authors is the definition of the stations in which the activities of drop-off and pick-up of goods can take place, as well as their location along the line. As a matter of fact, is not possible to have the service available at every station of the chosen line, because of crowding and passengers' traffic on one side and the capability of the infrastructures on the other. Furthermore, in stations where the sorting of goods is allowed, the drawback of the increased travel time suffered by passengers that have to wait for pick-up and drop-off operations to take place at metro stops becomes significant, leading to lower overall efficiency of the piggybacking system and feeding the general dissatisfaction of passengers towards the metro service. The cost of the ticket must be revised, and travellers might decide not to use the metro service anymore if the price overcomes a tolerable threshold. Regarding the economical part of the analysis, four factors of influence were considered for identifying the stations available for simultaneous exchange of goods and passenger service: infrastructure cost, transport cost, logistics cost and passenger transport impact cost. By using Voronoi diagram and p-median cost optimization analysis, the authors were able to obtain the final number of stations were the mixed activities for passengers and goods can take part.

The work carried out by Zheng et al. is only one of the many regarding metro freight transport. A noticeable number of studies were undertaken around the globe, from Europe to Asia, and the majority of the papers released shown a positive attitude of people and economics towards the mixed metro system. A graphical representation of metro vehicle converted to freight operations is presented in Figure 2.4, where the hypothetical distribution of the internal spaces of a cabin of the "series 3000" model operating in Madrid is shown, rearranged for providing delivery services.

Figure 2.4: Internal space organization for freight transport through metro vehicles

Source: [24]

Two other relevant studies on metro systems for delivery operations that are worth mentioning can be found in literature. The first one deals with the possibility of implementing the system in Newcastle upon Tyne in England [25], where freight is moved thanks to dedicated vehicles during off-peak hours (with the advantage of having negligible infrastructure costs due to utilization of the already existent infrastructures of the metro system), while the second one regards the situation of the city of Sapporo in Japan, where the MULS was thought to counteract the heavy snowfalls during winter afflicting the territory which exert influence on the resilience of the road network system [26]. Both paper works show favourable results about using the existing metro infrastructure to perform also freight transport, in terms of increase of profits, optimization of the utilization of resources and creation of new businesses. Moreover, the study undertaken for the city of Sapporo reveals that the opinion of citizens, acquainted through surveys, appears to be very positive towards the project.

Before addressing the potentiality of the metro line considered for providing mixed transport service, its characteristics must be deeply acknowledged. If the line is already fully saturated with passenger service, it is likely to be not suitable for combined passenger and freight transport. Similarly, if the existent metro network is already not performant for citizens, then a successful implementation for freight transport is unlikely to succeed, because the metro network crosses zones which are not interesting for customers both of passenger and freight services. For many cities equipped with a metro network, this LPT system is marginal with respect to overground railways and bus applications, so the level of development of the infrastructure could be not sufficient for the implementation of the project. On the other hand, the cities in which metro systems are widespread are the biggest and richest ones, with consolidated interest in the performances and conditions of the entirety of the LPT lines. For these cases, the MULS could reveal to be profitable, and municipalities could be fascinated by this project.

2.2.2 Description of the four main European cases of tram applications and derived literature

The second branch of the topic of using LPT vehicles for logistics service deals with the opportunity to use trams. In literature, the most significant applications of freight trams are four case-studies implemented in different European cities. These projects are considered the biggest ones regarding tram vehicles and were the pioneers of the upcoming research studies on the subject. They were developed mainly to reduce environmental pollution and increase the efficiency of the freight transportation network, and the different aims and issues they presented led to opposite outcomes. Arvidsson & Browne [27] have performed an inspection about the four applications and analysed the reasons behind their success or failure. The details of their consideration about the four projects are reported along the paragraph.

The first case of tram application is dated in 2002, when Volkswagen decided to open a new factory in the city centre of Dresden, in Germany. Since the city itself is small and consequently particularly sensitive to heavy trucks traffic, Volkswagen decided to collaborate with the LPT company of Dresden in order to move the goods needed by the company through vehicles without overloading the tram line and increasing traffic congestion on roads. Cargo trams proved to be the best fitting solution: with just little additional infrastructure costs, freight vehicles were able to operate on the tram railway system alternating with the movement of vehicles dedicated to passengers. The projected was establish under the announced desire of Volkswagen to build a transparent factory, where anyone could witness the manufacturing of cars during every step of the supply chain. The logistics system application, named "CarGoTram", have been a prosperous project since its very beginning and nowadays the trams transport the equivalent of 60 trucks to the Volkswagen factory each day, with a drastically reduced environmental impact. A photograph of a vehicle of the CarGoTram project is reported in Figure 2.5. It must be highlighted that CarGoTram was a purpose-built project with very specific conditions, being implemented for facilitating delivery operation of one customer only (Volkswagen) on one route. The LPT operator of Dresden is currently looking for new applications for cargo trams in the city, such as the possibility to serve multiple business activities of a shopping mall located in the city centre.

Figure 2.5: Freight tram operating in Dresden (GE)

Source: Public-Transport.net

The second project, commissioned by the CEO of the municipal public waste disposal and recycling company of Zurich in 2003, was thought to fulfil a completely different requirement: the initial objective was to collect bulky waste from households located near the tramway path, then the collection was extended to electronic and industrial equipment. The project was favoured by the deep tramway infrastructure of Zurich, which serves the majority of the city areas. Furthermore, there were additional tracks along the city not previously used for the transport of people that could serve for the purpose of waste collection. Another advantage of using trams was that they are faster and cheaper than garbage trucks, being free of congestion related costs and delays. Basing on these preconditions, the project gained success and nowadays nine different tram stations of Zurich are served by cargo trams, mostly along turning points at the end of tram lines. The disposal of waste carried out by the cargo tram reported in Figure 2.6 is calculated to achieve a reduction of 37500 litres of diesel per year, thus avoiding equivalent emission of CO_2. Another key for the successful implementation of the project was the reduced initial costs due to the already existent infrastructure system and to the conversion of out-of-work vehicles into cargo trams.

Figure 2.6: Waste disposal tram in Zurich (CH)

Source: Limmattaler Zeitung

Pushed by the precedent success of the technology adopted in Dresden, a similar concept was developed in Vienna in 2004. The name of the project is “GuterBim” and deals with the possibility of implementing cargo trams for transporting goods within the city using the existing rail network, to reduce road congestion and increase the efficiency of the rail transport system. The project investigated several potential applications, e.g., hospitals, shops and waste disposal, and a pilot operation on a selected route was performed in 2005. In the same year a possible combination of rail and tram freight transport was tested to fulfil the demand of densely populated areas. The success of the project pushed the Austrian Ministry of Transport, Innovation and Technology to propose a joint venture between different mobility actors and many follow-up projects were developed for the city. Tests have been performed considering different retailers, to find low-cost solutions for a reliable delivery of their stores and sales points in the city developing techniques for fast handling. A picture of a cargo tram belonging to the GuterBim project is reported in Figure 2.7.

Figure 2.7: Vienna cargo tram application (AT)

Source: www.slideserve.com

The fourth case-study presented was developed in Amsterdam under the name of "CityCargo" in order to implement freight tram delivery together with electric vehicles for last-mile trips to supply shops in certain districts of the city. CityCargo is by far the biggest project among the four presented and according to the initial feasibility studies performed in 2007, it was intended to replace almost 50% of the truck movement for transporting goods by using trams. This ambitious statement inevitably attracted many investors, who donates up to 70 million to boost up the project. Consequently, the city council of Amsterdam gave permission to carry out some trial operations in 2008. The trams were responsible for delivering goods to the city business companies. Cargo tram operations were restricted to the lines which have enough capacity to avoid problems with passenger trams and were performed during diurnal hours to avoid noise disturbances during the night. This project could have resulted into a reduction of 2500 HDV movements within the city per year and the particle pollution in the air by 15 percent according to calculations made by the company. Although the premises were encouraging, the project failed because of lack of finance and instability of the company board. The time of financial crisis surely did not help the development of the project, because at the time banks were more interested in bigger projects rather than smaller and riskier ones. Hence, CityCargo developers were obliged to look for other investors and, after failing in involving the city municipality itself for subsidizing the additional capital required, the project went bankrupt at the end of 2008. Figure 2.8 reports a picture of a freight vehicle belonging to the pilot project of CityCargo.

Figure 2.8: Freight tram vehicle operating in Amsterdam (NL)

Source: NL Architects Blog - WordPress

The four projects presented are among the oldest ones related to freight trams, considering the novelty of the subject. From the successes and failures presented by the analysis of the most relevant applications, literature have grown at high pace and many implementations of freight trams were proposed worldwide in the last decade. Pietrzak O. & Pietrzak K. proposed different modalities to perform mixed passenger and freight distribution through cargo trams in Poland, considering the city of Szczecin as area of research [28]. The work of the authors is based on the concept of cargo hitching, which is a form of capacity sharing mainly aimed at utilising unused capacity of public transport for parcel transport. The authors reported three possible solutions to carry out cargo hitching using trams: freight wagon behind passengers' vehicles, cargo located into passengers' vehicles and dedicated freight vehicles. The use of freight wagons behind passengers' vehicles allows to carry a considerable amount of goods in a single ride, in the form of unitised and palletized cargo, ensuring a permanent separation between freight and passenger space thus increasing safety for both people and goods. This solution seems tailored for loop-to-loop solutions, without loading and unloading at intermediate stations but only at the final ones.

Possible negative aspects of this solution are the necessity of applying an additional engine to the freight wagon, like in multiple-unit trains, and the possibility of overcoming the maximum permissible length allowed for trams, which can be limited through a reduction of the passenger-dedicated section of the vehicle. The solution of the cargo located into passenger vehicles allows to carry on board only small packages and seems to be fitting for serving many dispersed senders and addresses and to serve all the tram stops along the route. The presence of a system of loading and unloading of freight that does not interfere with the passenger space or compromise their safety becomes relevant for this application. A potential drawback of this solution is the decreased space dedicated to the passengers which may result in deteriorated comfort of travelling, reducing the competitiveness of the tram with respect to other passenger transport systems. The last solution is to utilise dedicated freight vehicles, which allow to carry an enormous amount of goods, although inevitably introducing an interference with the passenger service dedicated trams. A detailed analysis of the time schedule of passengers and freight services must be performed, since the number of vehicles operating on the tram network is increased with the respect to passenger service only. By using Delphi analysis, the authors concluded that, for the particular scenario presented in the city of Szczecin, the best fitting solution is to divide passenger from freight transportation by adopting dedicated vehicles to perform the delivery operations. However, their work assumes greater importance when extended to general scenarios, because it presents advantages and disadvantages for all the three different modalities of transport of people and freight discussed.

The successful project developed in Zurich led different scholars in recent years to follow the footsteps left by the Swiss case-study, considering the possibility of using trams to collect household waste or end-of-life products. Rubio et al. deal with the possibility to create a connection between urban logistics and Reverse Logistics (RL), identified as the logistics service focused on the recovery of products once they are no longer desired or usable in order to obtain economic return through reuse, recycling and remanufacturing [29]. Following the global trend of e-commerce and a rooted attitude towards consumerism of the current society, the authors affirmed that by 2027 customers will return nearly $1 trillion in merchandise annually. Therefore, many of the biggest companies in hardware and technology sector like Apple, Dell, Hewlett-Packard, IBM and others have already developed and implemented RL systems to collect and manage end-of-use and end-of-life products, together with commercial returns. Commercial returns and refunds normally occur because the product purchased by the consumers does not meet their needs or expectations, or has not been delivered in the right conditions; thus, a product return process is created. By addressing the importance of Reverse Logistics, the supply chain management can finally be understood as a whole, where the links between traditional logistics operations and Reverse Logistics associated with return flows need to be considered.

Zilka et al. analysed the possibility of using cargo trams for mixed urban and reverse logistics [30]. Their focal idea is to transfer municipal waste into sealed large volume containers positioned in local transfer stations and transport them over long distances using specifically adapted cargo trams. The case-study is the city of Prague, and cargo trams are supposed to reach the incineration plant at Malesice, located at 20 kilometres from the central districts of Prague. Cargo trams are put in comparison with a truck-based waste management operation, performed by either the fleet of diesel trucks already in use for waste management or new Euro 6 trucks. Trams represent a more efficient form of transport because, differently from trucks, they theoretically operate always at full load once the containers of the stations are saturated and, moreover, the time of transportation is constant and does not vary depending on traffic congestion. Furthermore, the mixed municipal waste could be transported during off-peak hours having minimum impact on passengers' circulation. In terms of environmental results, cargo trams are most advantageous with respect to the other solutions, but the outcome is not the same regarding the economical analysis. As a matter of fact, Zilka et al. concluded that the cheaper solution is to replace the high number of diesel garbage trucks with new Euro 6 vehicles. The main reasons why the cargo tram solution is expensive are its initial investment cost, corresponding to half of the total of the project, together with the high occupancy of the tram network, especially during daytime. Basing on what has been affirmed above and on a Life Cycle Assessment method, the authors concluded that the use of cargo trams would be beneficial if merged with a noticeable shift from fossil fuel sources of energy to renewable ones, because at the present state the reduction of emission in the operative section of the cycle is not good enough to justify the investment, because emissions are only moved from the operating phase to the energy production part of the cycle.

In conclusion, Reverse Logistics is a mobility problem that is gaining greater importance, directly related with the global trend of e-commerce. Since at the moment is difficult for companies to know in advance the number and the type of goods that would be sent back, only few companies can afford to invest in RL systems. In case of waste disposal, conversely, the quantity of garbage can be addressed knowing how many people live in a district and how many garbage they produce, thanks to the use of surveys. The type of waste that is collected during one day of the week is scheduled to be the one decided by the waste management company of the city, thus avoiding the collection of waste that is not fitting with the indications provided. So, the use of public transport system for managing waste at dedicated windows of the day could be an efficient solution not only for traffic congestion but also for pollutants emissions.

2.2.3 Conversion of Local Public Transport vehicles into mixed-operation ones

Different models can be used when estimating whether is possible to convert LPT vehicles into freight ones. Nevertheless, any modification proposed must rely on a deep analysis on the territory in terms of morphological, social and commercial inspections. Different typologies of software can be used to perform this action. Geographic Information System (GIS) is a well-suited family of software to accomplish the analysis of the territory. GIS are free, open-source software that are used to create, manage, analyse and visualize geographic data [31]. The tasks that can be accomplished with GIS software are data visualization and exploration, data creation, data editing, data storage, data conflation (i.e., integration of data from different sources), data queries to select a subset of the data, data analysis, which is the creation of new information from existing data, data transformation and, lastly, the creation of maps. In fact, a generic GIS software allows to download different maps and information directly from libraries of data available on webpages and geoportals. These data contain information about residences, streets, water courses and plot of lands which are registered by the national census agency. In this way, insights about the dimension of the buildings and the number of people living in a determined area are ready to use.

Once the zoning of the territory is defined and completed through GIS software, some Socio-Economic (SE) parameters can be obtained, which can be related to the economical welfare of the city object of the research, e.g.; the Gross Domestic Product (GDP) of the region in which the city is located, or directly associated to the population of inhabitants of the zone studied, such as the number of employees and students, the proportion between males and females, a classification of the inhabitants based on their age, and so on. These pieces of information are fundamental to obtain a primordial sample of the inhabitants of a city, which could represent the potential users of the LPT of the considered municipality. Other useful parameters that can be found are the routes of the LPT vehicles in service, together with the number and the position of the stops along the route. The time schedules of the urban vehicles are also useful to assess the travel time of LPT vehicles and the distance between two or more stations. The information about the time schedules of LPT services can be easily found on the official website (or mobile app) of the LPT company operating in the city of interest.

Socio-Economic parameters are able to provide useful indications to the consulters about the type of planning which is best suited for a particular application. In literature, there are three types of planning levels classified according to the time of intervention they require: strategic, tactical and operational planning [32]. Strategic planning is a long-time implementation which consists in organizational and infrastructural interventions having considerable effects on the whole transport system of an area and elevated initial costs. It involves the highest levels of management and requires large capital investments over a long-term horizon. Tactical planning is a medium-to-short time implementation (from 2-3 months to a couple of years) having effects on a single transport system, which aims to improve the performances of the considered transport system. Lastly, operational planning is an immediate implementation which aims to an optimization of the use of the available resources from a business point of view and has effects on the users of a single service. The introduction of a mixed logistics service is likely to be considered a strategic or tactical planning, depending on the city object of the study and the objectives set by the decision-makers (municipalities, participants, shareholders, sponsors, …). Even though the gathering of data is mainly related to the existent urban transport system dedicated to passenger service, is also possible to search for data which can be helpful for the implementation of the freight service. For example, the characteristics of the LPT vehicles used in terms of capacity and commercial speed are indicators for choosing one vehicle rather than others for delivery operations, because these values can have an impact on the potential effectiveness in terms of delivery time and overall capacity of the freight service. Also, the area in which the passenger service take place is another factor: some lines could serve touristic zones while others can be located near business activities which could represent potential future customers for the freight service.

Field observations and surveys are needed to understand people's consideration and interest over the implementation of a hybrid service dedicated to passengers and freight. Some of them, for example, may be less prone to use trams if dedicated freight vehicles would alter the congestion rate of the network. It is important to understand that the overall efficiency of the mixed logistics system needs to overtake a certain threshold in order for the service to be implemented. If the benefits of having a freight market on trams are counteracted by a considerable loss in the efficiency of the passenger service, the success of the project is put at risk. Predicting the human behaviour is an extremely difficult activity because people do not always have rational behaviours and, furthermore, their opinions about things and services change very quickly. One method to assess the preferences of a sample of people is by using surveys, which can be conducted online, by telephone or physically. Through the use of surveys is possible to acknowledge the choices of the user of a service. Travel choices may be revealed, if they are referred to revealed preference of travellers in a real context, or stated, if they are referred to stated preferences of the users in a hypothetical context [33]. In the former case, the survey expresses the Revealed Preference (RP) in a real context and can be useful to know the number of actual users of an LPT service; in the latter case, the survey is called Stated Preference (SP) and express the stated behaviour of people in a hypothetical future context. This type of surveys can be also useful to address the future customers of the freight service. In this case, users are not people but companies and retailers and through the results obtained is possible to define whether they are interested in a freight market performed by LPT or not.

The demand of a service is a crucial operation for definition of LPT services and is directly related to the supply system. A demand flow is an aggregation of individual trips, and each trip is the result of multiple choices made by the transportation system users, that is an individual traveller in case of passenger transportation or an operator (manufacturer, shipper or carrier) for freight transportation [34]. Demand and supply are interdependent, since the supply (service offer) is shaped around the demand estimated, as shown in Figure 2.9. The image shows that demand, supply and SE activities take part in a recursive path and only after many iterations the service offer can be computed correctly. Therefore, a good demand model is usually the outcome of a trial-and-error process in which the specification–calibration–validation cycle is repeated several times until a satisfactory result is obtained.

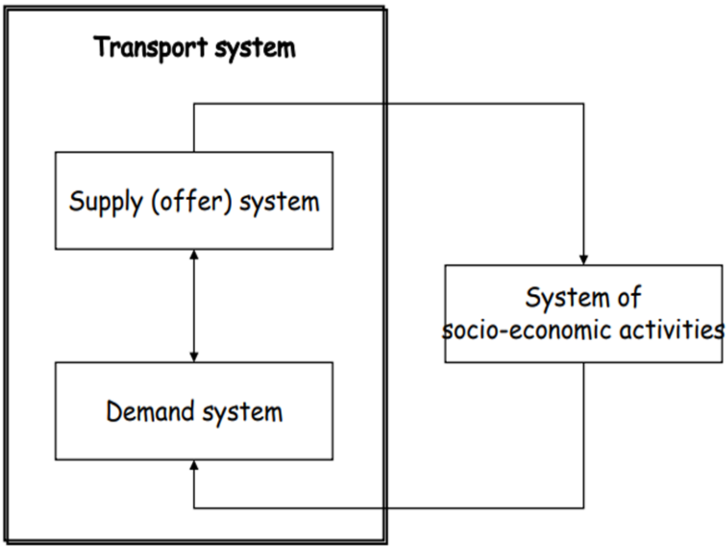


Figure 2.9: Relationship between supply and demand

Source: course "Transport Planning and Economics" provided by Politecnico di Milano, held by Borghetti, F.

Another way to assess the behaviour of the people is through the utilization of Random Utility Models (RUMs), useful when people need to choose between alternative vehicles to move from an origin to a destination, or when shop activities have to pick one of the different options between the modality of receiving of a parcel or a supply. Well-known examples of RUMs are the perceived utility, the logit system [34,35] and the Multinomial Logit (MNL), proposed for the first time by McFadden in 1974 [36].

Thanks to surveys and RUMs, the interest of future customers over a tram-based freight service can be outlined. For the case of freight transport, it results beneficial for the analysis to involve also the preferences of the main shop activities and retailers which are settled in the zone of study. The freight service implemented would be, indeed, related to business activities only and account for the passengers' preferences only in terms of willingness to share the same vehicle infrastructure with a freight service which does not involve them directly, but can influence the efficiency of the passengers' dedicated service. Under this circumstance, the implementation of a freight urban public transportation using trams is possible by improving the complex schemes of traffic development and organization, carrying out the needed rolling stock renewal, reconstructing the light rail network and implementing the measures for energy savings [37].

Models dedicated to the simulation of the demand for freight transport are preferred rather than using methods intended for passenger service adapted to freight transportation demand. The demand for freight transportation is closely connected to the production and distribution of goods and therefore to the economic system of the zone of the city studied and its interactions with the external economic system. In case of freight service, demand flows represent movements of freight quantities (usually expressed in tons), while the relevant characteristics are normally associated with commodity type (e.g., raw materials, semi-finished products and finished products), with sectors of economic activity, with characteristics of firms (e.g., firm size or logistic organization), transportation characteristics (e.g., shipping frequency, size, and value) as well as with transportation modes. At the same time, SE variables reflect the economics of production (e.g., value of production by sector, number, and size of production units) and consumption; and the transportation system variables are related to the attributes of the different transportation modes and services [34]. These considerations suggest that the mechanisms underlying the formation of freight transportation demand and its fulfilment by transportation services are considerably more complex and intercorrelated than those for passenger demand. There is no single decision-maker for freight, but rather a complex and connected set of decision-makers responsible for production, logistics (storage and shipping), distribution, and marketing. Freight transportation demand models have been studied and applied to a lesser extent than passenger models, mainly because of the complexity of the underlying phenomena that influence freight transportation. There is no universal paradigm but rather only individual examples, which depend on the type of application and the data available.

When dealing with the conversion from passenger service to mixed service, the number of adjustments the need to be made to the whole system of transportation is considerable. The payment methods need to be adjusted as a consequence of the freight service implementation in the LPT framework. While the price of the tickets for passenger service would probably undergo slight to no variations, the tariff of the delivery service must be modelled according to the Business-to-Business (B2B) contract signed by the deliverer company and business activities. Contrarily to the case of revenues from passengers, where the financial contracts involve in many cases an agreement between the municipal authority and the company which provides the service, when referring to the payment of the freight service only, the contracts made with the interested customers and retailers does not involve the participation of the municipality and the company which provides the service could offer customer-tailored prices and accommodation to their clients. Raj et al. [38] provide an interesting analysis on how the payments of the supplies and procurements of products are organized and the agreements between the vendors of services and the buyers. Payments of products and delivery services can be carried out entirely in one solution or diluted in time. Customers can also pay for the service in advance, by credit or in real time with respect to when the service is provided, according to the type of contract they signed with the vendor. Moreover, payments can be made using cash, via physical or digital circuits of payments, or using blockchain. Blockchain is a trustworthy, shareable, and distributed ledger with information sharing and responsibility tracking. However, some issues still take part: privacy, security and inclusion are topics of serious concerns in online transactions, thus people are not eager to use this type of payments, mainly because these issues further lead to lack of trust and imminent negative effects for internet transactions.

The stations of the LPT line chosen for serve freight management operations needs to be accounted and revamped accordingly. Among the operation to compute for the assessment there are the evaluation of the number of passengers which are served at each stop of the line and the calculation of the necessary space to reserve to pick-up and drop-off operations, ensuring at the same time safe operations both for passengers and goods. The number of possible customers of a certain station in terms of retailers must be acknowledged as well. In literature, different modality to pinpoint the favourable locations for mixed operation performed in designated stations can be mentioned. Zheng et al. [23] provided a model based on a weighted Voronoi diagram to assess the number of stations to be served with logistics services, starting from the analysis of all the stations of a metro line and gradually, thanks to a proper cost function, exclude some stations from the final solution. Another example is provided by Apichottanakul et al., which adopted a Mixed-Integer Linear Programming (MILP) problem to define the number and position of stations to be utilized for mixed operations [39]. The main driver for selecting the stations is the total cost, followed by the capacity of each station to serve a specific amount of customers and to handle the highest possible number of parcels. Through the optimization operation described, the authors were able to identify 13 rail distribution hubs along a line having 97 stations in total.

2.3 Two-level freight distribution system

The two-level freight distribution system configuration consists in splitting the delivery of goods in two parts, the first addressing the path starting from outside the city of interest to inner depots positioned in specific locations of the cities, while the second is focused on reaching the final destinations starting from the depots reached at the first level of the operation. The system described belongs to the family of the multi-level distribution system configuration, of which the two-level case represents a particular application. Multi-level distribution systems are composed by the 1st level, which connects the depots to the 1st level intermediary facilities, (N–2) intermediate levels connecting the different intermediary facilities and the Nth level where the freight is delivered from the (N-1)th level intermediary facilities to the final destination [40]. Naturally, in a distribution system composed by only two levels, there are no intermediate levels: the first level brings the freight from outer zones of the city to the inner core, while the second level of the system is performed by vehicles which takes the freight from 1st level vehicles and deliver them to the final customers.

The possibilities regarding the vehicles to be used for the first level are broad and dependent on factors that may vary for different contexts and applications, e.g., the distance to be covered or the level of development of the transport infrastructures available in the examined city. Possible alternatives may be represented by regional cargo trains and road vehicles such as LDVs and HDVs, but also vehicles having purpose of passenger service like metros, trams and buses. In many cases, the vehicle chosen belongs to the pool of LPT services of the city, which already has a defined path and timetable, high penetrability in the inner zones of the cities interested and high potential freight delivery capacity. Buses represent the best solution among the LPT vehicles in terms of capillarity, since they generally do not depend on electricity wires or constrained paths and therefore, they are able to reach almost any place, as long as the size of the vehicle does not represent an impediment. However, buses have an important drawback with respect to the two competitors: they do not operate on dedicated lanes, with only rare exceptions located principally in South America and USA [41] and have lower commercial speed with respect to the competitors. Both characteristics make the buses highly vulnerable to congestion. Moreover, buses are vehicles having lower available space than trams and metros and thus in case of overcrowding there will be little space left for parcels to be stored and be dropped off or loaded in at the stations, if freight and people are transported simultaneously. Due to the inefficient characteristics described, is rare to find applications of freight-buses used as 1st level vehicles currently in service. Trams not only have considerable advantages over buses, but also have some features that make them preferable with respect to metros. As a matter of fact, they allow a better coordination with 2nd level vehicles (which are generally electric road vehicles, performing the level on the same ground of trams) and they have the possibility of leaving the goods in a cargo wagon parked in dedicated secondary rails, which are difficult to construct and require higher investments when located underground like in case of metro applications. The movement of goods through vertical infrastructures is more complicated because different ground levels need to be reached, thus making trams a better solution thanks to a more manageable flow of operation. On the other hand, metro station is far wider the trams counterparts, with the consequence of having more space for the allocation of freight in the stations. In case of trams, consequently, the stations must be enlarged to install storage systems as smart lockers, but this action is not always possible to perform because of the physical constraints of the surroundings of the trams.

The research works aiming at the optimization of the two-level logistics systems have to cope with Two-echelon Vehicle Routing Problems (2E-VRPs), which are a typology of mathematical problems dealing with the identification of the optimal routes both for 1st and 2nd level vehicles of the logistics service and the synchronization between the different level of the logistics service, in order to provide the fastest modality of delivery possible with the lowest number of missed deliveries. Although the problem is well-known by scholars, the research for a unified and general solution is still on-going and, currently, is far to be achieved. The solutions in provided by authors for different case-studies are indeed appliable only within the boundaries set by the authors themselves, thus lacking a systemic framework able to adapt to different situations. The authors chose between different models to solve the problem, which vary from metaheuristic method such as Large Neighbourhood Search (LNS) to stochastic predictive ones. By using dedicated and specific models for solving 2E-VRPs, it becomes arduous to extract information on general basis, since the efficacy of the algorithm utilised is highly dependent on the transportation system performances of the city analysed, together with some simplifications and boundary conditions set by the authors.

One example of 2E-VRP analysis is provided by Perboli et al. which also introduced time as a variable of the problem [42]. The authors reported two variants of the 2E-VRP taking into account the time dependence: Two-echelon VRP with Time Windows (2E-VRP-TW), where the arrival or departure time at the satellites and customers are considered, and Two-echelon VRP with Satellites Synchronizations (2E-VRP-SS) where 2nd level vehicles for delivery actions, named city freighters, are organized to be ready at satellites in order to promptly load the freight brought by 1st level vehicles without idle times. The authors utilize a math-based heuristic method to solve the problem, based on the information they obtained by solving the linear equations obtained through the boundary conditions. Their results show that, for the case presented by the authors, from a computational point of view is feasible to solve the 2E-VRP using the model proposed, both from the computational and the solution quality point of view.

One of the few examples to be found in literature regarding the use of buses as 1st level vehicles is the one provided by Masson et al. The aim of the authors is to deliver parcels to shops located in the city centre through a two-tiered delivery system using buses and city freighters to act respectively as 1st and 2nd level vehicles [43]. The customers of the service proposed by the authors have frequent demand, but the quantities vary from one day to another. Consequently, it results convenient to set the scheduling horizon to one day, because more time-distributed organizations may lead to incorrect goods deliveries. The bus line operates by following an already known time schedule, so one of the main problematics for the implementation, as in all multi-level logistics systems which involves LPT vehicles, is the coordination between passengers and freight transport. Buses have a limited space available for locating goods on board with respect to other LPT vehicles, heavily influenced by the crowding of the vehicle and so by the time of the day for which the delivery activities take part. The aim of the paper is to address the minimum number of city freighters needed to perform the two-level freight distribution system. The authors use the method known as Adaptive Large Neighbourhood Search (ALNS) to identify the trips of the city freighters by iteratively removing from the final solution the positions of the customers that require excessive time to be reached within acceptable amount of time and at the same time by adding customers' positions which have less impact on the total time of the trip analysed. To conclude, Masson et al. described the case-study of La Rochelle and propose a mathematical model based on minimizing the number of 2nd level vehicles for final delivery and, in case of tie conditions, choosing the one with less total costs.

An example of application of two-level freight distribution service using tram is provided by Fontaine et al., which analysed a possible implementation of the two-level city-logistics in the city of Paris, using trams as 1st level [44]. The authors' aim is to propose a new model able to address the main dimensions of the problem (capacity of satellites, number of 2nd level vehicles, …) considering a multimodal setting, combining traditional road-based and mass transport vehicles. The objective function minimizes the total generalized cost for moving inbound and outbound demand flows, organizing the freight traffic from satellites. In order to solve 2E-VRP, the authors resort to the Benders decomposition, which is a math-heuristic method used to simplify a problem that requires extensive computational effort by dividing it in more easy-to-solve sub-problems.

The literature regarding two-level freight distribution systems shows that there is space for improvement in terms of optimal routes research optimization and vehicles synchronization. Furthermore, one of the future areas of research for the topic could be the development of a unified method to address the 2E-VRP which is resilient, at least with a good degree of robustness, to the variations of the boundary conditions from case to case. Through the analysis of the research works reported, it emerges that nowadays thanks to mathematical algorithms is possible to identify the optimal route for a vehicle and then to extrapolate costs and benefits of the choice using cost functions. However, the solution of any case of VRP (being 2E-VRP, VRP-SS or VRP-TW) requires enormous computational effort by calculators, since this type of mathematical problems are among the hardest to solve from a computational point of view. The reason of their complexity is that there is a considerable quantity of factors upon which the equations are written, together with a sizeable number of constraints to take into account, such as the number of vehicles involved in the logistic service, their maximum capacity and the travel time for each vehicle. The problem of route optimization is generally related to 2nd level vehicles, since the ones used for the 1st level generally operate on constrained paths, being metros and trams. Conversely, 2nd level vehicles are in general road electric vehicles, which can run freely along the network, so their movements need to be planned to avoid failed deliveries and road congestion issues. There also cases in literature when VRP solving algorithms are used for determining optimal routes for 1st level vehicles, as in case of the utilization of buses [43]. When 1st level vehicles are not constrained by rails, some variations on their routes may be accounted for increasing the efficiency of the freight service.

2.4 Multi-Criteria Analysis for the evaluation of mobility projects

The definition of the positive and negative outcomes derived by the implementation of mobility projects are assessed through the Multi-Criteria Analysis (MCA) technique. MCA was introduced as a decision-making process in the late '80s as a tool to consider, along with economical parameters, environmental impacts of the projects proposed. The technique refined along the years and nowadays it is an instrument able to establish preferences between options by reference to an explicit set of objectives that have been identified and for which performance indicators have been defined [34]. Multi-Criteria Decision Making (MCDM) methods deal with the process of decision-making in presence of multiple objectives. In order to compare the contribution of different options towards given objectives, it is necessary to have criteria that reflect the options' performance in meeting those objectives. In simple situations, the process of identifying and assessing objectives and criteria may alone provide enough information for decision-makers. The objectives are usually conflicting and therefore the solution is highly dependent on the preferences of the decision-makers and the result is often obtained by a compromise [45]. MCA yields results that are more effective, clear and logical than single-criteria approaches.

A key feature of MCA is its emphasis on the judgment of the decision-makers in establishing objectives and criteria, in estimating relative importance weights and in judging the contribution of each option towards each evaluation criterion. MCA are founded based on decision-makers' proper choice of objectives, criteria, weights, and their assessments of the performance through which achieving the objectives. MCA enables to perform sensitivity analysis by varying the values of the weights. In such way is possible to establish if the solution proposed is robust with respect to changes in the parameters, which are intrinsically arbitrary [34]. Hence, thanks to the sensitivity analysis, the most critical parameters for the approval or rejection of the project could be identified. MCA methods are well-suited for transportation planning since, for the implementation of mobility projects, different factors must be considered, such as economic, environmental, social and health [46]. The efficiency of a project is indeed a result of multi-criteria considerations, which gives final results that depend heavily on the importance given by the decision-makers to each criterium considered. First, the financial efficiency needs to be assessed, as in any business project. Then the economic analysis is carried out, regarding non-financial benefits and costs for the community.

Financial analysis is traditionally associated with private operators that attempt to maximize profit under constraints such as regulations, service obligations, concessions, and similar. In this case, benefits and costs have a natural expression in monetary terms: the former come mainly from the revenues obtained by means of service sales, while the latter from the financial costs of service production such as construction, maintenance, operating costs, tolls, and taxes [34]. The financial profit for investors, along with Net Present Value (NPV), Payback Period (PBP) and other financial indexes can be obtained as a profitability estimation of the project. There are different models in literature which can quantify the costs for the delivery service together with the passenger service. One of them is provided by Halkin et al. and it is based on the maximisation of the NPV intended as difference between all cash flows derived from the project and all type of expenses [47]. As highlighted by the authors, the project can assume different shapes, having different values of cash flows and expenses. The implementation of the project with the higher NPV is the best among all the alternatives.

Economic analysis, conversely, is traditionally associated with public decision-makers. Alternative projects are evaluated considering benefits and costs (positive and negative impacts) with respect to the objectives of the community, or sub-groups of it that are homogeneous in terms of SE characteristics and of project impacts on them [34]. Indeed, some transportation system users may benefit from a particular project in terms of reduced travel times and costs and increased accessibility, whereas others may receive lesser advantages or even disadvantages from it, for example increased travel times and costs. Economic impacts can be defined as any variation in the economic system caused by the implementation of the project. This includes changes in residential and commercial property values and changes in the economic consequences of accidents directly and indirectly related to the project. Economic externalities are directly measurable in monetary units, or at least can easily be translated into such units.

Along with better understanding and modelling of the mechanisms underlying transportation systems, the range of effects considered for the users of the transportation systems has gradually increased. More consideration is now given to impacts on all users, both current and project-induced, calculating the changes in generalized costs, both perceived and not perceived, for the different transportation modes. Some examples of criteria considered in the most recent iterations of MCA are land use, social, environmental, and technological.

Land use impacts are related to land use and its quality. Examples of land use impacts are changes in land use type, from residential to commercial and vice versa, and land use intensity, or more in general the relocation of housing and economic activities brought about by accessibility differentials. This category includes changes in the geographical structure of a region or in the urban quality of specific neighbourhoods.

Social impacts can be defined as the externalities caused by the project in terms both of passenger and delivery services. The subjects affected could be people and social institutions such as families, local communities, education, government bodies, and more. Different types of effects can be listed: social effects of accidents, changes in accessibility to social activities (schools, public offices, parks, etc.), changes in cohesion and stability of local communities, as well as impacts on historic and cultural sites. Changes in social equity, i.e., changes in the distribution of travel-related opportunities with respect to space and Socio-Economic status, like income class or age, can also be considered as social impacts. For the case of projects involving modifications on transport systems, the community of customers (and citizens in general) could be positively affected by means of increase of ride comfort for passengers. Data regarding social impacts are usually difficult to obtain and, most of all, to express in numbers.

Environmental impacts can be defined as the effects of a project on the physical environment surrounding it. These can be further classified as effects on the ecosystem, on noise and air pollution, and on visual perception. As a matter of fact, a mixed logistics system could increase the network efficiency in terms of reduced number of diesel vehicles on the streets, with consequent reduction of traffic and pollution, increasing the network speed and reducing noise level in the central core of cities. Public authorities are always pushing for greener transport systems and the possibility to display environmental convenient modalities to perform two of the most pollutant actions for the world of transportation, namely passenger and freight transportation, is beneficial for the final success of the project. Transportation system projects, especially new infrastructure in rural areas, can also alter the ecological balance of plants and animal populations. Furthermore, any transportation system generates noise and air pollution, and a project may significantly change their intensity and distribution in the affected areas. Lastly, transportation infrastructure and vehicles affect the scenery over a potentially large area and this impact depends on the visibility of the transportation infrastructure and its contrast with the background.

Technological impacts provided by the installation of a project could be addressed as the advancement in software and instruments used by the provider and customers of a service, which are indicators of a community which is developing in terms of smart mobility and shared information.

It is important to highlight the fact that benefits, as well as negative effects, can occur in different time horizons and can be assessed either in short-term vision or long-term perspective. In case of mobility projects involving mixed passenger and freight operations, short-term effects may include behavioural customer acquisition process, modifications on urban freight transport and logistics, while long-term effects could be modification of future lines and schedules to best suit the service and localization models for DCs and shopping activities [37].

2.5 State of art summary and contribution of the thesis work

The literature regarding the topic of multilevel distribution systems is growing relentlessly in the recent years, thus reinforcing the possibility of the implementation of this type of delivery concept in the near future. Different solutions were considered about what are the vehicles the best suits the technology, with several scholar that exploited the advantages presented by LPT vehicles for using them at least for performing one section of the multilevel delivery framework. The enormous steps forward made by I.T. and computer science enable researchers to create algorithms that can solve problematic related to the topic that were impossible to imagine up to the last years, thus taking the multilevel distribution system increasingly closer to see its definitive completion and assessment. Algorithms like LNS [42,43] or Benders decompositions [44] could be indeed useful when solving the family of VRPs related to logistics services, but many questions remain unsolved. Notwithstanding the fact that the algorithms used in literature are useful as academic methods to solve the VRPs, when it comes to real world applications, they exhibit too many limitations. For this reason, mathematical algorithms like the one reported are not suited for real applications of VRPs. More efficient methods are rather used by the decision-makers of the delivery companies to address the planification of the routes for delivery vehicles. Nowadays, I.T. knowledge-providers are selling in dedicated software to solve the different declinations of the VRP. However, these software are currently underdeveloped and therefore not yet reliable, without mentioning the enormous initial expenses needed for purchase the software [48].

For the scope of the thesis, VRP algorithms are not used, mainly for two reasons: their intrinsic complexity and their purpose. Regarding the latter, the scope of the thesis is not to find the optimal route for the vehicles involved in the freight service, but rather to address whether is possible from a technical point of view to implement a two-level system by using an already existent tramway infrastructure. The instrument provided by the thesis work is therefore a tool which enables decision-makers to consider whether is advantageous or not to implement freight service together with passenger service using an already existent tram infrastructure. The assessment of optimal routes and the synchronization problems regard phases of the projects which are processes that are faced afterwards with respect to the technical analysis.

The thesis work aims at describing a specific implementation of Two-level Mixed Logistics System from a technical point of view, describing the main feature of trams' infrastructure and configuration for optimizing the distribution of freight along the network. Particular attention is set on the coexistence of both services of passenger and freight transportation within the same infrastructure, leading the research work towards urbanistic and logistics thematic rather than mathematic and I.T. ones.

3. Description of the Two-level Mixed Logistics System implementation using trams

3.1 Two-Level Mixed Logistics System using trams as 1st level vehicles

The idea beyond the Two-level Mixed Logistics System (2L-MLS) proposed in the thesis work is a two-level freight distribution system for Last-Mile Delivery with an efficient tram network able to transport passengers and freight. The two activities are performed by dedicated vehicles, which share only the infrastructure they move onto. By adopting this modality, the two activities can be optimized separately, without considering the negative effects that one activity could have on the other. As a consequence of dedicated vehicles, the number of trams on the network will eventually increase. The two-level freight delivery system is considered an efficient solution for bringing goods from the outer zones of the city to the central core without affecting the traffic congestion, and by coupling this activity with tram systems it is able to provide beneficial effects in terms of efficient utilization of the current resources, contributing to a reduction of road congestion caused by the avoided movement of vans and trucks in the inner core of the municipalities thanks to 2L-MLS implementation.

This paragraph focuses on the explanation of the characteristics of the whole tram system which are need for the implementation of the proposed 2L-MLS, providing guidance towards an assessment of the predisposition of existent tramway lines for being used to perform the 1st level of the implementation. Minor modifications to be applied to existent tram systems are also considered, such as the installation of storage systems in the stations dedicated to freight transport and the construction of secondary infrastructure next to the one currently used for passenger service.

3.1.1 2L-MLS: Main characteristics of tram vehicles and infrastructures

In Chapter 2.2, the possibility of using trams to move freight and people using the same infrastructure has already been discussed and portrayed throughout the analysis of some real cases of implementation. Beyond the analysis of the single case-studies emerges an overall increase of the effectiveness of the mixed logistics solution for an ecological development of the cities, along with advantages in terms of avoided congestion. The key element of a tram-based 2L-MLS is represented by the infrastructure of the system. The construction of a brand-new tram line for the purpose of passenger and freight service could be taken in consideration, but the fixed costs for building a new tram infrastructure are considerable and for that reason the focus of 2L-MLS implementation is to optimize existent tram lines by making them suitable also for the traffic of goods. It is estimated that the cost for the linear tram infrastructure for the city of Paris is between 1.15 and 3.5 million of Euro per kilometers, while the whole infrastructure cost is equal to 22 M€/km, accounting for the costs of implementing an entirely new station [49]. It can therefore be derived that, by generalizing the specific case of Paris, the overall infrastructure costs for tram applications for the principal European metropolis can be vary within a range of 20-30 M€ per kilometer, depending on the specific characteristics of the city and the objective of the local administrators. Since the application of a two-level logistic model is currently considered an innovative topic and there are few existing implementations to take as reference, it is difficult to persuade founders and shareholders to build a completely new infrastructure for the sole purpose of combined mobility, considering that is yet a risky business for municipalities. Since the linear infrastructure cost is not so heavy to withstand, municipalities can consider the implementation of some parallel railway lines. For these reasons, the implementation of the two-level mixed logistics system could be based on utilizing an existent tramway line and, with few economical affordable arrangements to the original layout, and eventually install some supportive linear infrastructure. For an efficient implementation of the project, the goal of tram-based transport system should shift from moving people efficiently to a newer perspective of heighten freight transport at the same level of passenger transport, though the exploitation of a twofold service from which the two actors can benefit at the same time.

If, on one hand, the fixed costs of tram infrastructures are considerable and thus limit the investment to few adjustments to the existent line only, on the other hand something more could be said about the investments on the vehicles used for the service. Siemens is one of the biggest manufacturers of trams in Europe and their models are currently operating in some cities of Germany, Austria, and United States [50]. In 2018, the company tested a new variant of the model Combino equipped with cameras, sensors and radar in order to be autonomously driven. The test was performed in the city of Potsdam, near Berlin, and the vehicle was certified reliable for operations by the company, as a result of its outstanding performances during its trial operation [51]. The Combino autonomous tram, reported in Figure 3.1: Combino autonomous tram developed by Siemens, was able to respond swiftly to crossing pedestrians, vehicles, and any other obstacle, and thanks to its sophisticated algorithm was capable to stop at the desired station to let the passengers get in and off the vehicle. Hence, in future years, the implementation of self-driving tram vehicles operating in the major cities could become reality and thus municipalities could be involved in replacing their older fleets with newer autonomous ones.

Figure 3.1: Combino autonomous tram developed by Siemens

Source: The Guardian

One important obstacle for the renewal of the fleet is that trams may have an historical value and their replacement could displease the inhabitants of the city considered.

Two examples are San Francisco and Milan, where the models of the trams are very distinctive and have touristic value. For similar cases, a solution could be the utilization of autonomous vehicles together with the historical ones and designate the self-driving vehicles to freight transport only, while people could continue to use the traditional ones to move across the city. Figure 3.2 shows one of the most famous landscapes of the city of San Francisco, California represented by uphill and downhill lanes crossed by the tram network.

Figure 3.2: Trams operating in San Francisco (US)

Source: www.openhousebcn.wordpress.com

Although Siemens tested the autonomous Combino vehicles for the purpose of passenger transport, the possibility of using them for freight transport appears to be solid as well. One advantage of using freight-dedicated trams is that the intersection with passengers at the stations is avoided. The synchronization between passengers and freight operations is difficult to achieve due to the variability of the number of passengers using the service during particular hours of day and depending on the specific day of a week. On the contrary, loading and unloading operations are conducted with fixed time and are easier to organize with respect to the movement of people. Also, by differentiating the traffic of goods from the one of people, the safety for both is increased and furthermore the risk of damaging the goods is lowered, as well as the probability of incurring in theft committed by passengers. One drawback derived by the mixed operation along a tramway line is that, although the overall efficiency would increase, the infrastructure becomes less resilient to failures and accidents. In fact, in case of damages on the rails or malfunction of onboard devices in the vehicles, the whole tramway traffic is affected. Tram vehicles move on constrained paths, consequently there are no alternatives for reaching a determined destination using different rails if the main ones are temporarily unavailable, leading to the loss of effectiveness of the service causing disservice to both passengers and customers. For freight transport the damage could be limited by using temporarily 2nd level vehicles to perform the whole distribution service, thus converting the two-level system to a single level one until the damage is repaired or the rail network is ready to operate again. However, the trips that 2nd level vehicles were required to cover in this particular situation are too long and dispersed, and it becomes impossible to assess the optimal routes with reduced costs, even through the use of VRP algorithms.

It is interesting to define the modalities through which the trams are loaded with freight, as well as the physical locations where the pick-up and drop-off operations are performed. It has been already clarified that trains are among the most used vehicles for freight transport, for which their performances make them a valid alternative regarding medium and long-haul transportation [52]. Trains for dispatching goods are parked in dedicated rails or platforms next to commercial areas of the cities in specific hubs, waiting to be loaded with freight. Once they have reached the required load conditions, freight trains leave the station in order to move to other commercial platforms from which the goods are dropped-off from the train and then taken to companies and customers generally using diesel trucks. The movement of goods by trams resembles the supply chain described, but at the moment commercial hubs for trams do not exist, making difficult to move freight on light rails. One peculiar case is represented by the city of Karlsruhe in Germany, where the light rails have access to the heavy rail network, so that the commercial hubs are unified between trains and trams [53]. Figure 3.3 shows a model of tram used both for passenger and freight operations in Karlsruhe. The urban rail architecture in Karlsruhe is modeled for both trams and trains to run on the same infrastructure, allowing consequently an efficient exchange of goods by using dedicated trams which can perform delivery operations through the same commercial hubs used by trains. However, Karlsruhe represents a niche case, since the German city has always had a keen eye on the efficiency of the urban railway infrastructure as a whole. Generally, tram stations must be deeply revised to make the tram infrastructure ready to embrace the transport of goods without the support of the railway network.

Figure 3.3: Delivery operations on trams in Karlsruhe (GE)

Source: www.trasportieuropa.it

The choice of the tramway line for implementing 2L-MLS must be considered properly. The most touristic lines could, indeed, be excluded for the application of the project since the movement of people in those cases is the primary activity and there is consequently no space for a freight implementation to conduct in parallel. The reason behind this decision is that the elevated traffic of people heading to the most touristic destinations of the city requires in general tight schedules, in which could be difficult to include also freight activities. Good candidates for implementing freight services could be tramway lines built around places of interest which move a sizeable quantity of goods, for example lines whom terminals are consolidated companies which attract different kinds of goods, such as supply manufacturers or shopping malls. The famous example of the city of Dresden owes its success to the presence of Volkswagen's factory located as a terminal of the line, which contributed massively to the development of the project.

One valid alternative to the presence of selling companies along the line to be served by 2L-MLS could be hospitals. Although the movement of people is a crucial feature when considering the territory surrounding medical buildings, hospitals need to be supplied continuously with medicines and medical tools for surgery and hospitalization. The usage of trams for the delivery of such items could reduce road congestion, so that people can reach the hospital using their private cars faster.

Furthermore, the movement of ambulances and medical cars in case of emergencies is facilitated by the removal of vans heading to the hospital occupying the road network. The transport of medicines by light rail vehicles allows also to deliver to the hospitals products which requires cold temperatures through refrigerated cells which could be placed inside the trams or stored in the detachable wagons which, once the vehicle reaches the hospital, could be unhitched from the tram in case of presence of a small hub in the proximity of the hospital. Figure 3.4 shows a terminal tram station located in proximity of an hospital located in France that could be considered for freight management operations in a 2L-MLS perspective.

Figure 3.4: Tram station located near the hospital in Orleans (FR)

Source: Flickr.com

The modality of integrating freight and passenger transport for the tram service can be exploited in different manners, depending on the characteristics of the existent tramway line of the city considered. As described by Pietrzak O. & Pietrzak K., freight transport could be arranged in three different variants: freight wagon behind the passenger vehicle, cargo inside a passenger vehicle and dedicated freight vehicles [28]. The application of 2L-MLS presented in the thesis work is based on the third variant, for which passenger and freight service has in common only the infrastructure and therefore the interference is almost null. For this variant, the two activities are not simultaneous and thus the freight service could be unbounded from the passenger one, resulting in an operating framework which is easier to arrange. This solution leads to different advantages, which will be discussed briefly. First of all, the freight tram is not forced to stop at every station, but it could perform the delivery activities only in few stops, the ones which are interesting for a commercial point of view and located in strategical positions along the line. For example, in case of long straight avenues where the tramway line has stations located consecutively and with few distance between them, the freight tram may stop at only one among the stations cited, otherwise the service would result redundant and alter too much the flow of traffic. The strategic positioning of the station to serve with the freight service will be one of the key parameters of the model proposed in the thesis work. The second advantage is that, since freight management operations require more time with respect to passengers' ones, in case of simultaneous service the vehicle is forced to stop for longer times at freight stations leading to long idle times, consequently influencing passengers' satisfaction towards the service, and increasing the congestion of the tram network. Besides, hypothetical hindrance to the flow of road vehicles must also be considered: if freight operations require high amount of time, it is inconvenient to locate freight stations where traffic is already relevant. For the specific case, indeed, the tram vehicle becomes a massive obstacle to other cars and road vehicles. By adopting a disjointed operation mode, since cargo trams does not deal with people and stop only at determined stations, the time gained by skipping unnecessary stops along the route could be used to perform freight management operations, without congesting the light rail network.

3.1.2 2L-MLS: Freight storage facilities

As mentioned in the previous paragraph, for freight trams the focus should shift from people to goods. In that sense, for any station where the concentration of shops and commercial activity is considerable, there must be a dedicated space for the storage and the exchange of the parcels which are loaded into the tram, just like the hubs described for trains. Since tram stations are smaller with respect to the train ones, the smarter way to store the goods into a station could be throughout the implementation of smart lockers installed in the proximity of the considered stations, having restrained dimensions, in order not to interfere with people waiting at the tram stop. In this way, one or more employees could pick up the goods from the freight trams and store them in apposite lockers, ready to be consigned to the clients through 2nd level vehicles. Smart lockers could also represent the final destinations for the products shipped by tram, since some customers could decide to fetch their orders whenever they are willing to do with their own private vehicles.

Different companies currently utilize smart lockers to offer a versatile delivery service to their customers, which have the freedom to decide the period during which retrieve the parcels instead of being forced to wait for the deliverer to reach the destination indicated. This type of service is generally available for Business-to-Customers (B2C) deliveries, for which the availability to receive the item is dependent on the preference of the customer. Smart lockers are indeed a helpful solution for people which are rarely at home and could potentially have problems in retiring the order, or for people which prefer not to depend on the uncertainties derived by an ambiguous time window for the delivery. The best-known example of company which utilizes smart locker is Amazon, which offers to the customers the possibility of selecting as delivery destination the Amazon smart lockers, located in particular zones of the city (which could be shopping malls, town squares and others), instead of giving the home address. Once the parcel is deposited by the deliverer, the customer receives a notification through a phone message or email by Amazon, which informs the client that the package has been deposited in the accorded smart locker, placed in the zone selected by the client. Furthermore, a 6-digit code plus a bar code are provided by the email, both necessary for the customer to be identified by the smart locker interface. After three days are passed and the package has not been retrieved yet, the deliverer takes back the parcel and brings it to the company depots. It must be mentioned, however, that not every package can be stored in smart lockers. The geometrical features of the lockers establish a limitation thus excluding some parcels from the smart locker service. Amazon sets the maximum dimensions of the packages that can be delivered to smart lockers equal to 50x50x50 centimeters and the maximum weight equal to 20 kilograms [54].

A similar offer is provided by one of the biggest supermarket companies of Northern Italy, which is Esselunga. In addition to the service of home-shopping, for which a customer can make a list of desired food that will be brought directly home with dedicated vans by couriers, the company offers to customers the possibility to deposit their order in smart lockers waiting for the pick-up operation [55]. The dedicated smart lockers, shown in Figure 3.5, are generally located inside the buildings of the supermarket and consequently the time for which retrieve the items is directly dependent on the opening schedule of the supermarket. The modality used for informing the customers is remarkably similar to the one adopted by Amazon, in fact through emails customers receive the alphanumeric code and, thanks to the use of a personal QR code provided by the mobile app, the customer can be identified, and the lockers can be opened safely. This service is useful for people having little time to spend for shopping and especially for elder people, for which spending hours for collecting all the needed food and beverages could be a laborious activity. However, elder people could have difficulties with the identification operation required to unlock the smart lockers, since they require an adequate level of knowledge of technological tools like smartphone apps and digital codes.

Figure 3.5: Esselunga smart lockers in Milan (IT)

Source: www.milanoevents.it

The usage of smart lockers, as described above, is dependent on the exchange of information between the deliverer and the customer. In this perspective, the implementation of 2L-MLS must rely on a continuous communication between suppliers and customers. Therefore, an online platform for the exchange of data is necessary to ensure the effectiveness of operation both for the first and the second level of the logistic process, as much as their synchronization. Employees working at the second level operations must be indeed advised when the item is placed into the smart lockers, so they can carry the goods to the final customers. Also, the business activities which want to fetch the items directly from the lockers must be notified when the package is available. Thus, the creation of a new internet platform for exchanging data and codes useful to unlock the lockers is fundamental for the two-level infrastructure, creating a network like the one used by Amazon and Esselunga. Through the digital platform, the customers can inform the provider of the service whether they want to retrieve the parcel by themselves at the lockers or wait for the 2nd level vehicle to bring them the order. In this way, an intelligent virtual framework is created between the three parties (1st level, 2nd level and customers) and the resources can be organized in the best possible manner allowing a precise synchronization between the parties, reducing the number of missed deliveries. The network could be accessible through a dedicated smartphone application, in order to be easily utilized by the people with their devices and allowing fast communication between the users.

For the model proposed, smart lockers are considered the standard way to store palletized parcels at the stations, but they are not the only facilities that can be used for storing items. As previously described, goods are transported either by completely new vehicles with the purpose of freight transport only, or by trams converted from passenger to freight service. In both cases, the space inside the vehicles can be fully occupied by the goods and is large enough to accommodate packages having different sizes. When the tram reaches a station of interest, the packages need to be stored somewhere to wait for the pick-up operations carried out by 2nd level vehicles or final customers. Smart lockers represent a good solution for the storage operation, but they have physical limits of capacity linked to their moderate dimensions. For this reason, some regulations are imposed on the maximum size of the parcels which can be stored into the smart lockers. However, due to geometrical limitations, some bigger items are excluded from being stored in smart lockers. For example, medium-to-big electrical appliances like fridges or ovens cannot physically be stored in the smart lockers because of their dimensions. In order not to limit the freight service to small packages only, some solutions could be studied to solve the geometrical dimensions issue. Products which require determinate temperature and humidity conditions cannot be stored too, because smart lockers are not equipped with sensors capable of monitoring such conditions.

One way to make 2L-MLS inclusive towards all the types of market is to develop a new type of storage system located internally to some selected stations. A feasible solution could be to attach dedicated cargo wagons to the freight trams, in which big-sized items and refrigerated cells can be transported. Once the tram arrives at the station for the drop-off operations, the entire wagon could be unfastened from the tram and, thanks to secondary rails which does not interfere with the run of trams and road vehicles, could be left in the station under the supervision of the freight operation employees. Once the wagon is unhooked, the freight tram can proceed to the next station while the wagon itself act as a moveable locker where the biggest items are stored. The action of detaching the cargo wagon is also faster than the entire process of unloading all the commissioned packages one by one from the freight tram at the station. Once the wagon is unloaded completely from packages, the next freight tram which reaches the station could fasten up the empty wagon and carry it away along its trip. Cargo wagons could also be attached in series; but in case of multiple cargo wagons the maximum permissible length could be overcome. In order to use cargo wagons for delivery operations, there must be space for a secondary rail infrastructure where the cargo wagon can be unhooked, that must be long enough to host the wagon when is unfastened, but at the same time relatively short for interfere the least with the traffic and avoid large monetary expenditures. The implementation of secondary rails is feasible only for particular conditions, for examples in large squares and less trafficked avenues, while for congested streets the unladen cargo wagon could be an obstacle for the regular circulation of the traffic.

The maximum capacity of the entire freight service is not limited to smart lockers and cargo wagons. Distribution Centres (DCs) can be placed in some parts of the city to store temporarily the freight into a dedicated area where goods can be stored even for several days. DCs are used in case of long-term deliveries, where the quantity of items is considerable, and the customer is not interested to have the stock in store immediately. If tram stations have enough available space, DCs could be installed in place of smart lockers due to their larger storage space they ensure.

In summary, the delivery solution proposed for the Two-Level Mixed Logistic System discussed in the thesis work will be a twofold service configuration for passengers' movement and distribution of goods performed by trams acting as 1st level vehicles, for which freight can be transported during the deliveries by using the internal space of the vehicle or through cargo wagons attached to the back of the tram, with the possibility of unhitching them in particular stations. Then, for the 2nd level activities, passengers are no more involved in the system and the city freighters are loaded with the freight and take them to the local activities operating in the zone considered, or to DCs in case of long-term deliveries.

3.2 Description of the model to be used for the preliminary technical analysis of the 1st level of the 2L-MLS using trams

This chapter of the thesis work proposes a model for the preliminary technical analysis of 2L-MLS, specifically referred to the choice of trams as 1st level vehicles. The procedure for the complete assessment of the 2L-MLS project, reported in Figure 3.6, consists in the preliminary technical analysis presented for trams, a technical analysis devoted to 2nd level vehicle and, finally, a custom-made MCA to assess benefits and drawbacks of the implementation. Since the parameters studied by MCA can be accounted only after the feasibility of a project has been already tested and certified for both the levels of the system, Multi-Criteria Analysis is an operation that has to be performed as conclusive step, in order to assess the parameters that are not related to technical features. Without the support of an adequate MCA, the project could be doomed to failure even though from a technical point of view is suitable. As a matter of fact, if financial and economical, as well as social and environmental, objectives are not met, the project will result as not convenient for stakeholders and communities, with the consequence of halting the entire project in the initial phases. Future studies can examine in depth which are the better methodologies to construct a Multi-Criteria Analysis which suits adequately the case of 2L-MLS proposed, as well as the criteria to consider. The aim of the model proposed is to give an answer to the following questions:

- Is it possible, from a technical point of view, to implement a tram-based 2L-MLS using a certain tramway line of the city studied?
- Which conditions are the most favourable for tram systems towards the implementation of 2L-MLS?
- How is it possible to select the most appropriate candidates among a defined pool of alternatives for the choice of the city and the line for 2L-MLS?

The utility of the model relies on its simplicity of application for assessing the suitability of 2L-MLS, given determined conditions. The model explained is a methodology for discerning the favourable from the unfavourable conditions for the implementation of 2L-MLS and is intended to be an important instrument upon which MCA lays its foundations. Moreover, the model can be appreciated for its replicability towards different contexts, which allows to use it under different circumstances.

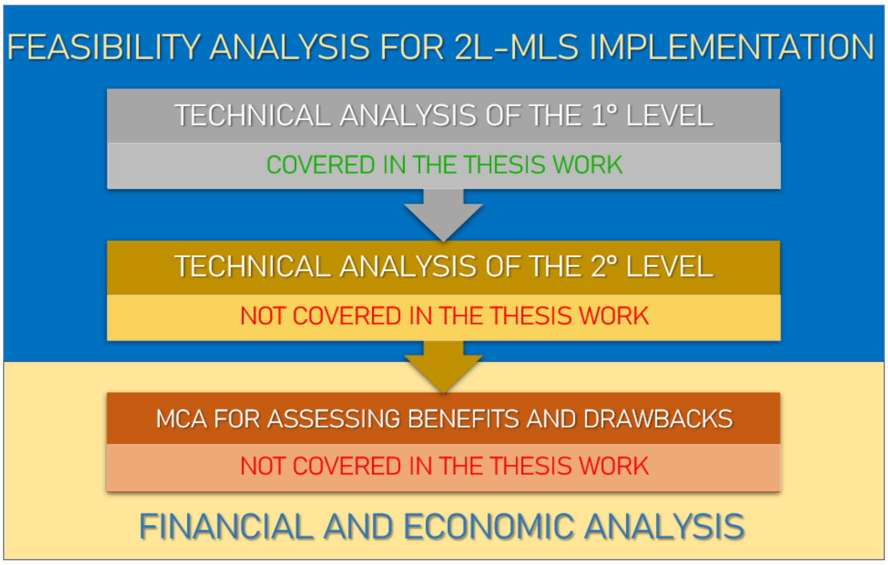


Figure 3.6: sequence of operations to carry on for the implementation of 2L-MLS

The core of the model proposed is to give support to decision-makers in understanding whether the urban context for which the implementation of 2L-MLS shows favourable conditions. Four main steps are recognizable in the procedure, as shown in the flow chart presented in Figure 3.7: the choice of the city in which implement the 2L-MLS, the choice of the line amongst the ones belonging to the city chosen, the choice of the stations in which implement mixed operations of exchange of people and goods and finally the selection of the time period in which introduce the freight service in the network. The flow chart accounts for every operation that must be carried out for completing the preliminary technical analysis of feasibility of the 2L-MLS project using trams as 1st level vehicles, from the definition of the pool of candidate cities to the choice of the time period for freight service of the logistics system.

TECHNICAL ANALYSIS OF FEASIBILITY FOR THE 1° LEVEL OF 2L-MLS USING TRAMS

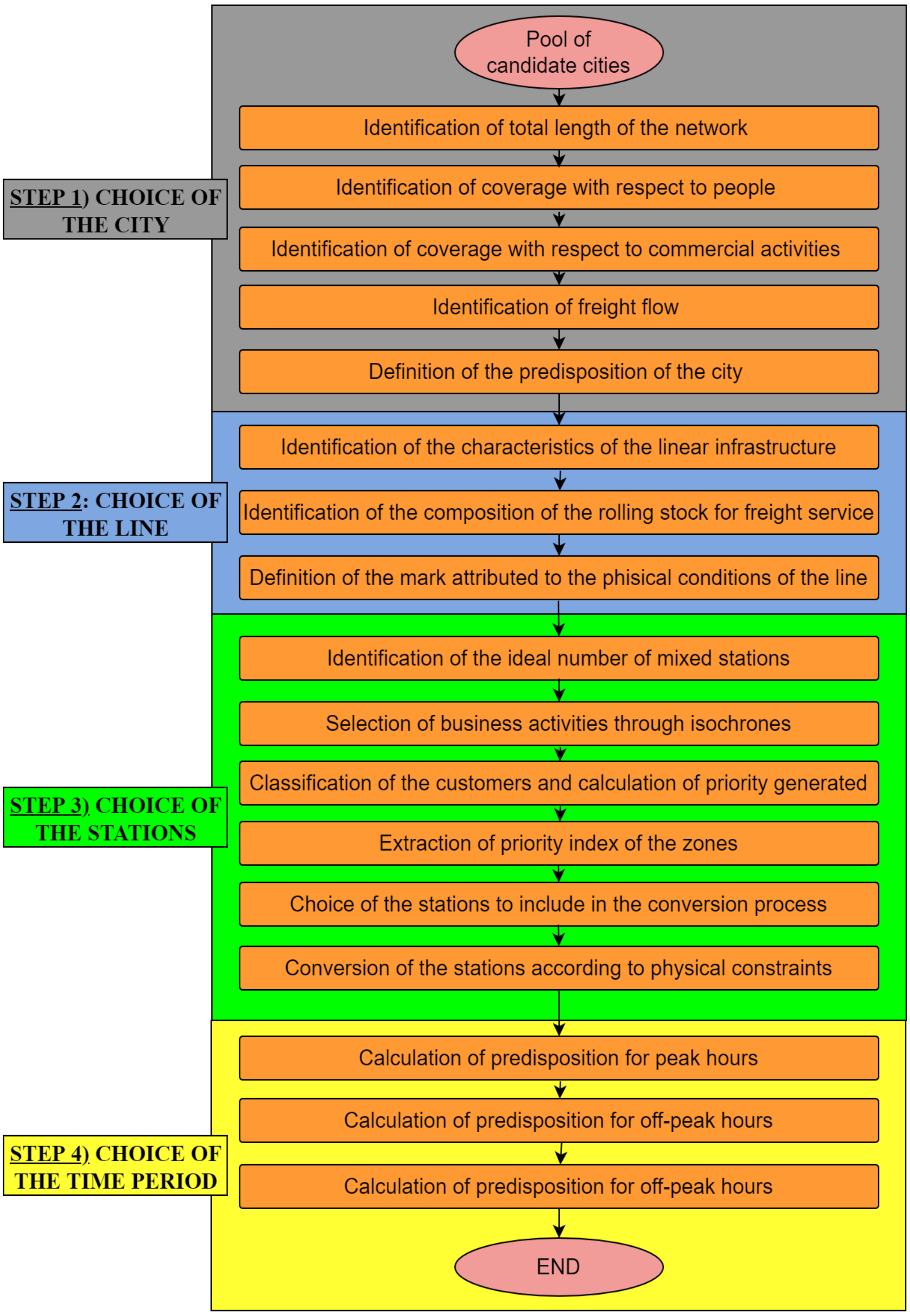


Figure 3.7: Flow chart of operations for the preliminary technical analysis of the 1st level using trams

The first step of the procedure is dedicated to the selection of the city in which the conditions are most favourable for the 2L-MLS implementation proposed. Once the most suitable city has been chosen, the next step is to select the tramway line of the city for the 2L-MLS operations. A broad evaluation of the characteristics of the tramway service and infrastructure is carried out in this phase, giving estimations about their performances, and classifying them by using marks. The third step of the procedure refers to the selection of the number and the location of the stations along the line to convert into mixed operation stations, according to the indications provided by the municipal authorities and physical constraints related to the installation of auxiliary infrastructures. The last phase of the technical analysis regards the time window in which implement the freight service, namely the time schedule of the freight trams. From the definition of the time schedule, two main parameters stand out, which could be utilized in the upcoming MCA for the financial assessment of the project: the number of vehicles needed to perform the freight service (related to fixed costs) and the headway between the trams operating in the network (related to organization and operational costs).

The main steps of the procedure are thematized using dedicated colours: grey is associated to the choice of the city, blue to the choice of the line, green to the choice of the stations and finally yellow to the choice of the time period for freight service. For visualization purposes, the tables referred to the steps reported are referenced using the colours aforementioned.

In order to choose which are the city and the line that better serve theoretically as actor of the 2L-MLS proposed, the parameters considered in the preliminary technical analysis are ranked by using marks, given to the city/line considered. The marks are the result of a hierarchical clustering analysis, where the number of levels identified is equal to 5: *"Excellent"*, *"Good"*, *"Fair"*, *"Ordinary"* and *"Poor"*. Alternatively, the method used in the model to assess preferences towards parameters, whether is not possible to establish a hierarchical classification for the parameters obtained, is the Delphi method, which is a technique used to address parameters which have not a quantitative definition and can be debated by experts having different points of view on the same issues.

Delphi is a method used for structuring a group communication process, so that it allows a group of individuals to deal with complex problems as a whole [56]. Typically, judgement of experts is obtained by surveys interspersed with controlled opinion feedback [57]. Thanks to this technique, is possible to properly give weights for values which may have more or less importance depending on experts' own opinion. Thanks to the advancement on the literature on the topic, nowadays is possible to build up the correct team of experts for any applications, identifying the precise number (5 to 20) of people involved, as well as their expertise sector, the heterogeneity of the pool selected, and the number of structured rounds to come to a fine result [58]. By following this principle, for the project of 2L-MLS using trams, the pool of experts must comprise technicians of tram infrastructure, urban and civil engineers, administrative figures and statistics specialists for a better assessment of the clustering method to apply for the classification of any parameter considered.

3.3 Step 1) Choice of the city

The implementation of 2L-MLS using trams can take place only in cities where several conditions are met. For the definition of these conditions, four parameters are considered, which are able to give an overall definition of the predisposition of the city towards the implementation. The cities having a total score of predisposition which is higher than a certain threshold are the ones in which 2L-MLS implementation can be considered. The sequence of operations to perform in order to obtain the value of predisposition of the city C is reported below:

- Identification of the total length of the network l_N and assignment of the correspondent mark for the city considered;
- Identification of the coverage with respect to people ρ_P and assignment of the correspondent mark for the city considered;
- Identification of the coverage with respect to commercial activities ρ_A and assignment of the correspondent mark for the city considered;
- Identification of the freight flows within the boundaries of the city f_F and assignment of the correspondent mark for the city considered;
- Definition of the predisposition of the city C.

The aim of this step of the preliminary technical analysis is to assign a value of C to any city belonging to the pool of candidates for the implementation of 2L-MLS. In this way, the cities of the pool can be listed and classified in terms of predisposition towards the implementation. The key feature for obtaining the final value of C is to assign a non-dimensional mark to each of the four parameters, so that they can be summed together for extracting the value of C. The marks are given taking in consideration the number of candidates of the pool of cities considered, thus varying from application to application, depending on the dimension of the pool considered. For example, a parameter for the choice of the city for 2L-MLS can obtain a high score when analysed over a national horizon, but the mark can be lower (or higher) when the comparison is made considering different candidates. Thus, the methodology followed is based on a comparative approach rather than an exclusive one.

In order to have non-dimensional values for the marks obtained, a relationship between the value of the measured parameter analysed and its correspondent mark must be outlined. Measurements of the selected parameter are performed for any candidate city, then the cities are classified according to Equation (3.1)

$$i^{th}\ position = 5 - (i-1) * \frac{5}{N-1}; \quad i = 1, \ldots, N \tag{3.1}$$

Where N is the number of candidate cities. By using the equation reported, the marks are assigned according to the relative positions of the cities of the pool, classified according to the calculated parameter, thus the distance between the values of the measurements is neglected, in favour of a more uniform distribution of the marks.

In order to understand better the definition of the marks for a generic parameter, an example of pool of candidates equal to 7 cities is reported. In this case, marks are assigned according to

Table 3.1.

CITY	POSITION	MARK
E	1st	**5**
A	2nd	$5 - 1 * \frac{5}{6} = \mathbf{4.167}$
G	3rd	$5 - 2 * \frac{5}{6} = \mathbf{3.333}$
D	4th	$5 - 3 * \frac{5}{6} = \mathbf{2.500}$
B	5th	$5 - 4 * \frac{5}{6} = \mathbf{1.667}$
C	6th	$5 - 5 * \frac{5}{6} = \mathbf{0.833}$
F	7th	$5 - 6 * \frac{5}{6} = \mathbf{0}$

Table 3.1: Example of assignment of marks according to a hypothetical pool of 7 candidates

The marks assigned in this way to the four parameters l_N, ρ_P, ρ_A and f_F, indicated respectively with L_N, P_P, P_A, F_F, have value between 0 and 5. Consequently, the value of C obtained through the weighted sum between the four parameters is also a number between 0 and 5. Based on the value of C obtained through the analysis portrayed, the cities are labelled according to Table 3.2, which shows the correspondence between the marks obtained and the predisposition of the city towards 2L-MLS implementation.

MARK	DEFINITION
$\mathbf{4 \leq X < 5}$	*Excellent*
$\mathbf{3 \leq X < 4}$	*Good*
$\mathbf{2 \leq X < 3}$	*Fair*
$\mathbf{1 \leq X < 2}$	*Ordinary*
$\mathbf{0 \leq X < 1}$	*Poor*

Table 3.2: Definition of grades corresponding to the marks

The cities labelled as *"Good"* and *"Excellent"*, corresponding to a mark higher or equal to 3, are the one considered for the implementation. A city can be labelled according to the labels defined in Table 3.2 depending on the pool of candidates which is compared to. As a matter of fact, by considered different candidates, the ranking changes as well. Moreover, by varying the number of candidates N, the numerical score assigned to the positions change as well, influencing the final value of C.

The first parameter to consider is the total length of the network l_N. This feature is a useful indicator of the current conditions of the tram network. The total length of the network is expressed in kilometres and could vary between few kilometres for small cities up to hundreds of kilometres for the most developed tram networks around the globe, with the longest tram network infrastructure that is located in Melbourne, Australia having length of 250 kilometres and generating over 200 million of journeys per year [59]. For the European situation, for example, the situation of the minimum and the maximum length of the network, corresponding to a score equal respectively to 0 and 5, is the following:

- Minimum: Sevilla, Spain = 2 km;
- Maximum: Saint Petersburg, Russia = 216 km.

The 10 biggest European cities for the total length of the tram network are listed in Table 3.3, where also the number of lines is reported for each city, updated to July 2019 [60].

CITY	COUNTRY	NETWORK LENGTH (KM)	N° LINES
Saint Petersburg	Russia	216	37
Odessa	Ukraine	208	23
Berlin	Germany	174	22
Moscow	Russia	170	44
Milan	Italy	170	19
Katowice	Poland	168	26
Vienna	Austria	165	28
Budapest	Hungary	160	26
Sofia	Bulgaria	154	14
Cologne	Germany	149	10

Table 3.3: Top 10 European cities classified according to the total length of the tram network length (km)

Source: [60] & [61]

The majority of the biggest European tramway networks are located in the eastern region of the continent, and the main countries are Russia, Ukraine and Poland. Regarding Central Europe, the cities having significant tram networks are located in Germanophone countries and Italy. Regarding the four main cases of tram applications of freight transport service, reported and described in Chapter 2, they were implemented in cities having a considerable total length of the network:

- Vienna: 165 km;
- Dresden: 130 km;
- Amsterdam: 94 km;
- Zurich: 81 km.

This means that one of the most important conditions for the implementation of the 2L-MLS is to rely on a well-organized tram infrastructure, adequately widespread across the city considered.

What is useful for the sake of the analysis of the predisposition analysis of the cities is the mark assigned to the measured value of total length of the network, indicated as L_N, which varies from 0 to 5 depending on the position of the city considered in the ranking. The length of the network represents only one of the parameters taken in consideration to assess whether a city is predisposed for the implementation of 2L-MLS using trams. Hence, the analysis of the suitability of the tram-based 2L-MLS for a determined city cannot be expressed only by the total length of the network, but rather by considering also other parameters which relate to the efficiency of the tram freight service, linked with the potential commercial activities that could be interested in the project and the flow of freight within the boundaries of the city.

The information obtained from the total length of the tramway lines can be combined with two parameters which account for demographic and economical characteristics of the city, which are the inhabitants of a city and the number of commercial activities of the urban area analysed. The ratios between the total length of the network and the two parameters abovementioned represent the second and third parameters for the computation of the predisposition of the city. Thus, the density of the tram network with respect to people and commercial activities can be calculated as shown in Equation (3.2) and Equation (3.3).

$$\rho_P \left[\frac{km}{10^4\ inhabitants}\right] = \frac{l_N}{p} \tag{3.2}$$

$$\rho_A \left[\frac{km}{10^4\ commercial\ activities}\right] = \frac{l_N}{a} \tag{3.3}$$

where p is the number of inhabitants and a is the number of the commercial activities in the considered city, divided by a factor of 10^4. High values of ρ_P and ρ_A correspond to a tram network which is able to serve people and freight adequately thanks to a good distribution of the tramway network along the city considered, while low values of ρ_P and ρ_A accounts for highly dispersed tram networks that barely cover the needs of passengers and freight. As usual, what is important to define for the definition of the predisposition of the city C is not the measured value, but the correspondent non-dimensional mark, indicated as P_P and P_A. Note that the city having maximum value for one parameter could be different when analysing the others, as not always the city having higher value of density with respect to people have also the higher value of density for commercial activities.

The fourth and last parameter useful for the computation of the value of C is represented by the quantity of freight per day which cross the boundaries of the city analysed, expressed as f_F. Instead of accounting for the number of parcels, generally in case of freight transport the unit of measurement used is the weight of the cargo expressed in tonnes. Thus, the unit of measurement which is the most interesting about urban freight transport is tonnes per hour [ton/h] of freight which enter and exit the boundaries of the city. Thanks to this parameter, the number of avoided trucks dedicated to delivery operations can be computed, thus obtaining a useful indicator of the reduction of the air pollution that can be achieved through the 2L-MLS implementation that can be evaluated in the successive MCA to be performed. As a matter of fact, once evaluated the total capacity of the 2L-MLS in terms of tonnes per hour, the number of equivalent trucks that would be replaced by 2L-MLS vehicles can be obtained as well, thus acquiring information about the avoided pollution derived from using 2L-MLS vehicles for delivery operations instead of trucks.

The freight flow is the only parameter of the four regarding freight movement. The total length of the tram network and the coverage with respect to passengers and freight are static value which do not depend on the movement of freight. The choice of considering mostly static parameters instead of dynamic ones is justified by the extremely limited availability of data regarding urban freight. Furthermore, there is also little consistency or standardization in terms of the data collected about urban goods and vehicle flows. Options to improve the current quality and quantity of urban freight data in many cities, and especially in developing countries, appear expensive and unlikely to occur quickly. Moreover, there is also a significant lack of performance benchmarking between cities and for this reason comparisons are difficult to be made and. Ranking systems and experts' support through Delphi analysis are therefore necessary for the model to be effective. The development of an international benchmarking tool, such as the Urban Freight Transport Index (UFTI), could assist cities in comparing their sustainable logistics performance, enabling the identification of suitable solutions and investment opportunities for local implementation [62]. This index could be developed through consultation with policy makers, logistics experts, shippers, carriers, third party logistics providers and industry associations. In order to evaluate the impact of the freight flow occurring in the city f_F on the predisposition of the city C choice of the city, as in the previous three parameters, the value obtained must be converted to a non-dimensional mark to ensure comparability between factors which accounts for different units of measurement, expressed as F_F.

The equation for the calculation of the predisposition of the city C can be finally written down, as shown in Equation (3.4).

$$C = w_1 * L_N + w_2 * \mathrm{P}_P + w_3 * \mathrm{P}_A + w_4 * F_F \tag{3.4}$$

The equation is composed by the mark assigned to the total length of the network L_N, to the coverage of the tram service with respect to people and commercial activities P_P and P_A and to the freight flow F_F. $W_c = [w_{C1}, w_{C2}, w_{C3}, w_{C4}]$ is the vector of the weights having the following characteristics:

$$0 < w_{Ci} < 1 \ ; \ \sum_{i=1}^{4} w_{Ci} = 1$$

The values of the weights w_i are assigned through Delphi methodology for ensuring a fair benchmark between the cities and their characteristics. The value of C will result to be a number between 0 and 5 and the cities of the pool will be defined according to the range of values indicated in Table 3.2. Cities that are labelled as *"Good"* and *"Excellent"* are considered suitable for 2L-MLS implementation, with preferences towards the ones occupying the highest positions of the ranking according to the value of predisposition C.

3.4 Step 2) Choice of the line

Once the decision over the city of interest to select for the implementation of 2L-MLS is taken, the following operation of the decision-making process is to select the line of the tram which is considered the best candidate for the implementation of the mixed operation system. Before looking at the elements situated in the proximity of the tram railway, such as shopping activities, locations of interest and others, which are of greater importance in the decision-making process and will be exploited successively, an evaluation of the existent tramway infrastructure and rolling stock is undertaken to understand if their characteristics are aligned with the requirements needed for operating the mixed service.

Similar to the case of the assessment of the city, the pool of candidates is referred to all the tramway lines of a city and the ones located at the top of the ranking are considered for the project. The main difference between the two decisional cases is that in case of choice of the line the marks assigned to parameters is related to specific characteristics and is not the result of a comparison. Hence, if different lines have the same physical characteristics, they can score the exact same mark for the parameters presented in this paragraph. The main driver for the choice of the line is the potential demand of freight generated by the implementation of the 2L-MLS service. Indeed, the more customers able to participate in the project and the higher are the revenues for the stakeholders of the 2L-MLS. Even though the demand analysis is performed in the successive phase of the model proposed, being related to the zones in which the station of the tramway line selected are located, it is equally important with respect to the physical characteristics. For this reason, the constraints on the physical conditions of the tramway lines are less tight: unless the mark attributed to the physical conditions of a line L is lower than 2.5 on a scale from 1 to 5, any line could be considered in terms of physical characteristics. For this step of the procedure, the minimum physical conditions of the line are sufficient for the implementation, while the analysis of the stations is the most important driver of the whole process of assessment.

The two parameters considered for the calculation of L are the linear infrastructure of the line I, focusing in particular on the situation of the terminals, which could be loop stations, switch-back terminals or a combination of both, and the tram fleet conditions V. The two parameters are then weighted based on experts' judgement and summed up to obtain the value of L.

The first thing to consider about the parameters related to the linear tramway infrastructure is the type of terminals of the selected line. Generally, there are two solutions: loop station, for which the tram is unidirectional and changes the direction of traffic through a circular arrangement of the railways at the terminal, and switch-back terminal. In the latter case, tram vehicles need to be bidirectional to perform the service in the other direction. Since the fleet used for freight service is either bought from zero or obtained by using passengers' vehicles of the line considered readapted to the transportation of goods, the typology of the terminal stations does not represent a main obstacle for the implementation of the tram freight service: if the former passengers' trams were operating in the said lines, being mono or bidirectional, the same vehicles could run the service also for freight. However, the modalities of transport of freight vary depending on the arrangement of the terminals.

In case, for example, of switch-back terminals, and consequently of bidirectional vehicles, cargo wagons hinged to the loco cannot be utilized because, after the change of direction, the cargo wagon positioned behind the tram would be instead located in front of the tram, thus impeding the regular operation of the service. For the situation of switch-back terminals, hence, cargo wagons are not accounted for the service and this decision has several consequences on the overall freight service: if, on one hand, the secondary rails are no more necessary, thus avoiding installation costs and modification of the zones around the line, on the other hand the overall capacity of the 1st level of the delivery of goods is heavily reduced, affecting inevitably the efficiency of the system. In order to be opened to the possibility of implementing secondary rails for a better coordination between tram vehicles, the better solution is always to consider lines having two loop terminals, solution that allow the usage of cargo wagons hinged at the back of the trams. Figure 3.8 shows two possible configuration of the terminals, one case in which both the terminals have a loop configuration and the other one in which there is a hybrid configuration with one loop and one switch-back terminal. If, in the first case, the cargo wagon can be hinged without impeding the driveability of the vehicle, the same cannot be said in the second case, for which during one route of the tram, the cargo wagon would stand in front of the main cabin, thus impeding the regular circulation of the vehicle.

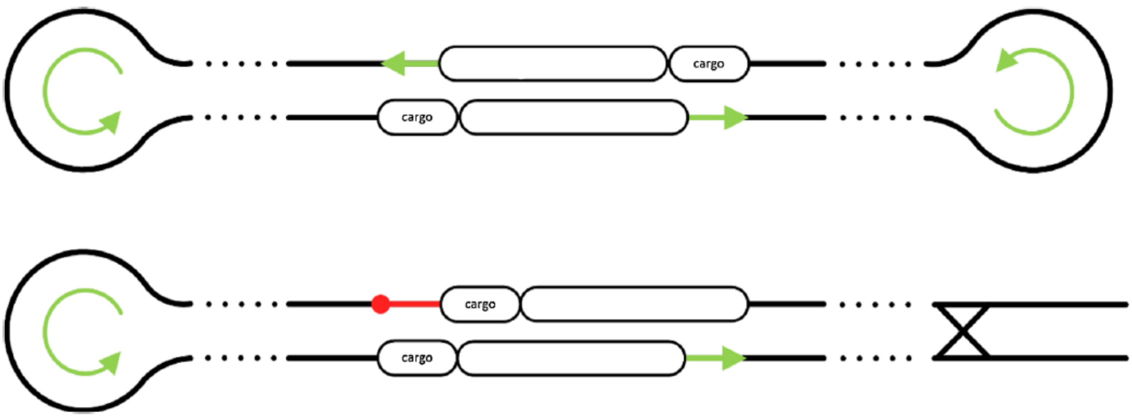


Figure 3.8: Loop terminals and mixed terminals configuration

Source: image readapted from [28]

The case of two switch-back terminals is represented in Figure 3.9, through which is possible to understand that the tram must be bidirectional and being able to ensure smooth operations for employees on both sides of the vehicle.

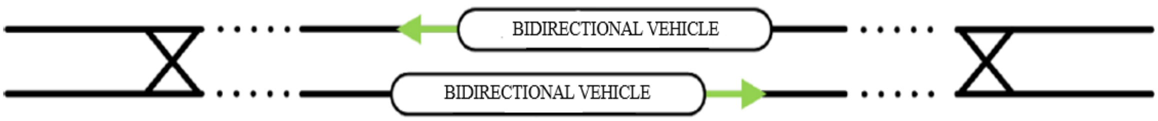


Figure 3.9: Switch-back terminals configuration

Source: image readapted from [28]

Two loop terminals are also the best condition if the freight service need to be implemented only in the two terminal stations, without serving any intermediate stop. However, for the described delivery operation, a coordination with the already busy passenger service is substantially impossible to implement. The only case in which is possible to implement freight services only for the terminals is during nightly operation, when passengers' circulation is not present on the line and the freight trams can travel without obstacle from one terminal to the other.

In case of two loop terminals arrangement, the freight vehicle can be hinged to a cargo wagon in order to increase the capacity of the transportation system as long as broaden the typology of freight that could be transported by the freight tram thanks to special cabins with temperature control which could be loaded on the wagon. Secondary rails are needed to leave the cargo wagon at the freight station for allowing freight management operations of the employees together with acting as an extra storage space located in the freight stations together with smart lockers. Secondary rails could be existent unused light rails adjacent to the passenger service rails or could be built totally from zero, where the physical constitution of the traffic network of the area of interest does not represent an impediment for the construction. The construction of secondary rails is indeed related to the condition of the surroundings of the specific tram stations along the line: not in every station is possible to increase the tramway infrastructure because of road traffic conditions, lack of space for construction and dedicated lanes which have no further space to enlarge the rail infrastructure. Secondary rails can also have an important scope: in addition to serve as storage space for cargo wagons and thus being useful only in cases of two loop terminals, they can be used as an instrument to allow the exchange of positions between two consequent trams. In brief, the freight tram can move faster or slower on the network with respect to passengers' trams, depending on the situation in which is involved. In order not to create traffic condition on the light rails, thanks to secondary rails the tram which is moving faster can overtake the one moving slower, thus increasing the viability of the system. This situation will be discussed in detail in the fourth step of the procedure, when the topic of the selection of the time period is exploited.

The combination of the characteristics described about the tramway infrastructure are ranked following the same principle as described at the beginning of the chapter, that is by using marks from 1 to 5 to express the preferences for the implementation of 2L-MLS in the analysed line, as portrayed in Table 3.4. Note that the most favourable condition is also the most difficult to implement due to the lack of urban space for construction that characterize the urban environment. The considerations reported about the disposition of secondary rails are linked with the capability of the vehicles along the line to overtake the precedent ones in case of network congestion.

LINEAR INFRASTRUCTURE	MARK
2 loop terminals with secondary rails for every station in which mixed activities are performed	5
2 loop terminals with secondary rails only for terminals and few stops along the line (without the possibility of unhitching the cargo wagons due to the impediment generated on the network)	4
2 loop terminals without secondary rails	3
2 switch-back terminals (or 1+1) with secondary rails only in few mixed stations	2
2 switch-back terminals (or 1+1) without secondary rails	1

Table 3.4: Ranking of linear infrastructure characteristics

The focus is now shifted on the vehicles used for 2L-MLS. The assessment of the fleet is related to the one dedicated to freight transport only. If the freight vehicles to utilize are going to be purchased, the preference is towards modern autonomous vehicles, even if at the present time is still difficult to imagine the implementation of a freight vehicles which can overtake passengers' trams when needed. An example of autonomous vehicle could be Siemens Combino, which seems to be a promising solution for the future of the tram service. Siemens sells on the market both the mono and the bidirectional models, named respectively Combino and DuoCombino [50], so the type of terminal infrastructure is not a driver of the choice for the introduction of autonomous vehicles, which can be implemented in lines having loop terminals or switch-back terminals indiscriminately. Currently the autonomous vehicles are still prototypes and thus not available on the market, but with the high development rate of the technology, is not difficult to imagine a future implementation of autonomous trams in the principal cities within the next 10 years. For the analysis portrayed, it is hypothesized that autonomous vehicles dedicated to freight transport are already available in the market, even though this condition will probably be achieved only in the next years.

The decisions about the rolling stock for freight operations are made considering the aging factor of the vehicles currently operating. If the conditions of the trams are still acceptable, the vehicles intended for freight service could be the ones currently used passengers' transport with few adjustments, which could be the elimination of the seats dedicated to passengers or the construction of platforms and dedicated space to ease the freight operations for the employees. The revamping of the existent fleet for performing freight service could be an efficient solution in terms of usability of the current assets and reduction of the costs, however it is always preferrable to opt for new vehicles to avoid failures when the project has been implemented. If the current rolling stock's conditions are considered not acceptable, or a renewing of the fleet was already programmed, newer non-autonomous vehicles dedicated to freight operations could be purchased. This solution seems to be the most realizable one in short-term perspective, since the technology behind autonomous vehicles is currently not mature yet for the use of them for freight service, also considering the coordination with the passengers' vehicles, difficult to program for autonomous trams. In long-term perspective, the best solution for the choice of the vehicle would be to have a fleet composed entirely by autonomous trams, but decision-makers could still opt for traditional trams. Table 3.5 shows the ranking of the composition of the freight rolling stock.

COMPOSITION OF THE ROLLING STOCK FOR FREIGHT SERVICE	MARK
100% autonomous fleet	5
Mix of autonomous and non-autonomous new vehicles	4
100% non-autonomous new fleet	3
Mix of new and revamped vehicles (non-autonomous)	2
Old fleet adapted to freight service	1

Table 3.5: Ranking of freight fleet compositions

Through a weighted sum between the score assigned to trams' infrastructure and fleet, is possible to compute the parameter accounting for the performances of the overall physical characteristics of freight trams for the line considered, which is shown in Equation (3.5).

$$L = \alpha I + \beta V \tag{3.5}$$

where L is the parameter related to the physical characteristics, I and V are respectively the score assigned to the linear infrastructure and the freight fleet, while the values of α and β are weights assuming values between 0 and 1. These values depend on the importance given by decision-makers to the characteristics of the infrastructure and the vehicles using calibrated weights. Regardless, L assumes a value between 1 and 5, being a weighted sum between two parameters having values in the same interval.

A noteworthy consideration is that 2L-MLS implementation could be not restrained necessarily to only one line of the city. If the conditions are favourable and the demand for freight service is high enough, two or more lines can be converted to mixed operation service. The feasibility of the mixed service on a line, however, does not ensure that the line will be chosen for the project. As addressed at the beginning of the paragraph, the driver for the choice is freight demand: if customers' interest in the project is too low, even if a line gains the maximum score amongst the other in terms of physical constitutions, that line will not be chosen for the implementation of 2L-MLS.

3.5 Step 3) Choice of the stations

The word "station" when talking about trams is intended as a synonym of the word "stop", which is the most accurate term to identify the place where the tram stops to allow passengers to get in/off the vehicle. The word "stop" for trams identifies a place in which the only activity possible is the movement of passengers, where no other services like info points, snack vendors or toilettes are offered. The stop is a small place for which people have just enough room to sit while waiting for the next tram, generally equipped with a projecting roof for protecting people from rain and snow and a time schedule of the service attached on the walls. Nowadays, since the trams are vehicles very similar to trains, the current terminology identifies the term "stop" as equal to the term "station", even though the definition of "station" for trains is wider and comprehend different services coexisting in the same place. So, for the analysis regarding trams as 1st level vehicles, the words "stop" and "station" are synonyms, even if the more correct work to identify a place where a tram stops to allow passengers' movement is the first one.

The topics discussed in this paragraph are strongly related to the ones of the choice of the line, since the disposition and characteristics of the freight stations of a line deeply influence whether the tramway line chosen is the most suitable or not. The more the line attracts goods and customers and the more the demand for the 2L-MLS is increased, which generates a higher traffic of goods moved by the freight trams, with positive environmental and social externalities, in terms of avoided congestion and pollution. While the previous paragraph revolves around the physical characteristics of a tramway line, the current paragraph takes in consideration the zones touched by the 2L-MLS implementation.

A tram station needs to fulfil certain requirements to be considered suitable for freight services, such as its dimension and the number of commercial activities around its vicinity. Only if a station can be widened in terms of available space, it can be considered available for freight service, given that tram stations have generally limited width for passengers. Consequently, to host freight operations and storage facilities in the same place, the station must be revised and enlarged. The freight management operations must be performed safely both for employees and for other people waiting at the stop, with the freight that must not represent an obstacle to the regular people's movement. Tram stops that are placed along a straight long course are unlikely to be considered as candidate for freight operations, since little space for implementation of storage systems and enlargement is available. Also, when the tram lanes are separated from the road traffic, it results arduous to build freight storage facilities, since the dedicated lane is usually put between the two roadways and the space for operation is rather limited.

The sequence of operations for the procedure for identifying the number and the position of the freight stations along the line is the following:

- Identification of the ideal number of mixed stations S_0 for the line analysed;
- Selection of the business activities through the use of isochrones;
- Classification of the business activities and calculation of the priority generated by the customers;
- Extraction of priority index of the zones, based on the cumulated priority generated by the customers;
- Choice of the stations to include in the conversion process, based not only on demand analysis but also on physical constraints;
- Conversion of the stations from passenger only to mixed operations of passenger and freight services, according to the physical constraints.

The first operation is the definition of the ideal number of mixed stations along the line S_0. It has been already discussed that having freight stations distributed over short distances is detrimental for the flow of the network, other than being redundant for the customers. The number of freight stations must be high enough to justify the investment of the 2L-MLS on the chosen line and low enough to allow a fluid circulation of both passengers' and freight vehicles. It is up to the agreements discussed between decision-makers and local authorities to define the exact number of mixed stations along the line, according to the already discussed physical and logistical limitations.

Once the definition of the number of stations is completed, the following operation is to choose which ones among all the stations along the tramway line are the best options to be selected as freight stations. The choice of the stations is based on a model which takes in consideration two main parameters: the traffic of freight generated and the promptness of delivery required by the customers which are served in the station. The combination of these two parameters results in a definition of priority levels generated by the customers considered. The number of potential customers of a zone is considered by including all the business activities which are willing to take part in the 2L-MLS project within a defined range of the station. The range of research for business activities in proximity of the station considered is defined using isochrones, having the station considered as centroid. All the activities that could be reached by

2nd level vehicles within a defined time are included in the freight demand analysis. The isochrones are calculated considering different traffic conditions and different vehicles that can be used for performing the 2nd level of the 2L-MLS, therefore the value of the isochrones must be studied considering different criteria. The value of the isochrones in the model is set according to the idea of "city in 15 minutes" proposed by Borghetti et al. [63]. City in 15 minutes derives from the idea that each person should be able to reach in maximum fifteen minutes all services related to work, housing, health, education, culture and leisure, starting from home. This innovative idea of smart city is also sustainable from an environmental point of view, increasing the accessibility of LPT services. By using the city model idea reported, isochrones are generated considering the stops of the tramway line as centroids and the business activities for the demand analysis within a distance by walking lower than 15 minutes.

For the priority analysis, only fixed deliveries are considered, in order to standardize the flow of freight and, thanks to fixed demand, allowing decision-makers and public authorities to create a time schedule for freight movement which can be invariant for long time periods. Therefore, e-commerce and B2C deliveries are not considered for the 2L-MLS implementation, given their unpredictability and variability from one day to another. Once the potential customers are assessed, any of them within the range defined is assigned to a number from 1 to 5, according to the level of priority that generates, as shown in Figure 3.10. The activities having the maximum score are the ones for which the 2L-MLS is the most favourable system to bring the goods, while a lower value results in decreasing priority rate generated by the activity. It is worth mentioning that not only business activities attract freight: public services and medical buildings could also represent potential customers of a freight service performed by trams.

DEMAND ANALYSIS OF THE ACTIVITY		QUANTITY OF PRODUCT [KG/DELIVERY]		
		HIGH	MEDIUM	LOW
PROMPTNESS OF DELIVERY [DELIVERY/MIN]	HIGH	5	4	3
	MEDIUM	4	3	2
	LOW	3	2	1

Figure 3.10: Freight demand analysis

Activities that generate the highest priority are for examples shopping malls, hospitals, food courts and all other retailers which requires enormous amount of goods to be delivered in a very short time. Grocery shops and coffee shops are defined by medium and low quantity required, but also high promptness of delivery, while electrical appliances vendors or industrial company suppliers require high amount of goods but with limited levels of promptness. The result of the classification is a vector of number having dimension equal to the number of customers considered, for which every value of the vector is a number between 1 and 5. The vector of the activities $A_i = [a_{i1}, a_{i2}, \dots, a_{in}]$ generated as described is computed, where:

- i = ID number of the zone/station;
- n = number of activities within the boundaries of the zone i;
- a_{in} = score assigned by decision-makers to activity n of the zone i.

Vector A_i has dimension equal to n, and since for any zone i considered the number of activities considered varies, a comparison of the stations based on the number of activities is not possible to perform. What can be done instead, is to count the number of activities having the maximum scores for each zone considered, to extract the information about the number of customers which require the considered rate of priority in the zone considered according to Figure 3.10. The algorithms presented are programmed on Matlab, a software designed for the analysis of data, the development of algorithms and creation of simulation models.

Algorithm 1 Extraction of the number of high-priority activities of a zone i.

```
A_i = [a_i1, a_i2, ..., a_in];
n = length(A_i)
count5 = 0;
i = 1
  for i = 1:n
    if A_i(i) == 5
      count5 = count5 + 1;
    end
  i = i + 1;
  end
count5
```

The last action of the algorithm allows the visualization of the number of activities having a mark equal to "5" in terms of priority. With slight changes to Algorithm 1, the number of activities having marks equal to the other values can be computed as well. For example, In Algorithm 2 the computation of the number of elements of vector A_i having a value of priority equal to 4 is shown.

Algorithm 2 Extraction of the number of activities of a zone i having value of priority equal to "4"

```
A_i = [a_i1, a_i2, ..., a_in];
n = length(A_i)
count4 = 0;
i = 1
  for i = 1:n
    if A_i(i) == 4
      count4 = count4 + 1;
    end
  i = i + 1;
  end
count4
```

Similarly, the number of commercial activities which generate priority equal to three, two and one can be computed. Finally, the vector containing the number of the activities having scores of respectively five, four, three, two and one of the zone i can be computed:

$$B_i = [count5, count4, count3, count2, count1]$$

Thanks to this procedure is possible to obtain, for each zone i, a vector representative of the situation of the priority generated by the activities in such a way that the vector B_i has always dimension equal to five, regardless of the number of activities considered for each zone. The definition of the series of vectors B_i enables to make comparisons between the zones.

With the vector of weights $W_S = [w_{S1}, w_{S2}, w_{S3}, w_{S4}, w_{S5}]$ is possible to assign an aggregate value of priority to any zone i, to be compared to the one generated by the other stations. The values of the weights are given by following the empirical indications provided by Equation (3.6) and Equation (3.7), from which emerges the relative importance given to activities having priority equal to 5 over the other ones.

$$w_{Si} = a * 4^{i-1} \quad for\ i = 1,2,3,4 \tag{3.6}$$

$$w_{S5} = b * w_{S4} \tag{3.7}$$

Parameters a and b are defined according to decision-makers willingness of highlighting the significance of the weights related to the highest levels of priority stand out with respect to the others.

The priority index attributed to a station i is computed through Equation (3.8), where the values of the vector of the activities B_i are related to their corresponding weights. Finally, the stations are ranked based on the priority index P_i obtained.

$$P_i = w_5 * count5 + w_4 * count4 + w_3 * count3 + w_2 * count2 + w_1 * count1 \tag{3.8}$$

The following operation of this step is the assessment of the feasibility of the conversion of passengers' stations into mixed operation ones. From the described inspection, S number of stations along the line selected can be converted. If the number of convertible stations S is equal or higher than the one previously assessed S_0, the stations in the first S_0^{th} positions of the ranking among the ones that can be converted becomes mixed operation stations. If, instead, S is lower than S_0, two things can be done: converting all the feasible stations into mixed ones even though the number of freight stations results to be less than the one ideally planned or reconsidering some parameters and then repeating the procedure. The latter operation represents the link between the choice of the stations and the choice of the line: decision-makers can opt for considering another tramway line of the city for the implementation of 2L-MLS.

Another important topic that can be discussed in this phase of the process is the possibility of implementing Distribution Centres in the zones around the freight stations. This operation enables to reduce transportation and operation costs of the supply chain and improves the operation efficiency and logistics performances [64]. The identification of DCs location is a crucial procedure in the design of efficient logistics systems, considering both cost and non-cost factors, and is heavily influenced by green economy policies. DCs for multi-echelon logistics services are located outside the main core of cities in order to provide a dispatching zone for goods, as well as an extra storage space in which freight can be placed for days or weeks being controlled by fully qualified employees. In a perspective of utilizing DCs for a 2L-MLS, small depots built internally to the zones of interest could serve not only as intermediate storage facilities between 1st and 2nd level, but also as intermediate points of the supply chain positioned between 2nd level vehicles and the final customer. Not all the parcels need to reach the customers in short times, either because a fast delivery is not possible or not specifically required. Thus, 2nd level vehicles carrying these types of products will take the goods from smart lockers and cargo wagons (when available) located in the freight stations to the nearest DC instead of picking up the parcels and heading directly to the customers. This procedure can be used to clear the storage systems of the freight station, thus creating space for the upcoming freight tram which will locate the freight into the previously emptied storage facilities.

DCs serve the purpose of increasing the maximum capacity of the delivery service in terms of storage of freight. If, indeed, without considering the presence of DCs the capacity of the system would have been entirely constrained by the freight storage infrastructure located at the stations, with the introduction of DCs there are specific locations dedicated to the storage of long-term delivery freight. DCs for 2L-MLS implementation do not need to be large as the ones located in the outskirts of the city, in fact they could be small instalments where items are temporally stored before completing the delivery. If the result of the demand analysis is that extra-space is needed for increasing the efficiency of the system, decision-makers can consider installing DCs in proximity of a freight station in order to increase the entire capacity of the storage systems of the area. When talking about tram stations, they are infrastructures located mostly in the residential and internal part of the cities, consequently it could be difficult to find locations for the implementation of DCs having close distance to the mixed operations station. One solution could be to use the space provided by parks and green areas, as well as squares and pedestrian zones to install small DCs in proximity of a freight station. In-depth studies must be carried out to assess the allocation of DCs in urban contexts. Since the thesis work is focused on the performance of trams acting as 1st level vehicles, the allocation of DCs is left to other studies mainly focused on 2nd level performances of the 2L-MLS. The model proposed accounts for the possibility of installing DCs near the stations considered when a panoramic about the stations is needed for the definition of the candidate stations to become mixed ones. The presence of eventual DCs is a surplus for the choice of a station, regarded as positive feature which, however, does not influence the choice of the stations, because it is referred to a flow of freight which is successive to the one moved by trams: as long as the tram have enough capacity to carry the freight to the freight stations, the demand is considered as fulfilled.

After having defined the number and the disposition of the stations along the line, the total amount of freight required by the customers of 2L-MLS can be obtained simply by summing up the demand of all the freight stations. An operational planning must be carried out to organize the time period in which perform the delivery operations for the customers considered. Thanks to the dilution of the deliveries during the entire working day, drop-off operations will be simpler for employees at the stations, which have both to load the smart lockers for parcel storage and load the 2nd level vehicles to complete the delivery. If all the freight were scheduled to arrive in a station at the same moment, the time needed for employees to manage the said operations will be considerable, having detrimental impact on the whole tram network.

Based on the freight demand of all the stations considered, a time schedule of the freight service can be outlined, and consequently the number of routes performed by freight vehicles are computed. The maximum capacity of a freight tram is equal to 16 tonnes [65] if a passengers' tram is converted to operate as freight tram, as the case of autonomous Combino models, but can be higher if vehicles are fabricated with the purpose of freight service, like in the case of CarGoTram in Dresden where the maximum capacity of the vehicle was equal to 60 tonnes [27]. Also, by considering the presence of cargo wagons, the maximum capacity of a converted passengers' tram could increase of extra 15 tonnes [66]. Hence, the maximum capacity of the freight service is related to the type of vehicle chosen and its composition. Since decision-makers already knows the type of freight vehicles are going to be used, as well as the possibility of hitching cargo wagons, the maximum capacity of the whole freight service is known a priori and consequently the number of routes needed for freight vehicles to fulfil the demand can be computed using Equation (3.9).

$$Routes\ \left[\frac{routes}{day}\right] = \frac{Demand\left[\frac{ton}{day}\right]}{Capacity\left[\frac{ton}{vehicle}\right]} \tag{3.9}$$

The definition of the demand coming from the totality of the customers served along the line is impossible to assess without contacting every single customer that will participate in the project. Making general assumptions on the potential demand is something that could be misleading, since the type of product delivered makes the difference in terms of weight. To make the model accessible to decision-makers before assessing the real freight demand of customers, since the capacity of cargo trams is at least equal to 60 tonnes when considering freight-dedicated vehicles, regardless of the freight requested by customers, the demand is always assumed as fulfilled. Moreover, in real cases, not all the commercial activities of the zones could be interested in receiving freight via 2L-MLS, thus reducing the number of customers served by the project. For these reasons, the capacity of the tram vehicles should not represent a limit to the implementation of the project.

3.6 Step 4) Choice of the time period

In order to define the period during which deploy freight vehicles in the tram network, some considerations can be made about how time schedules for LPT services are assembled. Tramway services generally follow tight schedules for which the time needed for trams to move from one station to the following one is in the range of 2-3 minutes, considering normal traffic conditions. The stations are located along the line having much shorter distances between them with respect to railway counterparts, generally situated within 400-600 meters [67]. It is intuitive to understand that, according to what has been written above, a tramway line which operates for 10 kilometres requires the presence of approximately 20 stops, which is a considerable number of stations to serve. Hence, trams' operations are scheduled considering frequent stops of the vehicle, affecting deeply the overall commercial speed of the service. The commercial speed of trams is lower than the one for trains, because the distances to cover between the stations are shorter and the tram stations are more copious with respect to trains, also considering the different power of traction between trains and trams.

Trams are LPT vehicles capable of performing with a high frequency of activity, with headways with ranges from 3 to 5 minutes when they perform the service in peak hours. For the implementation of 2L-MLS, decision-makers have to estimate which is the hypothetical frequency of the passage of freight trams and arrange both passengers’ and freight trams schedule allowing a fine coordination between the two services avoiding situations of overlapping of the vehicles. The definition of the time schedule of freight trams is crucial to identify the number of vehicles needed to perform the service. The three alternatives considered for the model for providing freight service through dedicated trams are during peak hours of the day, during off-peak periods and during night-time.

The integration of trams dedicated to freight operations in the network without affecting the time schedule dedicated to passenger service is a hard task to accomplish, because the headway between two consecutive passengers’ tram is already short, especially for peak periods. In such a way, inserting an elevated number of freight vehicles in the network enhances the risk of saturate the viability of the network, thus creating favourable condition for congestion with the possibility of having multiple vehicles stuck one behind the other. The main consequence is a direct impact of efficiency of the system, which lead to dissatisfaction either for travellers or for customers of the delivery service. Even if the choice of the time window within the freight operations occur is set during off-peak hours, a slight adjustment to the schedule is still required. The reason is that because passengers’ trams, despite being reduced in terms of number of vehicles and consequently having longer headways, are still running onto the same light-rails used by freight trams, with the only difference with respect to the passengers’ ones represented by a longer headway. The only period of time for which the freight transit can flow without obstacles is during night-time, with duration that varies depending on the LPT operator and city analysed. During this period, passengers’ activities are not performed and the whole network is at disposal of the freight operations. Feasibility studies must be undertaken in case of night operations and special permits must be acquired to operate on tram network during this window of time. The rails, for example, may not be able to mechanically withstand a continual operation for 24 hours per day and furthermore nightly operations can cause a disturbance to the people living nearby the tram network.

The model proposed for the choice of the time period is not exclusive towards the candidates. As a matter of fact, a combination of the three solutions proposed is possible if the results obtained are satisfactory. Before studying the three periods considered for freight service, it is important to know what the parameters over which the passengers' schedule are shaped and make some considerations about their interdependence. First, the distance between two stations is a constant value, since freight services will be implemented in an already operative framework, the location of the stations will be same with respect to passenger service only. Another parameter that can be considered fixed is the commercial speed of the vehicle, depending by the model used in terms of tractive power. This parameter is also influenced by the distance between stops and the number of stations along the line where the vehicle stops for let passengers in and out. Once the distance between consecutive stations is knows, together with the commercial speed of the vehicle, is possible to compute the scheduled arrival time of trams i at a determined stop. The equation of the scheduled arrival time at stop $(n + 1)$ is reported in Equation (3.10):

$$t_{i,0}(n+1) = t_{i,0}(n) + \frac{d_j}{V_{c,j}(n)} \tag{3.10}$$

where $t_{i,0}(n)$ is the scheduled arrival time at the previous station n, d_j is the length of section j between the two tram stops and $V_{c,j}(n)$ is the scheduled commercial speed of the tram in section j.

This procedure can be applied both for passenger and freight trams. In the latter case, the distance between the stops is higher because freight trams can skip determined stations which are considered not interesting for freight transport. By repeating the procedure for every stop of the tramway line, the entire schedule of the trams is built up, from the starting station to the final terminal. The difficulty lies in the scheduling of two different services with vehicles moving at different speeds whilst sharing the same infrastructure. In fact, freight trams move faster on the network because they skip some stations, but the few times that they stop for picking up and dropping off goods they expend considerable time.

3.6.1 Peak hours operation

During peak hours, the headway between passenger trams is supposed to be the shortest possible, to be able to fulfil travellers' high demand. For instance, a headway equal to 5 minutes in peak hours conditions is chosen. Consequently, in this case a station is reached by 12 vehicles in one hour of peak period, one every 5 minutes of activity (without considering delays). Given that during peak hours is difficult to increase the number of vehicles running on the infrastructure, which is already saturated, feasibility studies may be conducted to understand whether is possible to replace at least one of the passengers' dedicated trams with a freight tram, without having detrimental impact on passengers' circulation. Figure 3.11 shows the sequence of vehicles operating during a peak hour of the day in one direction, assuming that the headway of trams is equal to 5 minutes, both for passenger service only and for the proposed mixed service. Passengers' and freight vehicles are indicated with "P" and "F" respectively.

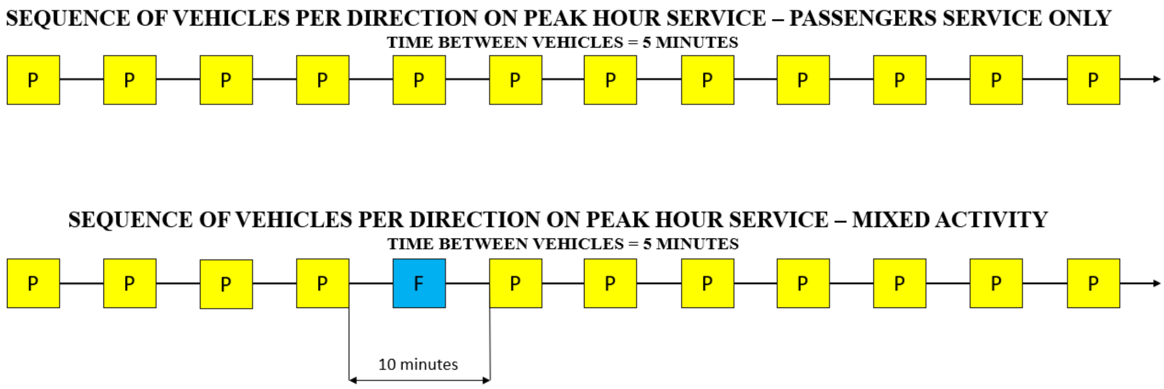


Figure 3.11: Tram service distribution of vehicles within one hour of peak service, considering 5 minutes of headway

For the section of the chain of the mixed activity service composed by P – F – P vehicles, passenger service occurs at a distance in time equal to two times the scheduled headway, which in the case described is 10 minutes. Hence, the freight tram has a margin of 10 minutes to operate between the two consecutive passenger trams without entering in contact with the passenger vehicles. Freight and passengers' trams, although they follow the same constrained path, operate through different modalities and so their relative distance is not constant: when the freight tram skips some stations, it gains time with respect to passengers' trams and approaches the vehicle which foreruns, thanks to its higher commercial speed, as shown in Figure 3.12. On the contrary, during the pick-up/drop-off operations the freight tram loses time, due to slower freight management operations with respect to passengers' flow of people on and off the vehicle. In this case the tram accumulate delay from the first passengers' tram and consequently the passengers' tram that follows approaches the freight tram, as reported in Figure 3.13. Hence, the freight tram has distances with respect to the passengers' vehicles that are continuously changing: once the freight vehicle skips stations, it approaches the first passengers' tram, while when the freight tram is managing freight operations in the stations of interest, it is approached by the upcoming passengers' tram. Note that the distance between the two passengers' vehicles is still the same, equal to 10 minutes in the example reported, because the passengers' vehicles have the same modality of operation.

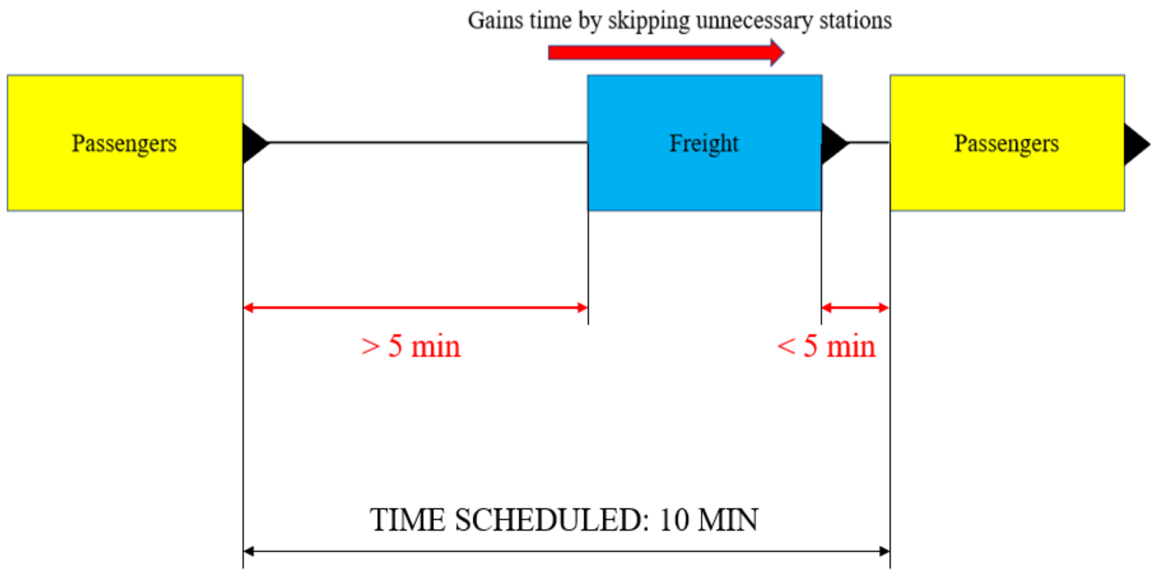


Figure 3.12: Time gained by the freight vehicle

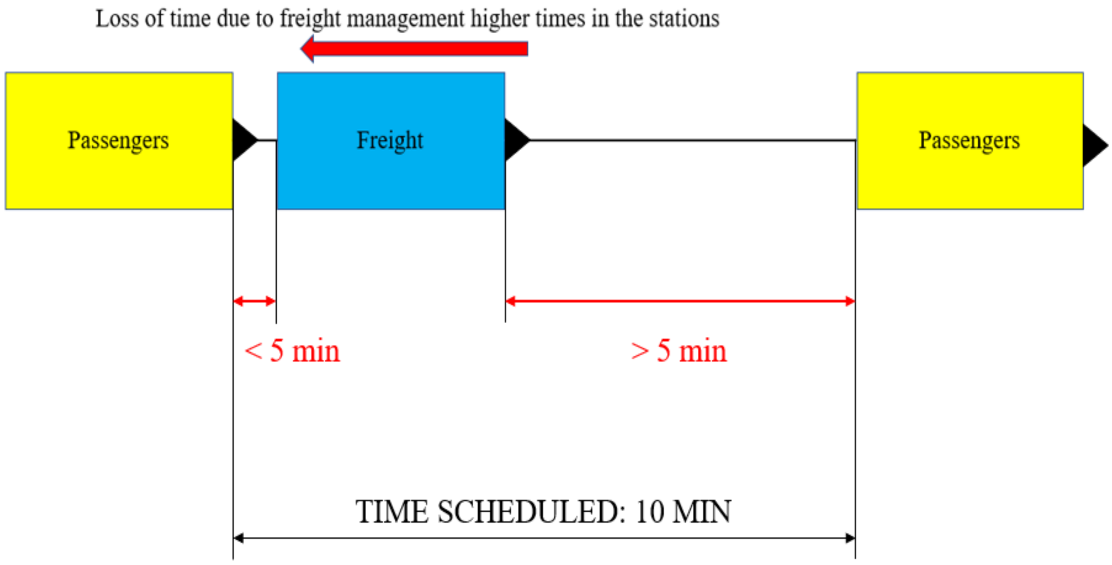


Figure 3.13: Time lost by the freight vehicle

When freight operations take more time than the expected one, which is generally set in a range of 3 to 5 minutes, the freight trams could represent a hindrance to the passengers' tram which follows. As a matter of fact, if the distance in time between the freight tram and the passengers tram which follows is lower than the one need by the freight management operators at the stations to complete drop-off/pick-up operations, it could happen that the passengers tram is forced to stop along the route because the freight tram is still carrying out the operations at the freight stop, thus accumulating delay and congesting the network. To avoid this unpleasant situation, secondary rails are used not only for the unhitching of the cargo wagon, but also to let the passengers' trams be able to overtake the freight trams and not create traffic along the tram railway. It is also to be considered that if the freight tram is overtaken by the passengers' tram, it will be positioned between two passengers' vehicle as before, but for this case the time in which it can operate is no longer equal to 10 minutes as scheduled, but it is reduced to 5 minutes. The reason is that, in the forecasted schedule, a gap of 10 minutes between two consecutive passengers' tram was predicted only one time, following the example reported in Figure 3.11. Nevertheless, since the stations where the freight operations take place are far less than the total ones of a line, the freight tram can catch up quickly to the passengers' tram which had been overtaken by. In this case, the passengers' tram has become an obstacle for the freight one, contrarily to the previous case. To allow the freight tram to overtake the passengers' vehicle, re-entering the 10 minutes gap originally disposed for the service, it is possible to build secondary rails also in stations where freight operations are not performed, to increase the locations in which trams can overtake each other to enter the scheduled operative framework.

Depending on the demand of the freight service, the number of vehicles operating in one hour for freight operations can be increased, as shown in Figure 3.14, where three freight vehicles are scheduled per hour per direction. Decision-makers must find the adequate number of passengers and freight vehicles to operate in the same period in order not to decrease the overall passengers service efficiency. Thanks to demand analysis, it is possible to identify the number of vehicles needed for freight operations: if only one freight route is enough to fulfil customers' demand over one hour of service, as for the example reported, a single vehicle is enough to operate the entire service, given that the length of the line is low enough to allow the freight tram to come back to the starting station within one hour and that loading operations are fast enough to let the tram in service according to the schedule. The less vehicles are needed for the service, the less the purchasing and operational costs, with the drawback of a less resilient service in case of defaults. Municipal authorities can force decision-makers to prioritize the passenger transport whether is possible (except the case of night shift in which passengers service is halted), so a maximum number of freight trams per direction per hour is set, depending on the period of the service: in case of peak hours, stricter limitations could be imposed on the maximum number of freight trams in circulation, while for nightly operation the constraints are less tight.

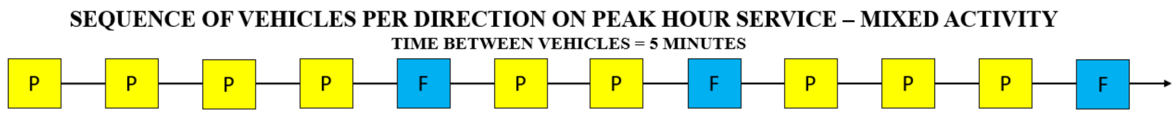


Figure 3.14: Multiple freight vehicles operating within one hour of peak period

Freight vehicles could also be scheduled to be consecutive along the sequence of vehicles, as reported in Figure 3.15. In case of higher demand from one or more customers to be delivered in short time, the vehicles that move goods are two in a short period of time, hence delivering twice the number of parcels to the station facilities. Nevertheless, the implementation of two consecutive freight tram has noticeable impact on passengers' circulation on the tram network. The result of having two freight vehicles moving back-to-back is indeed that the two passengers' trams between which the dedicated freight trams are operating would have a headway that is too high to deploy an efficient service for passengers. Moreover, since the capacity of the freight vehicle is consistent, is unlikely that a single customer would need two vehicles for completing the delivery order. Consequently, the disposition of consecutive freight trams is not considered for the 2L-MLS application.

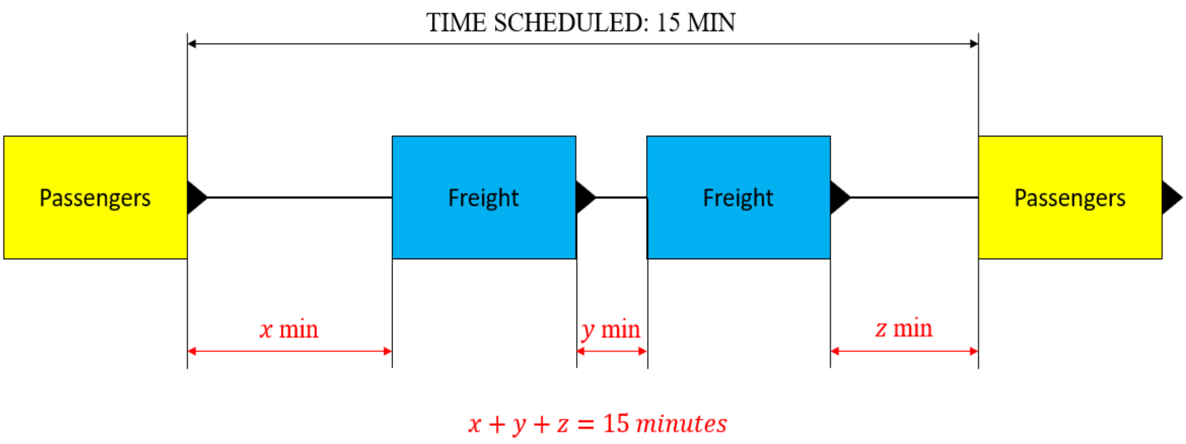


Figure 3.15: Time situation with two consecutive freight trams

In the following tables, the main parameters related to peak hours operations are listed and ranked with value from 1 to 5. In Table 3.6, the marks are given accounting for the minutes of headway of the regular passengers' trams: if the headway is high, the number of freight vehicles that could be inserted in the network is high, therefore the efficiency of the freight service is better. On the contrary, an overly congested network is not suitable for implementing freight service during peak hours, resulting in inefficient use of the network for freight operations.

SCHEDULED HEADWAY OF PASSENGERS' TRAMS	**MARK**
8 or more minutes	5
7 minutes	4
6 minutes	3
5 minutes	2
Less than 5 minutes	1

Table 3.6: Classification based on the frequency of passengers' tram (peak hours)

The higher the number of freight vehicles in service per hour, the better the 2L-MLS results in terms of satisfaction of the freight demand. A compromise must be found when looking for the correct number of freight vehicles to use, because an overly large number of freight vehicles operating together with passengers' trams would only be detrimental for both the services, since they share the same infrastructure. The maximum number of freight vehicles which can perform the service sharing the network with passengers' tram is equal to 1/3 of the total number of vehicles in the network per direction. For higher proportion, the number of freight vehicles on the network is too high to guarantee an efficient passenger service. Hence, for the number of freight vehicles per direction per hour in the network performing the service, there are two extremes:

- Minimum: one vehicle;
- Maximum: 1/3 of the vehicles in the network.

If the total number of vehicles is number which cannot be divided by 3, the number should be rounded to the higher integer. Marks equal respectively to 1 and 5 are attributed to the abovementioned conditions. Since the 2L-MLS implementation is focused on the performances of the freight delivery service, a higher number of vehicles results in a better mark, even though it afflicts the performances of passenger service. For all the alternative solution between the two extremes, a linear interpolation between 1 and 5 is performed to extract the mark correspondent to the number of vehicles per direction per hour selected. For the example considered, three alternatives are possible, with the correspondent marks reported in Table 3.7.

NUMBER OF VEHICLES	MARK
3	5
2	3
1	1

Table 3.7: Mark assigned to the number freight vehicles for the specific example reported

The value of the mark equal of "3" to the condition of having two freight vehicle per direction per hour on the network is given through the linear interpolation between 1 and 5. Since this alternative correspond to the mean value of the number of vehicles of the other two alternatives, the mark assigned is the mean value between the marks of the minimum and the maximum number of vehicles. Notice that the assignment of marks to the number of vehicles is strictly related to the number of vehicles per direction per hour, consequently it changes for any period of service and for any line analysed, depending on the headway set between trams.

The last parameter to take in consideration for the computation of the favourability of operating during peak hours (and the other periods as well) is the resilience R of the system to inconvenience that could be traffic jams or failures of the infrastructure. This value needs to be identified through Delphi analysis, by consulting the pool of expert which are able to perform a measurement based on different parameters and express a univocal value on a scale from 1 to 5, namely from *"Poor"* to *"Favourable"* condition of resilience of the network. Although the exact value is obtained by Delphi method and consequently known only after experts' decisions, it is possible to identify a pattern of the behaviour of R with respect to the different time period analysed: the more the network is congested and the more the service is sensitive to any inconvenient. So R will have lower values in case of peak hour implementations, while its value will rise for off-peak and nightly freight service.

The value attributed to peak hour service is expressed through a weighted sum of the scheduled frequency of passengers' trams, the number of freight vehicles operating in one hour in one direction and the coefficient of resilience R, as shown in Equation (3.11).

$$T_{peak} = \gamma * h + \delta * V_F + \rho * R \tag{3.11}$$

where γ, δ and ρ are weights having values between 0 and 1, h is the headway of passengers' trams and V_F is the number of freight vehicles to insert in the network in one hour of service.

3.6.2 Off-peak hours operation

For the case of off-peak hours of service, the considerations are the same of the peak hours condition, with the difference that the headway between passengers' trams is higher and thus is less difficult to insert in the network freight trams. During this period more vehicles and consequently more freight is moved with respect to peak hours. The synchronization with 2^{nd} level vehicles is also easier to organize since they operate in a less congested road network with respect to peak hours, making just-in-time deliveries more efficient.

Table 3.8 refers to the headways of passengers' trams during off-peak hours. In this case the headway between passengers' vehicles is higher with respect to peak hours because passengers demand is lower, hence the values of headways associated to the correspondent score is different.

SCHEDULED HEADWAY OF PASSENGERS' TRAMS	MARK
10 or more minutes	5
9 minutes	4
8 minutes	3
7 minutes	2
Less than 7 minutes	1

Table 3.8: Classification based on the frequency of passengers' tram (off-peak hours)

Thanks to the higher headway between trains with respect to peak hours, a higher number of vehicles can run on service. The choice of off-peak hours is thus suggested when higher freight demand is required by the service. As in case of peak hours operations, the number of freight vehicles operating in the same hour must be defined considering the potential interference with passengers' vehicles, in order not to congest the network. Higher headways allow for a higher number of vehicles, thus the higher limit of number of vehicles in the network is set equal to 1/2 of the vehicles running per hour per direction:

- Minimum: one vehicle;
- Maximum: 1/2 of the vehicles in the network.

In case of odd numbers, is better to give priority to passenger service, so the rounding is carried out to the lower integer. As mentioned for the case of peak hour operations, the intermediate marks are assigned through linear interpolation.

The value of resilience *R* of the system to inconvenience and faults is higher in case of off-peak operation, as a consequence of the lesser number of vehicles in service. Once again, this value needs to be appraised by Delphi analysis, since different types of actions can affect the overall resistance of the network.

The value attributed to off-peak hours service is expressed through the same formula used for the assessment of peak hours operations, as shown in Equation (3.12).

$$T_{off-peak} = \gamma * h + \delta * V_F + \rho * R \tag{3.12}$$

In this case, the values of γ and δ could be different from the ones used for peak hours analysis, due to a variation of the importance of the parameters h, V_F and R when dealing with off-peak hours situations. For example, during this period more emphasis could be given to the number of freight vehicles because the demand to fulfil is higher, while, since the passengers transport is more relaxed, the value of the headway of passengers' trams could be less important for this period, with decision makers that could decide to assign a lower value to γ with respect to δ.

3.6.3 Night hours operation

In case of nightly operations, the scheduling of the freight service could be implemented without considering the share of infrastructure with passengers' trams. More vehicles can be involved if the demand is high enough, without considering network congestion since the passengers' vehicles are absent and loading and unloading operation could be performed in a smoothly manner. Moreover, the possibility of transportation of goods from one terminal to the other can be exploited through the night implementation, thanks to the fact that freight vehicles do not need to overtake any other vehicle in the network. The terminal-to-terminal freight operations could take part in case of having one important company located in one of the tram terminals with the main supplier located in the other terminal (similarly to the case of Dresden discussed in Chapter 2.2) or having hospitals and shopping malls located in the proximity of one terminal while the loading of the freight occurs on the other. This type of freight operations allows a fast travel from the starting to the final station, given that all the intermediate stations are skipped, with the biggest advantage of having more vehicles involved in the freight deliveries and, thus, a bigger capacity of transporting goods.

The completion of deliveries is difficult to perform because some business activities are closed during this period, so the freight must be stored in storage facilities until 2nd level vehicles complete the delivery operations during daytime. DCs are fundamental to sustain this delivery system since they allow for available space to store the freight. For this reason, the presence of DCs represent a discriminant of the choice of the period in case of night operation, therefore if is not possible in the zone selected to implement DCs, nightly operations become difficult to sustain.

For the freight trams to operate during night-time, the infrastructure must be turned on 24 hours per day, with passengers' trams operating during daytime and freight trams operating during night. Accordingly, the overall operational costs of the 2L-MLS are higher. Electrical and mechanical components of the infrastructure do not have a period of distress, affecting the overall resilience of the service. However, the benefits gained from a tram network freed from passengers' vehicles and road congestion are potentially higher than the drawbacks. Dedicated studies to the specific condition of cities when implementing 2L-MLS represent a key for the successful implementation of the nightly freight service. The problem of noise pollution for inhabitant of the zones near the stations and authorities' regulations are still barrier difficult to overcome for night deliveries to take the scene of urban freight transport. For the model presented, the municipal authorities give full permission on the circulation of freight trams during night and so the only restriction for the implementation of the delivery system is the presence of DCs, which are fundamental to store the freight.

The number of vehicles moving per direction per hour is still an indicator of the usability, and thus of the efficiency, of the nightly deliveries. Since there are no passengers' vehicles on the network running the service during night-time, the number of vehicles is an absolute number, differently from the two previous cases. To guarantee smooth and silent operations for employees (necessary given the hours in which the service is being implemented), the headway between freight vehicles must be rather wide. It is estimated that a headway of 10 minutes between vehicles is necessary, for the considerations written above. Hence, the maximum number of vehicles per direction per hour in service is set equal to 6. The ranking presented in Table 3.9 presents the cases in which the number of vehicles is lower than 6.

NUMBER OF FREIGHT VEHICLES PER HOUR PER DIRECTION	MARK
6	5
5	4
4	3
3	2
1-2	1

Table 3.9: Classification based on the number of freight vehicles per hour per direction (night hours)

The overall value attributed to nightly deliveries is shown in Equation (3.13). For nightly operations the headway between passengers' vehicle is obviously not considered, while assume great importance the presence of DCs.

$$T_{night} = \epsilon * DC + \delta * V_F + \rho * R \tag{3.13}$$

In this equation, DC can assume two values: 1 if there are no DCs and 5 if one or more DCs are present in the areas served by the 2L-MLS. Analogously to the other two cases, V_F is the score attributed to the number of freight vehicles per direction per hour and δ is the weight given by decision-makers.

At the end of this phase, the values of T_{peak}, $T_{off-peak}$ and T_{night} are compared to understand which delivery time-window is more favourable for 2L-MLS. The choice of the time window is not exclusive: two, or even all the three alternatives can be considered if the relative scores are high enough to permit the 2L-MLS to operate during more the analysed time window. This possibility is generally influenced by the urban context in which the 2L-MLS takes part and by the overall demand of customers for the entire line during the working days, as well as municipal authorities' indications. Allocate the delivery operations on different time-windows allows for better utilization of resources, as well as a better scheduling process for both the service of passengers and freight.

After the decision over the period of implementation of the freight service on the time network is made, the preliminary technical analysis for the first level of 2L-MLS can be considered completed and the following process of preliminary technical analysis of feasibility for the 2nd level can begin.

4. Application of the model over an Italian horizon

In this paragraph the model presented in Chapter 3 is applied to evaluate the implementation of 2L-MLS applied to Italian cities. The main source for the statistical data used is the Italian Institute of Statistics (ISTAT) [68], while in order to work on metadata coming from online geoportals, the use of GIS software may prove to be a smart methodology. Geographical Information System (GIS) software are useful when mapping the territory of a city and making calculation related to statistical data belonging to parts of a map. For the development of the thesis work, QGIS, belonging to the family of GIS software, is used to provide visualization of map and the assessment of the freight demand for the choice of the station. The images presented in this chapter are all extracted by QGIS using OpenStreetMap as basic layer and drawing geographical elements on the opened map, unless a different source is mentioned.

The procedure for the preliminary technical analysis of the 2L-MLS considering Italian cities is divided in 4 main steps, as reported in Figure 4.1, following the logical passages reported in the flow chart portrayed in Figure 3.7. The first step is an analysis of the predisposition of the Italian cities, considering all the municipalities in which tramway service is currently operating. From the analysis undertaken, the value of Milan emerges, as it stands on top of the ranking among the Italian cities according to the predisposition towards the implementation. The second step of the procedure is the assessment of the physical characteristics of a particular tramway line of Milan, which is Line 4, presented as case-study, together with general considerations about the fleet currently performing the passengers service in Milan and the constitution of the potential freight fleet. The third step is represented by the choice of the stations along Line 4, where performing freight activities in parallel with passengers' ones, according to the demand analysis and feasibility criteria described in the model presented and, finally, the fourth step is the identification of the best time window in which perform the freight service for Line 4.

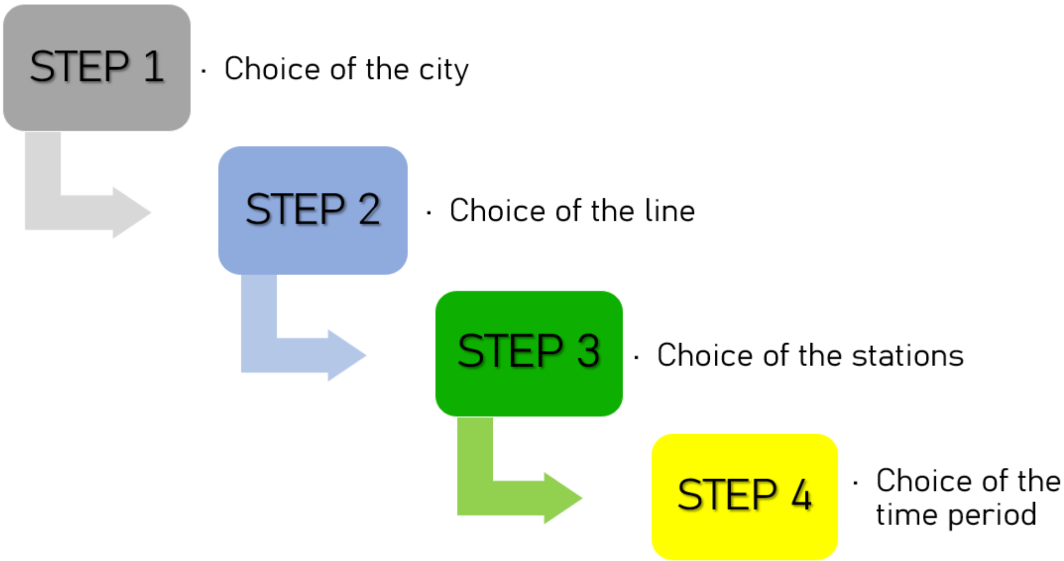


Figure 4.1: Sequence of the analysis for the case-study presented

The four steps are thematized by the same colours used in the presentation of the model, consequently all the tables and references related to the step defined are recognizable through the chromatic choice reported in Figure 4.1.

4.2 Step 1) Choice of the city

4.2.1 Application of the model

The outcome of step 1 of the procedure is the definition of the value of C, which is the indicator of the predisposition of the Italian cities when compared over a national horizon. The number of Italian cities provided with tramway service for movement of passengers is equal to 13, so the number of candidates of the pool N is equal to 13. Once the value of N is known, is possible to create a table in which the marks corresponding to the thirteen positions are expressed, through the application of Equation (3.1). Table 4.1 shows the results of the procedure.

POSITION	MARK [0-5]
1st	5
2nd	4.583
3rd	4.167
4th	3.750
5th	3.333
6th	2.917
7th	2.500
8th	2.083
9th	1.667
10th	1.250
11th	0.833
12th	0.417
13th	0

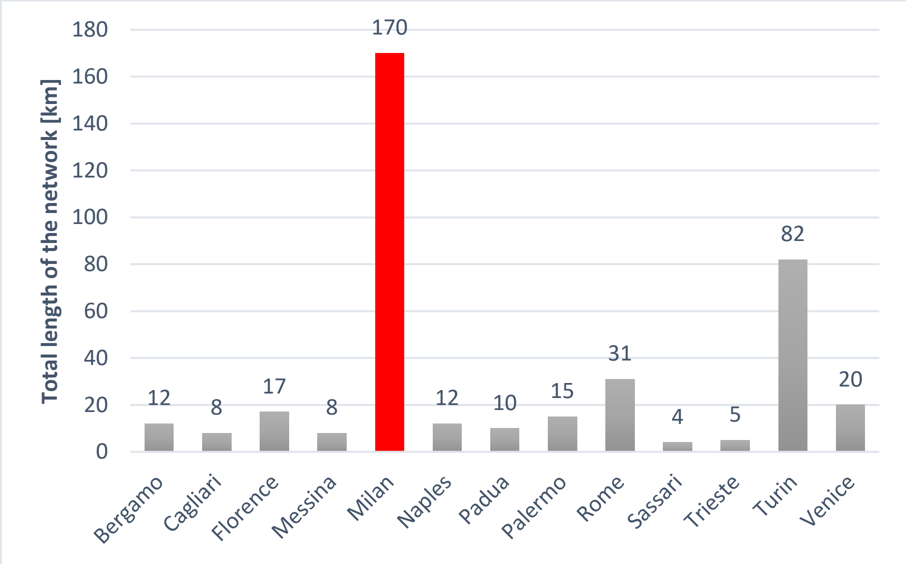
Table 4.1: Assignment of marks to the corresponding positions

The first parameter to assess to build up the equation of C is the total length of the network l_N. In order to assign the mark L_N correspondent to the measured total length of the network for the 13 cities, the values of l_N for all the cities of the pool must be obtained. These data can be found in the municipal data archive of the cities considered. For this purpose, municipal and regional geoportals represent formidable sources of data for the gathering of material related to the territory.

The minimum and the maximum values of l_N for the cities having a tram infrastructure are the following:

- Minimum: Sassari; $l_N = 4\ km$;
- Maximum: Milan; $l_N = 170\ km$.

Milan is positioned on top of the list thanks to the longest tram network among all the Italian ones, equal to 170 km. Consequently, the mark L_N assigned to the total length of the network of the city of Milan is equal to 5. From the histogram represented in Graph 4.1, an additional consideration can be outlined: the value of the total length of the network for the city of Milan is greater than the double of the one of Turin, which is place second in the ranking. If the marks were assigned linearly based on the physical value of lengths, the second city, Turin, would have scored less than 2.5 out of 5. To avoid this gap in terms of marks between 1st and 2nd position of the ranking, the marks were decided to be given based on the position of the cities instead of the measured value of l_N.



Graph 4.1: Value of l_N for the Italian cities

The Italian cities classified according to the length of their tram network are reported in Table 4.2. In the last column of the table the marks L_N attributed to the measured parameter l_N of the correspondent cities are reported.

CITY	l_N [km]	L_N [0 – 5]
Milan	170	5
Turin	82	4.583
Rome	31	4.167
Venice	20	3.750
Florence	17	3.333
Palermo	15	2.917
Naples	12	2.50
Bergamo	12	2.083
Padua	10	1.667
Messina	8	1.250
Cagliari	8	0.833
Trieste	5	0.417
Sassari	4	0

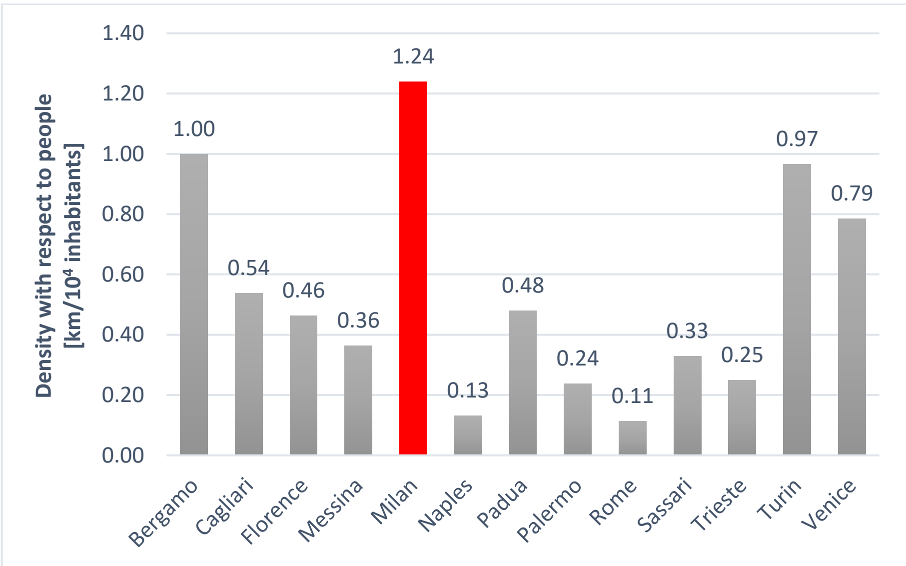
Table 4.2: List of Italian cities where tramway service is operating, classified according to l_N

Source: [60] & [61]

It is interesting to see that, if the study was conducted over a European horizon, the score assigned to the city would have been different from 5, being Milan the fifth city for length of the network according to Table 3.3. This underlines the importance of the definition of the context in which the implementation of 2L-MLS would take place, namely the composition of the pool of candidates. Therefore, a city that could be declared suitable for 2L-MLS project over a national horizon, could become not favourable when reasoning over an international point of view.

The second parameter to obtain for the assessment of the predisposition of the city is the mark assigned to the density of the network with respect to people for the city of Milan. To obtain this parameter, the operation to compute is the ratio between the values of the total length of the network obtained previously and the number of inhabitants of the municipalities equipped with tram infrastructure, obtained from ISTAT and updated to 31st December 2021. The entire roaster of values of ρ_p is reported in Graph 4.2 and the minimum and the maximum value for the density with respect to people ρ_p are the following:

- Minimum: Rome, $\rho_P = 0.11 \frac{km}{10^4\ inhabitants}$;
- Maximum: Milan, $\rho_P = 1.24 \frac{km}{10^4\ inhabitants}$.



Graph 4.2: Value of ρ_P for the Italian cities

The classification of the cities according to their value of ρ_P is reported in Table 4.3, together with their correspondent marks.

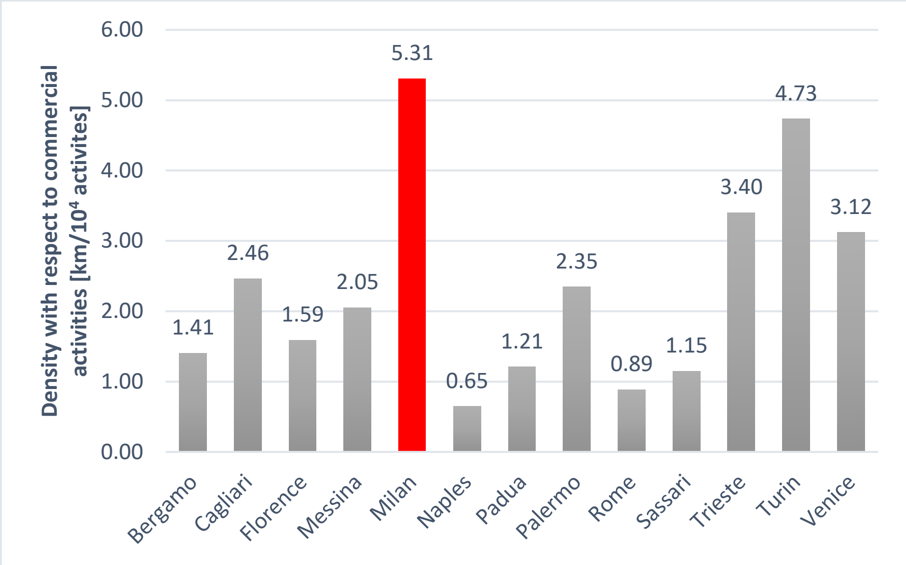
CITY	$\rho_P \left[\frac{km}{10^4\ inhabitants}\right]$	$P_P\ [0-5]$
Milan	1.24	5
Bergamo	1.00	4.583
Turin	0.97	4.167
Venice	0.79	3.750
Cagliari	0.54	3.333
Padua	0.48	2.917
Florence	0.46	2.500
Messina	0.36	2.083
Sassari	0.33	1.667
Trieste	0.25	1.250
Palermo	0.24	0.833
Naples	0.13	0.417
Rome	0.11	0

Table 4.3: Classification according to the value of ρ_P

The third parameter to consider is the value of the density of the network with respect to the number of commercial activities in the city considered ρ_A. The number of activities currently registered in the 13 cities of the pool can be obtained through the data provided by the Italian chamber of commerce of the correspondent municipalities [69]. However, these data require in some cases permissions to be consulted. Luckily, ISTAT provides interesting data as well without requiring permission to consult them. ISTAT conducted a study over the number of currently operating activities within the confines of the province of each city of the list, updated to 31st December 2020. Although the inspection carried out by ISTAT considers the number of business activities of the entire province, these data can also be considered in place of the ones regarding the municipal boundaries, since they account for business activities not located in the cities that require goods whose delivery chain regards the city considered. Once the value of the number of activities located in the provinces of any city of the pool is extracted, the density with respect to commercial activities ρ_A can be computed. The histogram representing the values of ρ_A for every city is reported in Graph 4.3 and the maximum and minimum values are the following:

- Minimum: Naples, $\rho_A = 0.65\ \frac{km}{10^4\ activities}$;

- Maximum: Milan, $\rho_A = 5.31 \frac{km}{10^4\ activities}$.



Graph 4.3: Value of ρ_A for the Italian cities

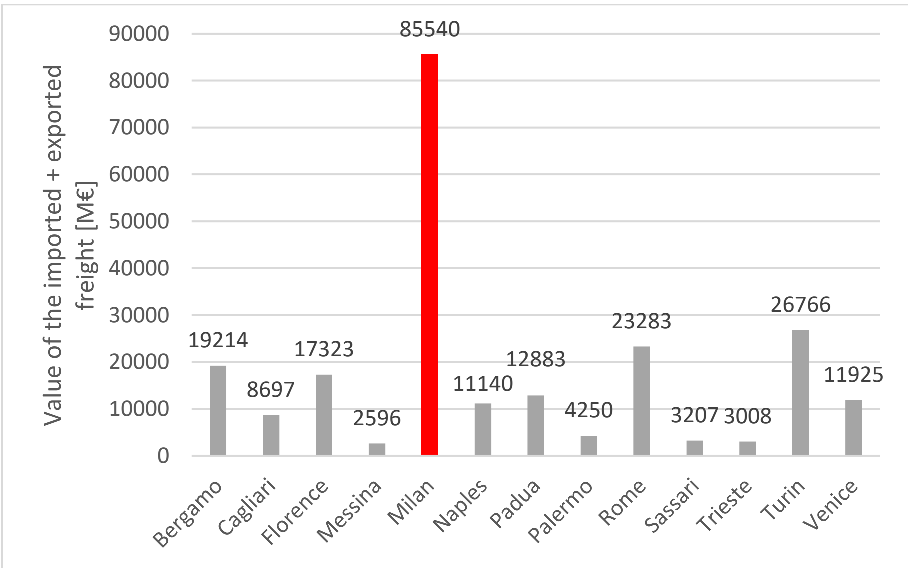
Table 4.4 reports the classification of the cities according to the density with respect to commercial activities and the assignment of marks to the cities.

CITY	$\rho_A \left[\frac{km}{10^4\ activities}\right]$	$P_A\ [0-5]$
Milan	5.62	5
Turin	4.73	4.583
Trieste	3.40	4.167
Venice	3.12	3.750
Cagliari	2.46	3.333
Palermo	2.35	2.917
Messina	2.05	2.500
Florence	1.59	2.083
Bergamo	1.41	1.667
Padua	1.21	1.250
Sassari	1.15	0.833
Rome	0.89	0.417
Naples	0.65	0

Table 4.4: Classification according to the value of ρ_A

There are different modalities to express the fourth parameter, which is the flow of freight f_F, for example based on the vehicles (train, trucks, ships, …), on the type (medicines, food, clothes, …), on the weight, and so on. When gathering these types of data, the difficult part is to find a parameter which is measured for any of the city interested, in a way that confrontations between the values, expressed with the same unit of measurement, can be performed. One of the few sets regarding the majority of the cities considered is the flow of freight of different cities is expressed through the value of freight imported and exported in the main provinces in terms of millions of Euros [70]. The values are referred to the period of January-September of 2019 and only the top 30 provinces are reported. For the tram cities not belonging to this classification, like Messina and Sassari, the value is obtained by taking the regional data of the value of import/export and scaling it proportionally with the number of commercial activities in the province considered with respect to the total number of commercial activities of the region. In order to obtain the value of f_F for this case-study, the value of the exports and the one of the imports of a single province are summed up, thus obtaining the total value (expressed in millions of Euros) of freight that is leaving and entering the province. Graph 4.4 represents the distribution of the values obtained in the previous table by means of a histogram. The minimum and the maximum values of f_F are the following:

- Minimum: Messina, $f_F = 2596\ [M€]$;
- Maximum. Milan, $f_F = 85540\ [M€]$.



Graph 4.4. Values of f_F for the Italian cities

The classification according to the freight flow is presented in Table 4.5. Even for the parameter of freight flow f_F, Milan is positioned at the top of the list.

CITY	EXPORT [M€]	IMPORT [M€]	f_F $[M€]$	F_F $[0-5]$
Milan	33710	51830	**85540**	5
Turin	13860	12906	**26766**	4.583
Rome	7633	15650	**23283**	4.167
Bergamo	12076	7138	**19214**	3.750
Florence	11918	5405	**17323**	3.333
Padua	7654	5229	**12883**	2.917
Venice	7815*	4110	**11925***	2.500
Naples	4756	6384	**11140**	2.083
Cagliari	3764	4933	**8697**	1.667
Palermo	1591*	2659*	**4250***	1.250
Sassari	1340*	1867*	**3207***	0.833
Trieste	1899*	1109*	**3008***	0.417
Messina	972*	1624*	**2596***	0
** = data obtained through interpolation with the proportion of commercial activities in the province over the total number of commercial activities in the region*				

Table 4.5: Classification according to the value of the freight flow f_F

Now that all the parameters needed to compute the value of predisposition of the cities C are known, the last thing that remains is a first attempt assignment of the values of the weights w_1, w_2, w_3 and w_4, to multiply respectively to the values of L_N, P_P, P_A and F_F according to Equation (3.4). Since there is only one parameter regarding the freight movement, and the project of 2L-MLS is shaped around the delivery of freight, it is more appropriate to give w_4 a higher value with respect to the others. The rest of the weights can be outlined based on the relevance that decision-makers want to give to the correspondent parameter. Given that the value of l_N is already contained in the formula for the calculation of ρ_P and ρ_A, the idea is to give w_1 a lesser value than w_2 and w_3. The values assigned to the weights and to the parameters studied in this paragraph are reported in Table 4.6.

WEIGHT	VALUE
w_1	0.1
w_2	0.2
w_3	0.2
w_4	0.5

Table 4.6: Assignment of weights for the calculation of C

Note that the exact value of the weight will be analysis of Delphi studies carried out by experts. By using Equation (3.4) with the values of the weights determined in Table 4.6, is possible to calculate the value of predisposition of the 13 cities over a national horizon, ranked in Table 4.7.

POSITION	CITY	$C\ [0-5]$	DEFINITION
1st	Milan	5.000	*Excellent*
2nd	Turin	4.500	*Excellent*
3rd	Bergamo	3.333	*Good*
4th	Venice	3.125	*Good*
5th	Florence	2.916	*Fair*
6th	Rome	2.584	*Fair*
7th	Padua	2.459	*Fair*
8th	Cagliari	2.250	*Fair*
9th	Palermo	1.667	*Ordinary*
10th	Naples	1.375	*Ordinary*
11th	Trieste	1.334	*Ordinary*
12th	Messina	1.042	*Ordinary*
13th	Sassari	0.917	*Poor*

Table 4.7: Ranking of the cities according to the value of predisposition C

The assessment of the predisposition of the cities considered outlines that the better cities in which implement 2L-MLS using trams are Milan and Turin, being labelled as excellent. Bergamo and Venice can still be considered for the implementation, obtaining a score higher than 3. For the model proposed and the pool of cities analysed, the other cities of the ranking are not suitable for 2L-MLS implementation using trams. However, in case the pool of candidates is modified, considering for example Italian tram cities located in the southern regions of the country, cities that are unfeasible for this application of the case-study can become suitable.

For the case-study of the thesis work the city chosen is Milan, since it has the higher value of predisposition towards the project. The next paragraph will provide some information on the city of Milan and its transport systems organization.

4.2.2 Overview of the city of Milan

Milan is the second biggest city of Italy, located in the northern area of the country in the commercially florid zone of the Po Valley. The city counts 1.37 million of inhabitants, registered on 31st December of 2021, according to ISTAT. A demographical downfall from the number of 1.4 million of inhabitants was registered after 31st December 2019, due to the spread of COVID-19 pandemic, which struck the Italian population particularly in the region of Lombardy, which has Milan as regional capital. Figure 4.2 and Figure 4.3 report respectively the political and physical maps of the region of Lombardy. Milan is located in the western side of the region, located in the core of the Po Valley. Although the province of Milan is not the widest of the region (1575 km^2 against 4785 km^2 of the province of Brescia), it is by far the most populated one, with a number of inhabitants higher than 3.2 millions. The data about the width and the number of inhabitants of the provinces of Lombardy are provided by ISTAT, registered in date 31st December of 2021.

Figure 4.2: Political map of Lombardy

Source: www.cartinadatieuropa.it

Figure 4.3: Physical map of Lombardy

Source: www.cartinadatieuropa.it

Milan is acknowledged to be one of the most developed and productive cities in Europe, standing out not only in terms of commerce, business, banking and trade industry, but also in terms of fashion and design [71]. The indicators related to education and employment support the image of Milan in terms of a rich territory in terms of human capital [72]. In fact, with more than one million of employees, Milan is considered one of the major business centres of Italy and Europe. Another indicator of economic welfare is represented by the number of enterprises which are sited in the city: 7% of the 3300 medium-sized Italian companies, as well as 32.4% of headquarters of multinational companies are located in Milan [73]. The boundaries of the municipality of Milan are reported in Figure 4.4.

Despite the positive qualities attributed to the city of Milan, the city has faced several economic, demographic and political problems in the last decades [74]. The demographic growth of the city that characterized the years after the II World War was halted from 1973 to 2013, followed by a new slight increase in the following years until the COVID-19 pandemic diffusion in the country took the wind out of the sails. The highest number of inhabitants of Milan was reached in 1973, where the population counted over 1.7 million of people. Another demographic challenge for the city is represented by aging: the average age of the citizens is 45 years and the decreased birth rates have been compensated by migration (nowadays 20% of the population of Milan is represented by immigrants). Also by a social point of view, the families have become very vulnerable and almost one-half of the Milanese families are single-parent ones. The most affecting issues for the city of Milan (and to Italy in general as a country) are a low growth of the Gross Domestic Product (GDP), aging population, new emigration of young and talented scholars towards other European destinations, lacking attitude towards long-term planning and interest in the public and private sector in terms of investments.

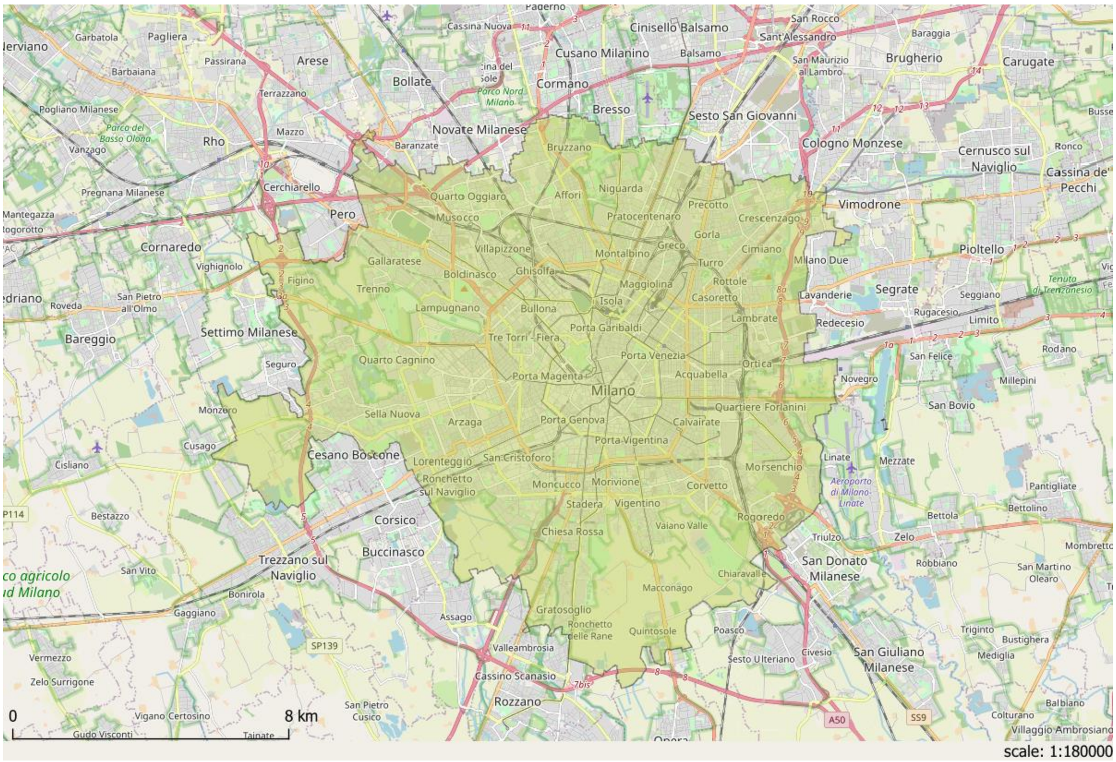


Figure 4.4: Municipality of Milan (yellow area)

From a transportation point of view, Milan generates a considerable demand for the utilization of LPT services. In Italy, Milan has the higher ratio of annual passengers over inhabitants, equal to 421, and the second highest number of passengers of LPT for year, equal to 568 millions (the first is Rome with 1.16 billions per year), registered in 2016 [75]. In general, on a national level, Milan is equipped with the widest and most demanded urban light rail infrastructure. The overall potential demand of the LPT services has increased thanks to the enlargement operations of the metro infrastructure of the city, while the rate of occupancy is slightly decreasing over time.

This last indicator is ambiguous, because it shows that the comfort rate is higher but at the same time LPT vehicles appears to be oversized with respect to the demand. In summary, the overall LPT framework of the city of Milan is one of the most advanced of the country, also in terms of the conditions of the vehicles in service. Figure 4.5 depicts the situation of Milan in terms of distribution of LPT lines operating at ground level, focusing on buses, trolleybuses and trams. As can be observed, the entirety of the city is well-covered by the spreading of the LPT lines, making every corner of the city easily accessible through the use of the network. The integration between different LPT vehicles is favoured by the unified ticket used for travelling within the municipal confines, with prices that vary depending on the number of circular zones crossed, defined following a ring-structure which develops form the centre of the city and extends to the peripheral districts. Figure 4.6, instead, focuses in particular on the situation of trams in Milan that, differently from buses, only in few cases operates in the external zones of the city (Line 15 and Line 31).

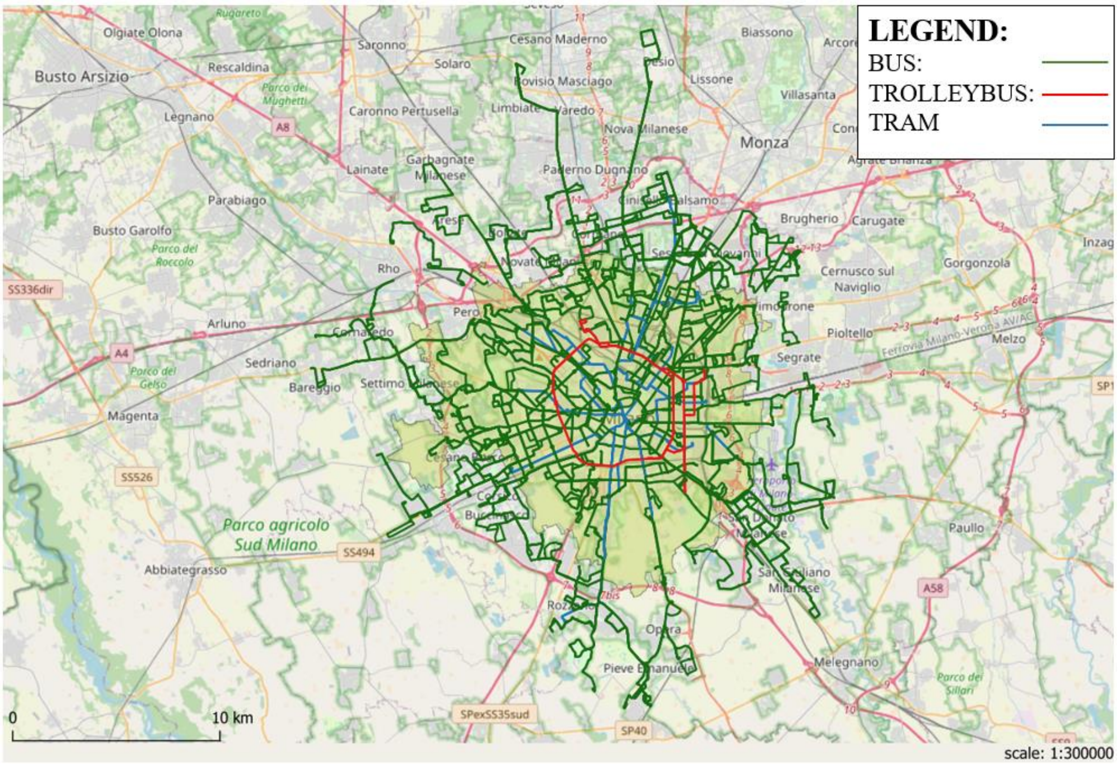


Figure 4.5: Ground level LPT network distribution on Milan

Figure 4.6: Tramway lines operating in Milan

4.3 Step 2) Choice of the line

Once the predisposition of the city of Milan over a national horizon has been acquainted, the next step is to identify the tramway line of the city in which implement the 2L-MLS service. The city of Milan has an historical tradition of tram services, consequently the majority of the lines of the city fulfil the minimum requirement for being considered as suitable for 2L-MLS implementation. Among the lines of the city, Line 4, reported in Figure 4.7, represents an interesting candidate for the implementation of the 2L-MLS project because it crosses the most central and flourishing zones of the city, like Piazza Garibaldi and Piazza Castello, over a distance of 7 kilometres and serving 21 stations in total.

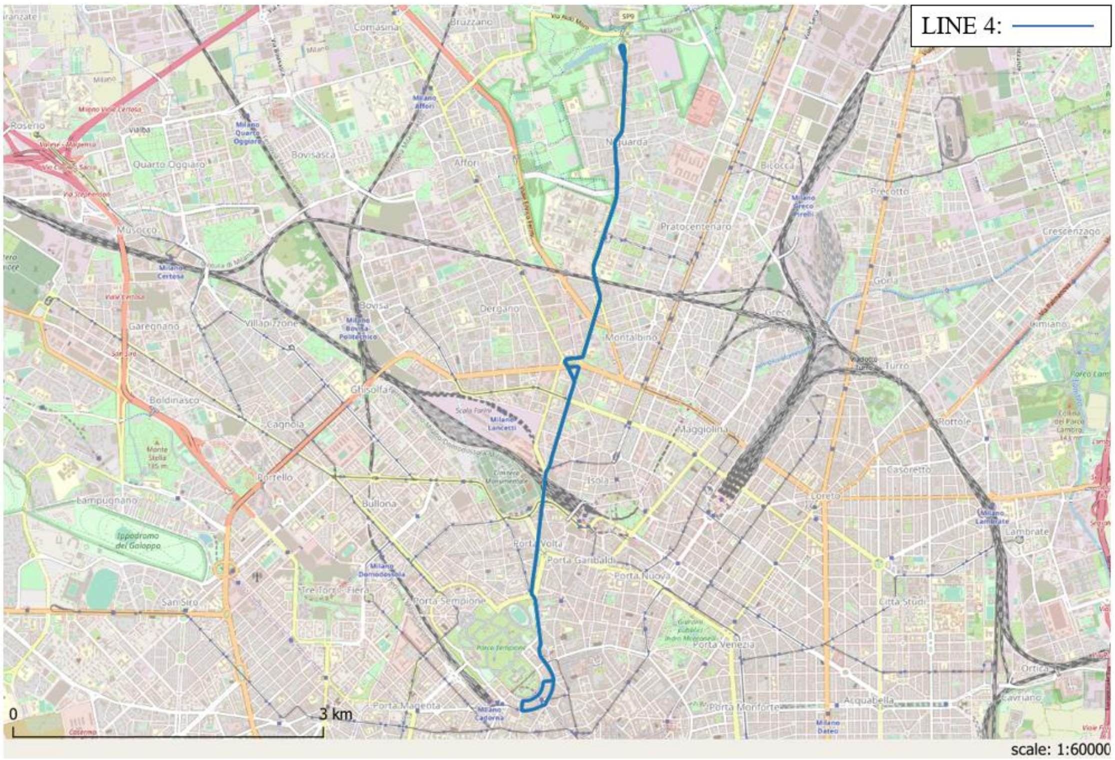


Figure 4.7: Location of tramway Line 4 in Milan

The conformation of Line 4 suggests that the demand, either for passengers or freight, could be potentially high enough to justify the investment. The area in which Line 4 operates is also a good candidate because of the presence of Hospital Niguarda, which is a leading Italian general hospital, built in 1939 and renovated from 2007 to 2014 [76]. For the demand analysis, indeed, the presence of the hospital is one of the main drivers for the choice of the line selected. The stops are reported in the following list, with the direction set from the outer zone of Milan to the inner one (from North to South) and they are displayed along the line through Figure 4.8.

1. Niguarda Parco Nord;
2. Cascina California;
3. Niguarda Nord;
4. Niguarda Centro;
5. Girola;
6. Ospedale Maggiore Niguarda;
7. Nizza;
8. Valassina;
9. Maciachini M3;

10. Via Farini, Viale Stelvio;
11. Via Farini, Via Alserio;
12. Via Farini, Via Valtellina;
13. Via Farini, Via Ferrari;
14. Piazzale Baiamonti;
15. Viale Montello;
16. Piazza Lega Lombarda;
17. Arena;
18. Lanza M2;
19. Piazza Castello, Cairoli M1;
20. Foro Buonaparte, Via Ricasoli;
21. Cairoli M1.

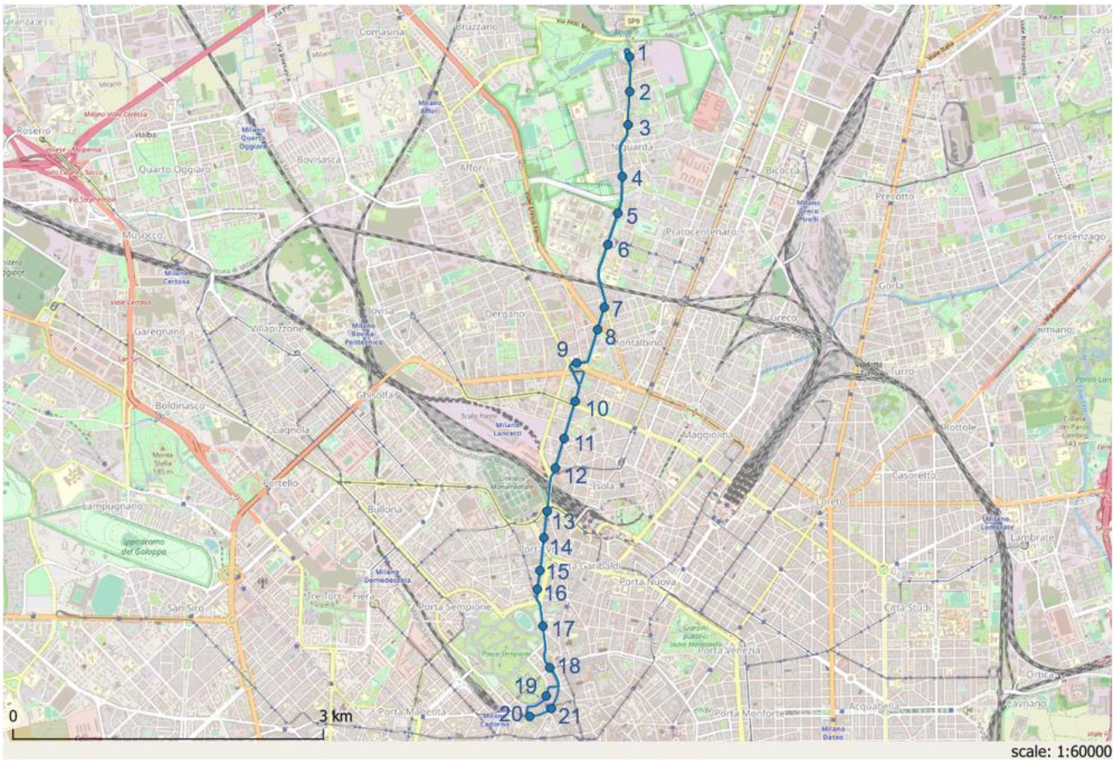


Figure 4.8: Distribution of the stops along Line 4

Once the territory over which Line 4 operates has been described, the analysis proceeds with the assessment of the physical characteristics of the tramway line and composition of the fleet. To compute the value of L, the marks assigned to the infrastructure I and the one assigned to the composition of the freight fleet V need to be obtained. For the computation of I and V, the marks range from 1 to 5 and they are correspondent to absolute characteristics of the parameter calculated, without making comparisons between different alternatives of the pool. With this approach, the predisposition of a line in terms of physical characteristics L is assessed in absolute sense rather than in a relative one.

For the assignment of the score correspondent to the infrastructure I, a deep observation of the entirety of the line is required. For what concerns the terminal stations, Line 4 has two loop stations. Niguarda Parco Nord terminal is located at the beginning of a small loop infrastructure, closed to other vehicles and used for the change of direction of the vehicle, as shown in Figure 4.9. A secondary rail infrastructure can be observed through the figure. Since the internal zone of the loop infrastructure is unused, a small depot could be installed, making the pick-up/drop-off operations easier for the operators. If the municipal authorities agree, a little requalification of the zone can be considered to implement, in addition to the depot into the loop terminal, the construction of a Distribution Centre in the zone, given the green spaces surrounding the tramway infrastructure.

Figure 4.9: Terminal station - Niguarda Parco Nord (1)

Things are more complicated when dealing with the other terminal station. Tram stops 19, 20 and 21 are placed on a branch of the loop infrastructure which crosses the following four streets: Via Quintino Sella, Piazza Castello, Via Ricasoli and Foro Buonaparte. Although this conglomerate of streets composes a loop terminal, it is more difficult to implement secondary rails in this branch of the line, with respect to the other loop station of Niguarda Parco Nord, because the space available for storage facilities and secondary rails is limited and the streets are open to cars, motorbikes and pedestrians. Things could possibly be different in the next future thanks to the modernization works carried out through year 2022 and lasting 500 days in the areas near the loop terminal. The intervention was set to create a new pavement for the zone between Piazza Castello and Largo Cairoli, making them accessible again to pedestrians. The restyling is currently proceeding with the construction of new kerbs and pavements along Piazza Castello, Via Beltrami and Via Lanza. Further intervention planned for year 2023 are the complete requalification of the square and streets that are linked to Foro Buonaparte and the plantation of trees at the edge of the streets [77]. Since the municipality of Milan is currently working on the zones described, the implementation of secondary rails could be discussed as well with the municipal authorities if the construction site is still opened. At the present state the three stops represented in Figure 4.10 could be considered as freight stations if the demand analysis provides satisfying results, but the available space is not enough for the construction of secondary rails, so the main aim of the loop is simply to invert the direction of the tram for the return trip. Nonetheless, the constitution of the terminals of Line 4 allows to implement cargo wagons for freight service, thus incrementing the maximum capacity of the vehicles and consequently a higher efficiency of the freight distribution system. Given the zones crossed by Line 4, the implementation of secondary rails along the entire route of the tram is hardly feasible, however, for particular stations, there is room enough for the implementation of secondary rails, even if the process of installation could require further feasibility analysis to understand whether the municipality of Milan is able to concede permissions for the installation of the secondary rail infrastructure. For the analysis of the case-study, it is hypothesised that is possible to implement secondary rails in the station converted to mixed operations, if the conformation of the streets allows for the construction in terms of available space.

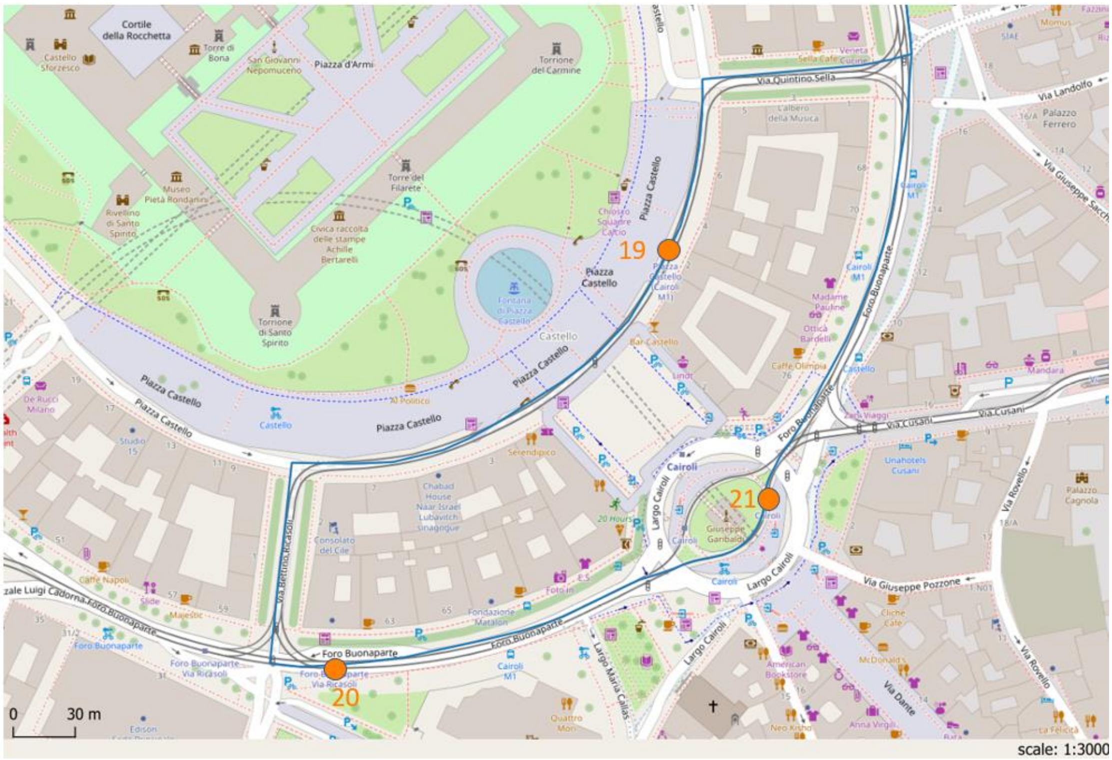


Figure 4.10: Terminal Stations - Southern branch (19-20-21)

Summing up, the mark to the physical infrastructure of Line 4 of Milan is given according to Table 3.4. It has been reported that there are two loop terminals, allowing for the possibility of the adoption of cargo wagons for freight services. It has also been said throughout the analysis of the terminals that the construction of secondary rails along the entire line is almost impossible to implement without a complete revision not only of the tram line, but also of the streets and zones crossed. However, for the application of the model, in cases where space and traffic conditions are more favourable, is considered possible to implement secondary rails at the designed stops dedicated to freight service and to vehicles' changing of position along the network. For these reasons, the overall score given to the parameter I for Line 4 of Milan is equal to 4, according to the definitions reported in Table 3.4.

$$I = 4 \rightarrow Two\ loop\ terminals\ with\ secondary\ rails\ only\ for$$
$$stations\ in\ which\ freight\ activities\ are\ performed$$

Before assessing the freight fleet to deploy for the freight service, insights about the current vehicles used for passenger service are reported. The city of Milan has always been keen to present itself as innovative and outstanding, having an historical tradition on trams. The social value of these vehicles is renowned not only among the inhabitants of the city, but also to all the Italian people as well. The fleet currently used for passengers' transport is partially composed by "Series 1500" models, produced by Carminati & Toselli under request of ATM. These vehicles are amongst the oldest tram vehicles produced, born between the 1928 and 1930 and still in service, revamped and modernized, along several lines of the city [78]. Figure 4.11 represents a Series 1500 tram vehicle currently operating along the venues of Milan.

Figure 4.11: Picture of an ATM Series 1500 tram model

Source: Milanotoday.it

Newly born vehicles were adopted in recent years to operate among the most congested line of the tram network. To produce these trams ATM outsourced the manufacturing to AnsaldoBreda, and the outcome were the vehicles identified as series 7000 to 7550, known also as "Eurotram", "Sirio" and "Sirietto", born in the years between 2003 and 2008. A picture of a Sirietto model is reported in Figure 4.12, while Figure 4.13 shows a Sirio model in service on Line 4.

Figure 4.12: Picture of an ATM Series 7500 "Sirietto" tram model

Source: Milanoneisecoli.it

Figure 4.13: Picture of a "Sirio" model operating on Line 4

Source: gratosNET.it

In 2020 ATM signed a six-years contract with the Swiss company Stadler in which the acquisition of new vehicles for passenger service was planned. As a result, eighty new tram vehicles "Tramlink" model will be delivered from Stadler within 2023 to the city of Milan. The vehicle, reported in Figure 4.14, is more silent and reactive in narrow streets with the respect to the current fleet used, ensuring a rapid management of passengers and more accessibility on board for disabled people. Moreover, Tramlink vehicles will provide an increase in safety for passengers, drivers and pedestrians, being equipped with an anti-collision device and internal cameras to enhance the visibility for the driver of the tram [79].

Figure 4.14: "Tramlink" model manufactured by Stadler

Source: Milanocittastato

The solutions that could be adopted for freight service are different and depend on the decisions taken by the municipality of Milan. Since the city is already interested in purchasing new vehicles dedicated to passenger service, one solution could be to invest also in brand new dedicated freight vehicles for the delivery operations. In long-term perspective the vehicles to be purchased could also be autonomous, but since the technology is not mature enough to guarantee a smooth and safe delivery operation and, more important, the synchronization with the other vehicles along the network is difficult to achieve, the most probable solution will be to opt for traditional vehicles. Given that the models Eurotram, Sirio and Sirietto can still be considered as new, being in service for less than 20 years, a solution for the freight fleet could be to purchase a small number of new vehicles and then convert Eurotram, Sirio and Sirietto vehicles for freight operations. A possible interesting object of study could be represented by research on the feasibility of the conversion of the vehicles series 7000 to 7550 from passengers service to freight transportation, giving explanation about the organization of the internal space converted for the storage of parcels and the on-board facilities to ease the operations of movement of goods for the employees of the service.

For the case of Line 4, which could be extended to most of the tramway lines of Milan, the value attributed to the freight fleet V, according to the definitions expressed in Table 3.5, is the following:

$$V = 2 \rightarrow Mix\ of\ new\ and\ old\ vehicles\ (non-autonomous)$$

Now that the values of I and V for the case study are defined, the last thing which is missing for using Equation (3.5) to calculate the value of L is the definition of the weights α and β. As mentioned in the chapter related to the model, the weights are all attributed through Delphi analysis, so for the calibration of the model the pool of experts selected must be consulted. A preliminary definition of the value of the weights could still be done a priori and then propose the values assigned to the experts.

First attempt values could be for example 0.75 and 0.25. The considerable difference between the two values can be explained by the fact that, since the characteristics of the infrastructure are proper of Line 4, it is decided to assign as first implementation an higher weight to the score of I with respect to the score of V, which could be extended to almost every tramway line of the city of Milan, giving higher importance to the characteristics which makes Line 4 outstanding with respect to other lines. Another reason for this difference between the weights is because the composition of the fleet dedicated to freight vehicles is linked to many uncertainties, depending also by the advancement of the technology of autonomous trams in the next years, which is difficult to predict. The data used for calculating the value of L for Line 4 of the city of Milan are resumed in Table 4.8.

PARAMETER	MARK [1-5]
I	4
V	2
WEIGHT	**VALUE [0-1]**
α	0.75
β	0.25

Table 4.8: Parameters chosen for the calculation of L

Hence, the calculation of the value of L can be computed as shown in Equation (4.1).

$$L = 0.75 * 4 + 0.25 * 2 = \mathbf{3.5} \tag{4.1}$$

The value obtained expresses the predisposition of the existent physical conditions of the line on a scale from 1 to 5. The result obtained is high enough to justify the choice of the line selected for the 2L-MLS project and to proceed to the further steps of the analysis without considering a change of line. In fact, in case the target of number to be converted to mixed operations S_0 is not met by the demand and feasibility analysis, the next action will be to reconsider the number S_0 instead of choosing a different line for the project.

4.4 Step 3) Choice of the stations

The third step of the analysis is related to the definition of the number of freight stations of Line 4, as well as their disposition along the route. The procedure adopted for the scope is the one described in Chapter 3, reported here as it follows:

- Identification of the ideal number of mixed stations S_0 for the line analysed;
- Selection of the business activities through the use of isochrones;
- Classification of the business activities and calculation of the priority generated by the customers;
- Extraction of priority index of the zones, based on the cumulated priority generated by the customers;
- Choice of the stations to include in the conversion process, based not only on demand analysis but also on physical constraints;
- Conversion of the stations from passenger only to mixed operations of passenger and freight services, according to the physical constraints.

The first action is the definition of the target value of number of stations S_0 that are to be converted into mixed operation ones. This number is generally defined by consultation with the municipality involved in the project: together with decision-makers, municipal authorities express their willingness to implement freight service in determined zones, according to different criteria, such as the attractiveness of freight of a particular zone served by a station, the conditions of the surrounding spaces and the congestion of the network as a result of the double operation of passengers and freight transport. As mentioned in the model, in order not to impede the regular operations of passengers' management, generally the number of freight stations along the line is limited to a certain fraction of the total number of stations. The number of S_0 for the case-study of Line 4 is set equal to 5.

As for the second point, the identification of the number of business activities considered is strictly related to the definition of the zones of interest within the freight demand is performed. These zones are identified through the generation of isochrones having as centroids the 21 stations of Line 4. The isochrones are built considering a time distance of 10 minutes from the station analysed moving by walking, smaller than the ones indicated in the model application according to the idea of city in 15 minutes [63]. In this way smaller zones are created, avoiding excessive intersection between the zones considered, since many business activities could be in common for different zones if the isochrones are calculated drawing wider boundaries. The ulterior advantage of building smaller zones is to allow customers to fetch the freight directly with their private cars into the storage facilities installed at the freight station, within a short amount of time, if clients are willing to. The more the zones are enlarged, the more intricated the routes of the 2nd level vehicle become for completing the delivery to final customers (thus complicating the VRP algorithms for the definition of optimal routes for the city freighters and the synchronization between 1st and 2nd level of the 2L-MLS). In any case, the dimension of the isochrones generated can be increased or diminished according to the aim and requirements of the municipality. Figure 4.15 and Figure 4.16 provide two examples of isochrones referred to the terminal station of Niguarda Parco Nord and to Maciachini M3. The yellow dots in the maps are related to big retailers of the city of Milan, data obtained through the geoportal of the region of Lombardy, while the green ones indicate the presence of hospital and medical centres.

Figure 4.15: Definition of the isochrone related to station Niguarda Parco Nord (1)

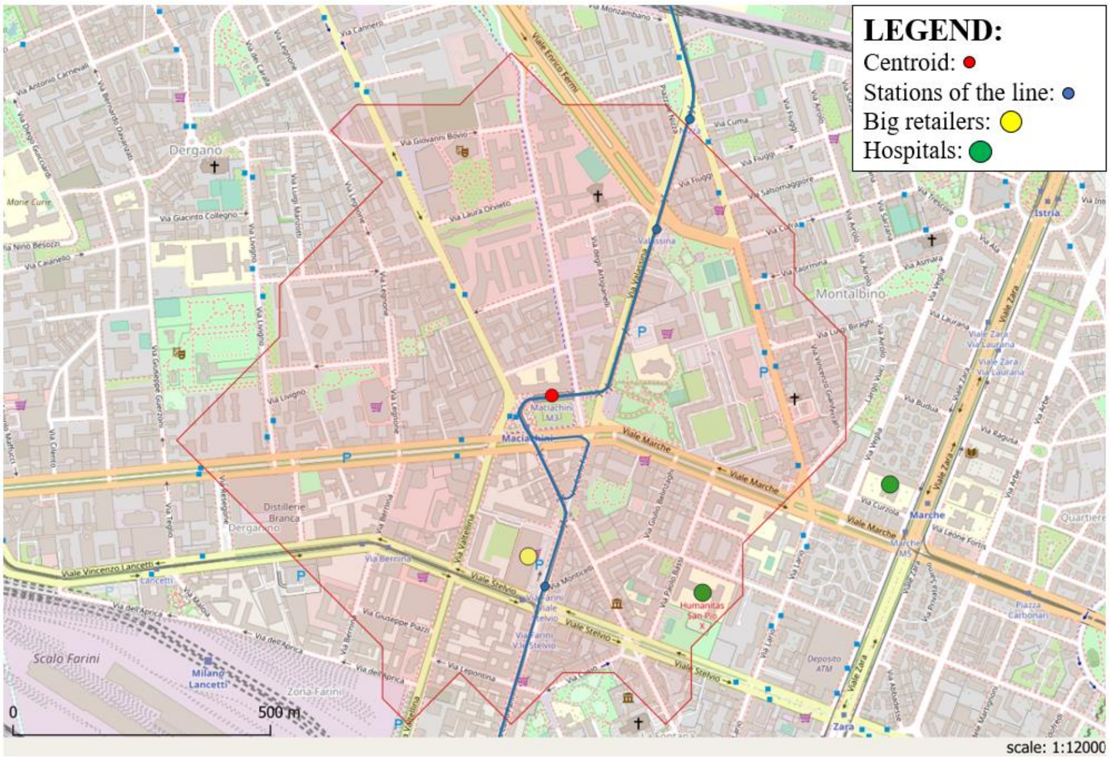


Figure 4.16: Definition of the isochrone related to station Maciachini M3 (9)

In order to visualize all the 21 isochrones generated around the stations of Line 4, the maps portrayed in Figure 4.17 and Figure 4.18 are generated. It can be clearly observed that most of the zones overlay, being the stops along the line close one to the others. The entire line comprises a total number of big retailers which is equal to 3, while the number of hospitals and medical centres located in the isochrones covered by Line 4 is equal to 2.

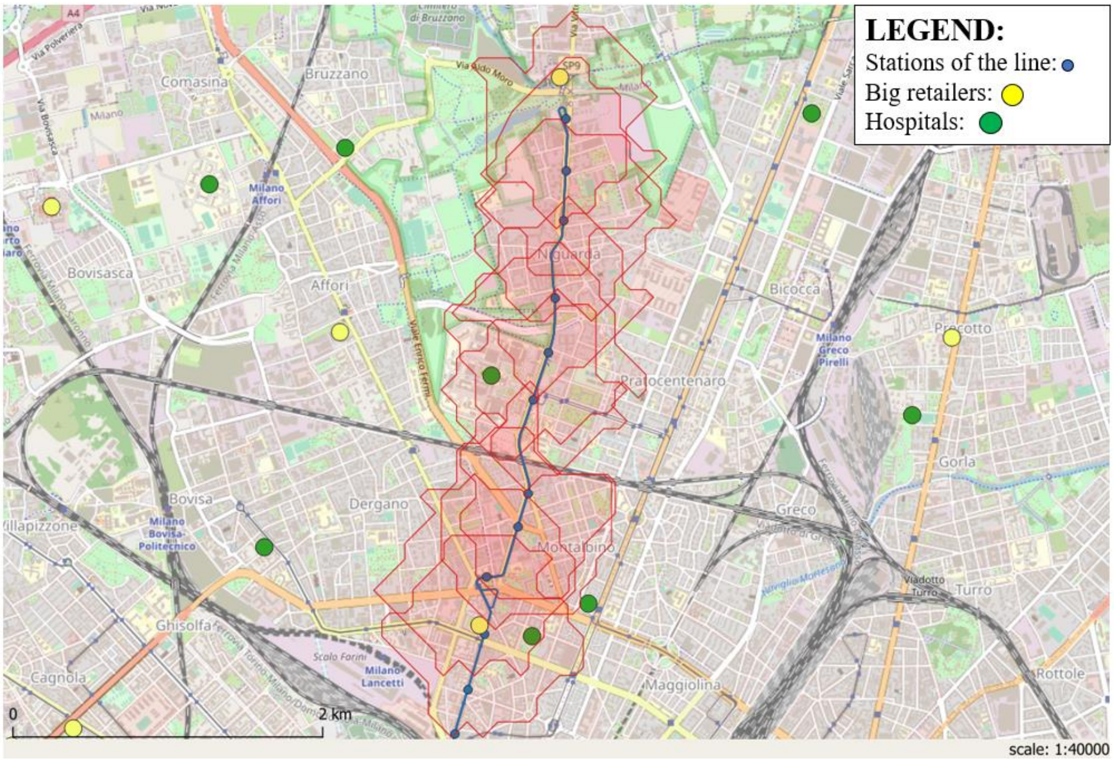


Figure 4.17. 10-minutes isochrones of the stations from 1 to 10 of Line 4

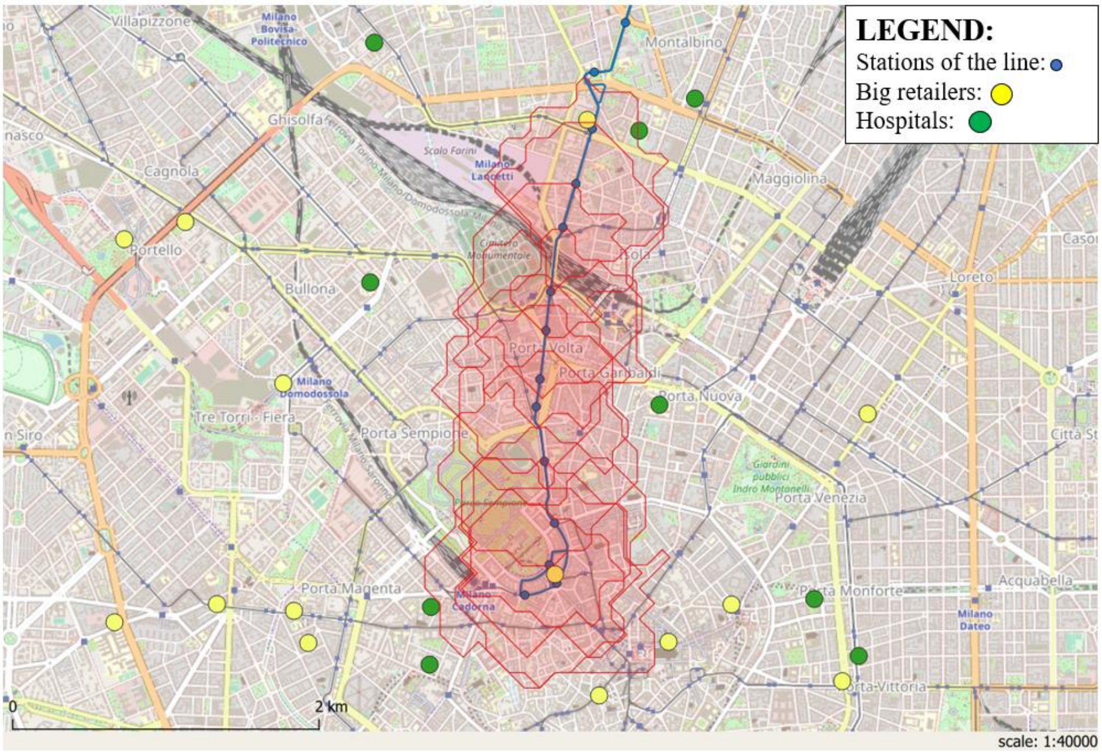


Figure 4.18: 10-minutes isochrones of the stations from 11 to 21 of Line 4

The next operation to conduct is the assessment of all the business activities contained into the isochrones generated and the levels of priority that they generate. In order to slim down the procedure, only one typology of activities is chosen for the application of the model, apart from including the biggest commercial activities of the city of Milan (yellow dots) and the hospitals (green dots), both generating a level of priority equal to 5. In the analysis portrayed in the case-study, the focus is set to commercial activities requiring food as freight. Through the use of OpenStreetMap as reference for the processing of data in QGIS, the levels of priority reported in Table 4.9 could be assigned to the different types of gastronomy activities, according to the priority matrix denoted in Figure 3.10.

GASTRONOMY ACTIVITY	ICON	PROMPTNESS [HIGH – MEDIUM - LOW]	QUANTITY [HIGH - MEDIUM- LOW]	PRIORITY [1-5]
Restaurant/Food Court		Medium	High	4
Fast Food		Medium	High	4
Bar		Medium	Medium	3
Pub		Medium	Medium	3
Café		Low	Medium	2
Ice Cream Shop		Low	Low	1

Table 4.9: Definition of priorities according to specific gastronomy activities

In total, considering also hospitals and big retailers, for the case-study presented eight activities are considered, with the level of priority indicated in Table 4.10.

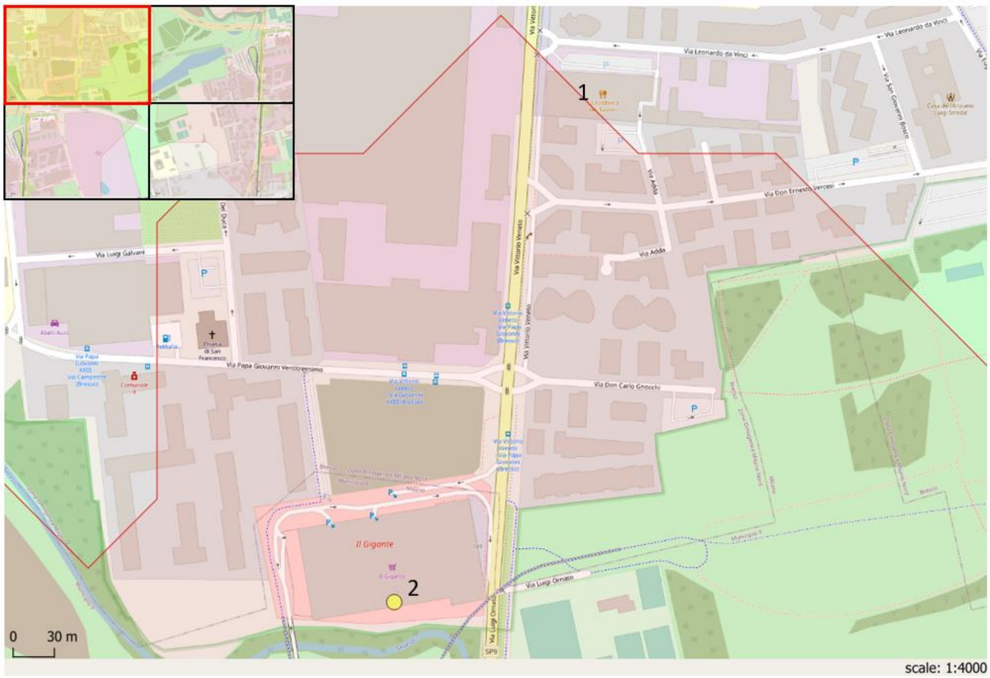
TYPE OFACTIVITY	PRIORITY [1-5]
Hospitals	5
Big Retailers	5
Restaurant/Food Court	4
Fast Food Restaurant	4
Bar	3
Pub	3
Café	2
Ice Cream Shop	1

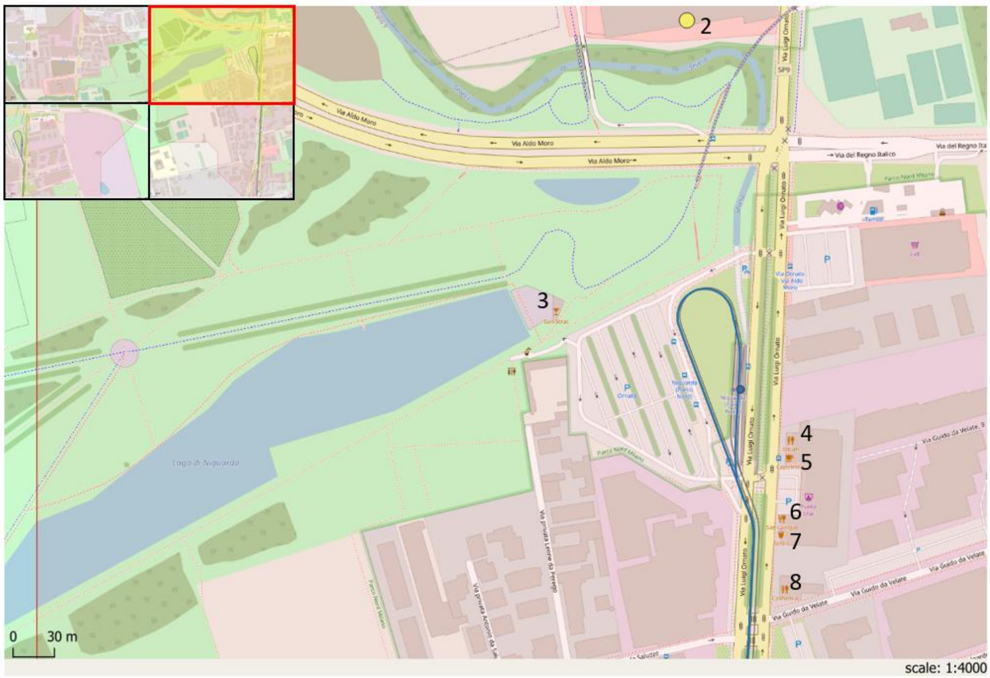
Table 4.10: Definition of all the activities considered for the case study

The next step of the procedure is to calculate the vector $A_i = [a_{i1}, a_{i2}, \dots, a_{in}]$, related to the priority generated by the n commercial activities of the type selected for every zone having as centroid the station. Thanks to the algorithms presented in the chapter referred to the model, is then possible to define for each zone i the vector of the number of activities having priority equal to five, four, three, two and one, defined as it follows:

$$B_i = [count5, count4, count3, count2, count1]$$

The procedure to conduct for obtaining the values of the vector B_i is shown for the zone regarding station number 1, Niguarda Parco Nord. First, the zone has been screened thoroughly by opening OpenStreetMap into QGIS in order to draw the isochrones for the identification of the commercial activities belonging to the 8 types reported in Table 4.10. Successively, an ID number is assigned to any business activity identified, as shown in the four maps of Figure 4.19.





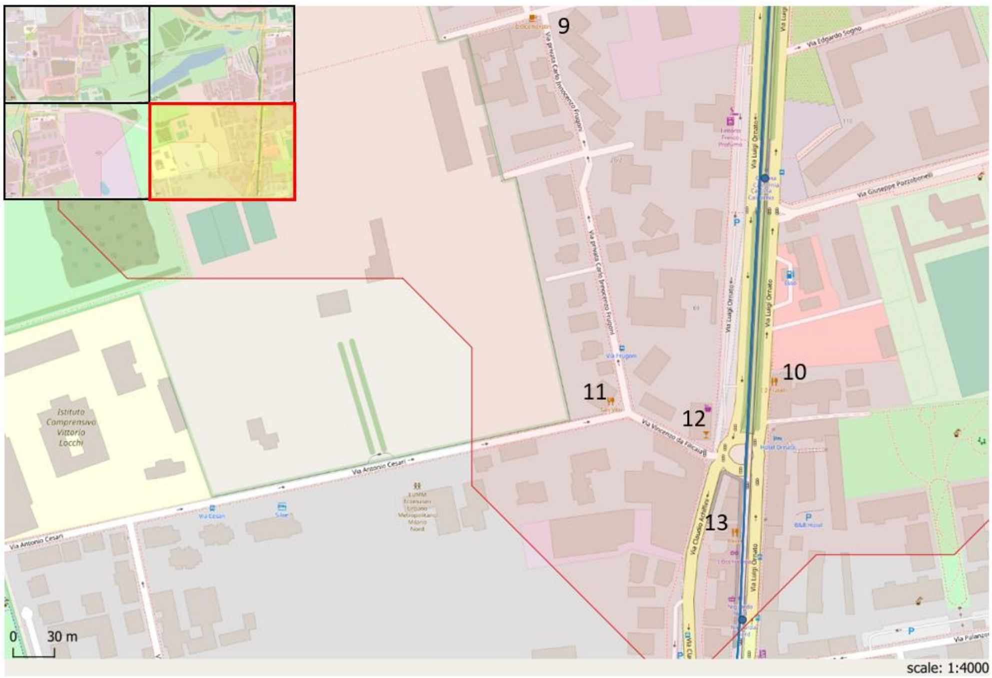


Figure 4.19: Screening of the zone of Niguarda Parco Nord (1) and assignment of IDs to the activities

The next step is the assignment of a priority value for any commercial activity extracted from QGIS, as reported in Table 4.11.

NAME OF THE ACTIVITY	ID	TYPE OF ACTIVITY	PRIORITY [1-5]
La Fabbrica Dei Sapori	1	Restaurant	4
Il Gigante	2	Big Retailer	5
Sun Strac	3	Bar	3
Eolian	4	Restaurant	4
Capolinea	5	Café	2
San Giorgio	6	Restaurant	4
Tardis	7	Pub	3
California	8	Restaurant	4
Dolce Kerstin	9	Café	2
I 2 Fratelli	10	Restaurant	4
San Vito	11	Restaurant	4
Bar Ornato 67	12	Bar	3
Youke	13	Restaurant	4

Table 4.11: List of activities considered in the zone correspondent to Niguarda Parco Nord

From the values obtained in Table 4.10 is possible to assess the vector of the activities A_1 of zone 1, composed as it follows:

$$A_1 = [4,5,3,4,2,4,3,4,2,4,4,3,4]$$

Finally, it is possible to define the values of the parameters $count5$, $count4$, $count3$, $count2$ and $count1$, useful to build the vector B_1, having the following composition for the terminal station of Niguarda Parco Nord:

$$B_1 = [1,7,3,2,0]$$

The same procedure is repeated for the other twenty stations of Line 4. Thus, every zone has been analysed carefully with respect to the presence of the eight types of activities mentioned and the level of priority that they generate, and finally the vector B_i related to any station i is constructed. The values of the vectors B_i obtained through such methodology are reported in the following list:

- $B_1 = [1,7,3,2,0]$;
- $B_2 = [1,8,3,2,1]$;
- $B_3 = [0,8,3,2,0]$;
- $B_4 = [0,5,2,2,0]$;
- $B_5 = [1,7,3,2,0]$;
- $B_6 = [1,0,1,3,0]$;
- $B_7 = [0,2,1,3,0]$;
- $B_8 = [0,11,3,6,1]$;

- $B_9 = [2,32,6,17,0]$;
- $B_{10} = [2,54,10,30,0]$;
- $B_{11} = [2.73.21.31.2]$;
- $B_{12} = [1,92,23,27,4]$;
- $B_{13} = [0,83,12,26,1]$;
- $B_{14} = [0,101,17,38,4]$;
- $B_{15} = [0,103,17,41,6]$;
- $B_{16} = [0,104,16,40,7]$;
- $B_{17} = [0,102,15,32,10]$;
- $B_{18} = [1,98,12,31,8]$;
- $B_{19} = [1,104,13,42,9]$;
- $B_{20} = [1,90,11,41,9]$;
- $B_{21} = [1,124,16,54,9]$;

Going from the outer zones of the city (Northern terminal) to the most internal part of Milan (Southern terminal), is possible to notice that the number of commercial activities increase profoundly. This trend is explained by the choice of the typology of the business activities analysed: in fact, in the case-study presented, gastronomic activities are considered, well-known to be gathered around places where the density of inhabitants, as well as social and economic welfare of the people, is higher. A different result could have been achieved considering other types of business activities. Through the assignment of the weights $W_S = [w_1, w_2, w_3, w_4, w_5]$, the result of the value of attractiveness generated by every station of Line 4 could be calculating. Table 4.12 shows the parameters utilized for assessing the value of the weights, together with the value of each weight, according to Equation (3.6) and Equation (3.7).

WEIGHTS	VALUE
a	4
b	50
w_1	1
w_2	4
w_3	16
w_4	64
w_5	3200

Table 4.12: Value of the weights for the calculation of the value of priority generated by each zone

Further studies could be aimed at defining the most accurate method for the definition of the five weights. For the presented definition of the weights, an activity generating the maximum level of priority weights as fifty activities which generate a priority level equal to 4.

Using the weights assigned in Table 4.12, is possible to define a ranking of the stations based on the priority generated by the business activities of the zones, according to Equation (3.8). The ranking, together with the total score for the priority analysis, is reported in Table 4.13.

POSITION	STATION	ID	PRIORITY INDEX
1st	Cairoli M1	21	11617
2nd	Via Farini, Via Alserio	11	11534
3rd	Piazza Castello, Cairoli M1	19	10241
4th	Via Farini, Viale Stelvio	10	10136
5th	Lanza M2	18	9796
6th	Via Farini, Via Valtellina	12	9568
7th	Foro Buonaparte, Via Ricasoli	20	9309
8th	Maciachini M3	9	8612
9th	Piazza Lega Lombarda	16	7079
10th	Viale Montello	15	7034
11th	Arena	17	6906
12th	Piazzale Baiamonti	14	6892
13th	Via Farini, Via Ferrari	13	5609
14th	Cascina California	2	3769
15th	Niguarda Parco Nord	1	3704
16th	Girola	5	3228
17th	Ospedale Maggiore Niguarda	6	3228
18th	Valassina	8	777
19th	Niguarda Nord	3	569
20th	Niguarda Centro	4	360
21st	Nizza	7	156

Table 4.13: Ranking of stations according to the priority generated by their commercial activities

For a stop along the line to be included in the total number of stations S that can be converted into freight stations, some prerequisites are necessary: the station must have additional space available for the construction of storage facilities and there cannot be two consecutive freight stops along the line. The latter condition is fundamental to have a more distributed freight network which can cover different zones of the city, because if the service is more spread along the line, more customers are involved. The isochrones generated for this application contain more than one tram stop on the line within their boundaries, since they are positioned at low distances, consequently in order to serve a wider consumer base, the location of freight station should be distributed along the line. Another reason for not having consecutive freight station is to allow a better synchronization with the passengers' trams, making possible to change position between tram vehicles if needed. In fact, in case the freight stations are positioned one next to the other, with long sections of the line which are not served by freight stops, the positioning of secondary rails along the line is unbalanced, with entire sections of the line that are not equipped with the said infrastructure, thus disabling the possibility of exchanging position between trams performing different services. Once the prerequisites are settled, is possible to skim down the list of stations and analyse the feasibility of the freight operation implementation for any stop, starting from the top one of the ranking presented in Table 4.14. The description of the zones has been performed through local inspections, thanks also to the assistance of GoogleStreetView.

STATION	ID	DESCRIPTION	MIXED OPERATIONS?
Cairoli M1	21	Placed in the middle of a roundabout, secondary rails difficult to implement and issues of synchronization with 2nd level vehicles which move in the external space of the roundabout	NO
Via Farini, Via Alserio	11	Placed along a straight avenue, secondary rails possible to implement over a lane dedicated to cars (cargo wagons cannot be unhitched in this station)	YES
Piazza Castello, Cairoli M1	19	Placed in proximity of a square, secondary rails cannot be implemented due to lack of space (street is too narrow)	NO
Via Farini, Viale Stelvio	10	Situation similar of station 11, but too close to it for implementing another freight station	NO
Lanza M2	18	Placed along a wide avenue, huge amount of available space for secondary rails (cargo wagons cannot be unhitched in this station)	YES
Via Farini, Via Valtellina	12	Situation similar of station 11, but too close to it for implementing another freight station	NO
Foro Buonaparte, Via Ricasoli	20	Placed along the terminal loop, little space even for installation of smart lockers	NO
Maciachini M3	9	Placed along a dedicated street for trams, secondary rails could be implemented if the street is widened (with the possibility of leaving the cargo wagons in the station), possibility of installing a small depot in the square adjacent	YES
Piazza Lega Lombarda	16	Placed along a straight avenue, not enough space for secondary rails	YES
Viale Montello	15	Placed along a straight avenue, not enough space for secondary rails, too close to station 16	NO
Arena	17	Placed along a straight avenue, not enough space for secondary rails, too close to station 16	NO
Piazzale Baiamonti	14	Placed along a straight avenue, not enough space for secondary rails	YES
Via Farini, Via Ferrari	13	Placed along a straight avenue next to a crossing zone, little space available for smart lockers, too close to station 14	NO
Cascina California	2	Placed along a straight avenue, not enough space for secondary rails	YES
Niguarda Parco Nord	1	Loop terminal, the space inside the loop can be used for implementing medium-size storage facilities, too close to station 2	NO
Girola	5	Placed along a straight avenue, enough space for secondary rails	YES
Ospedale Maggiore Niguarda	6	Placed next to hospital square, enough space for secondary rails, too close to station 5	NO
Valassina	8	Placed along a straight avenue, not enough space for secondary rails, too close to station 9	NO
Niguarda Nord	3	Placed along a straight avenue, not enough space for secondary rails, too close to station 2	NO
Niguarda Centro	4	Placed along a straight avenue, not enough space for secondary rails, too close to station 5	NO
Nizza	7	Placed along a straight avenue, not enough space for secondary rails	YES

Table 4.14: Results of feasibility analysis

As a result of the consideration expressed in Table 4.14, the number of stations that can be converted into mixed operation stations S is equal to 8. Line 4 represent an example in which $S > S_0$, being S_0, the ideal number of mixed stations identified by decision-makers and municipal authorities, equal to 5. Thus, the first 5 stations of the ranking that can be converted according to the priority generated are the ones that become mixed operation stations:

- Maciachini M3 (9);
- Via Farini, Via Alserio (11);
- Piazzale Baiamonti (14);
- Piazza Lega Lombarda (16);
- Lanza M2 (18).

The disposition of the stations along Line 4 is reported in Figure 4.20, where the red dots represent the mixed stations along the line. It could be observed that they are distributed mostly on the southern part of the line. The main reason of the heterogeneity of distribution is that the location of the freight stations is driven by the different demand generated by the customers of the zones.

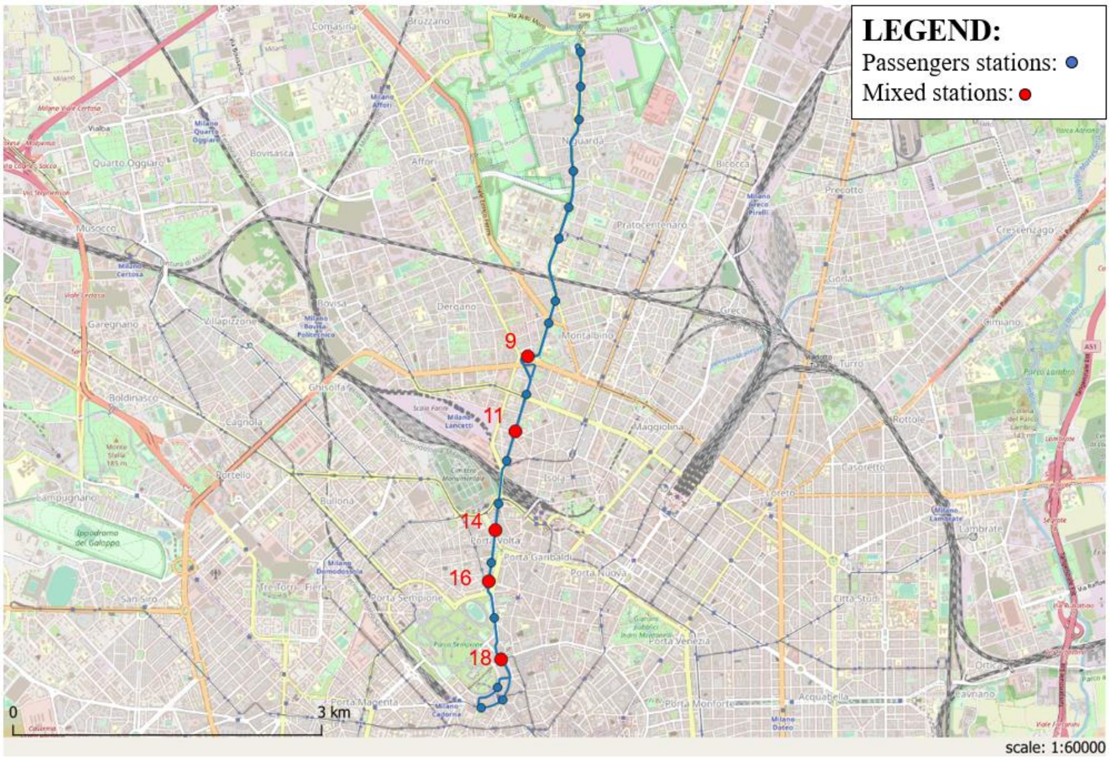


Figure 4.20: Mixed stations along Line 4

Table 4.15 describes how the stations along Line 4 would change in case the 2L-MLS project is implemented, according to the information obtained in Table 4.14.

STATION	ID	MODIFICATIONS TO THE ORIGINAL LAYOUT
Niguarda Parco Nord	1	Construction of a small depot in the internal space of the loop + potential implementation of DC in the zone (it depends on the willingness of the municipality of Milan)
Maciachini M3	9	Smart lockers + secondary rails + small depot in the near square having capacity equal to the one of the cargo wagons
Via Farini, Via Alserio	11	Smart lockers + secondary rails
Piazzale Baiamonti	14	Smart lockers
Piazza Lega Lombarda	16	Smart lockers
Lanza M2	18	Smart lockers + secondary rails

Table 4.15: Modifications to the stations reported

In case other types of activities were selected for the analysis, the location of the freight station might become quite different from the one presented in Figure 4.20. If, for example, the focus was set to medical merch only, with customers like hospitals and pharmacies, is more probable that the presence of Niguarda Hospital would attract most of the freight delivered by trams, thus modifying the configuration of Line 4 proposed for the implementation of 2L-MLS.

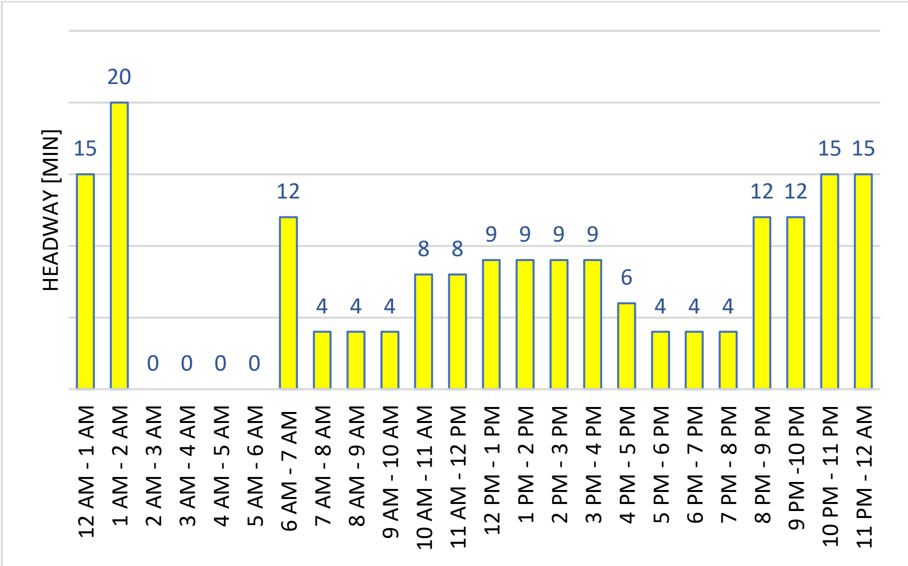
After having decided which stations are converted into mixed operation ones, the third step of the procedure is completed. The next and last step will be the assessment of the time period in which implement the freight service of 2L-MLS.

4.5 Step 4) Choice of the time period

For the analysis of the time period in which implement freight delivery service for Line 4, is fundamental to acknowledge the existent time schedule of the line. On the official site of ATM, three different timetables are reported, referred to working days, Saturdays and public holidays [80]. For the assessment of the better time period for performing freight services, the timetable referred to working days is considered. The passenger service is currently scheduled as shown in Table 4.16. In order to better visualize the values of the headways, Graph 4.5 shows a histogram in which the headways of passengers' trams to each of the 24 hours of the working days are reported. It can be observed that the lowest values of headways are correspondent to the hours in which people travel from home to work and vice-versa, except for night hours when the passengers service is suspended.

ACTUAL TIMETABLE OF LINE 4 ON WORKING DAYS (NIGUARDA PARCO NORD – CAIROLI M1)		
TIME-BAND	**PERIOD**	**HEADWAY [MIN]**
2 A.M - 6 A.M.	Night hours	--
6 A.M - 7 A.M.	Off-peak hours	12
7 A.M - 10 A.M.	Peak hours	4
10 A.M - 12 P.M.	Off-peak hours	8
12 P.M – 4 P.M.	Off-peak hours	9
4 P.M – 5 P.M.	Off-peak hours	6
5 P.M – 8 P.M.	Peak hours	4
8 P.M – 10 P.M	Off-peak hours	12
10 P.M – 1 A.M.	Off-peak hours	15
1 A.M – 2 A.M.	Night hours	20

Table 4.16: Timetable of Line 4



Graph 4.5: Histogram of the headways of trams during working days

The timetable presents different headways along the day. Furthermore, periods belonging to the same group (peak hours, off-peak hours and night hours) presents different headways between vehicles during the different hours of the working days in which the service is operative. In order to make an evaluation of the three periods coherent with the one reported in the presentation of the model, the headway between vehicles is standardized for each period considered. The modifications reported in Table 4.17 to the actual timetable are performed.

MODIFIED TIMETABLE OF LINE 4 ON WORKING DAYS (NIGUARDA PARCO NORD – CAIROLI M1)		
PERIOD	**TIME-BAND**	**HEADWAY [MIN]**
Peak hours.	7 A.M. – 10 A.M. 5 P.M. – 8 P.M.	4
Off-peak hours	10 A.M. – 4 P.M. 8 P.M. – 10 P.M.	9
Night hours.	10 P.M. – 6 A.M.	--

Table 4.17: Modified timetable of Line 4

In the current paragraph, the parameters of T_{Peak}, $T_{Off-peak}$ and T_{Night} are calculated, according to the model presented in Chapter 3, in order to understand which is the best period for the implementation of the freight service for Line 4. From the modifications of the timetable presented, the total amount of hours per day of peak, off-peak and night hours of service can be outlined. Peak period lasts for 6 hours, while both off-peak and night periods are 8 hours long. Hence, not only for peak hours condition the vehicles on the network are less then the ones for the other periods due to the contemporary presence of a tight passengers' service, but also the period is two hours shorter. The main consequence is that the capacity of the freight service during peak hours operation is far less than the one for the other two periods.

4.5.1 Peak hours operation

The situation for peak hours operations is presented. The headway between passengers' trams is equal to 4 minutes and the service is running 6 hours per day in these conditions. Consequently, within one hour of service the stations along the line are reached by 15 vehicles per direction, which become 90 considering the entire period of 6 hours. Wherever the freight vehicles are put into the sequence of 15 vehicles, they have a range of operation equal to 8 minutes, being squeezed between two passengers' vehicles in the timetable with a scheduled time interval of 4 minutes from the forerunning and the following trams. For the entire route, the freight vehicle stops 6 times to pick-up/drop-off goods (5 times in the freight stations implemented and one additional time at the terminal Niguarda Parco Nord for loading/unloading the freight from the installed DC), while the passengers' vehicles stop 21 times. The time gained by skipping 15 stations (thus having higher commercial speed) is accumulated and than is used for performing freight management operations, which takes longer times than passengers' movement. The constitution of the future Line 4 for 2L-MLS allows only for the positioning of secondary rails along four stops. In these stations, the possibility of changing position for the vehicles is exploited. However, the range of operation equal to 8 minute is quite restricted, thus for a fluent exchange of positions the number of stops equipped with secondary rails is too low. With the current headway for the vehicle, it is highly likely to incur in congestion of the tram network due to freight operation times too long to be effective. With these premises, there is little possibility to implement more than one freight vehicle per hour per direction, otherwise the problem of positioning of the vehicles along the sequence will progressively worsen, leading to inefficient utilization of the tram network. Figure 4.21 depicts the sequence of vehicles that will be utilized in case of peak hours operations, according to the considerations made. As always "P" and "F" refer respectively to passengers and freight vehicles. In total there will be 6 freight runs per direction per day, one per peak hour of service. Considering both directions, 12 vehicles will be operating during peak hours, accounting for an overall full-load capacity equal to 900 tonnes per working day, if freight operations are performed only during peak period.

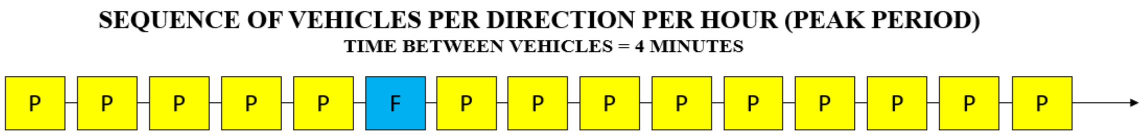


Figure 4.21: Situation of the 2L-MLS for Line 4 during peak hours

About the value of the resilience of the network R, it must be considered that Milan is the fourth most trafficked city in Italy, according to the Inrix Global Traffic Scorecard of 2021 [81]. This means that, especially during peak hours, the driveability across the city is awful and the probability to incur in traffic jams is severely high. Trams share the network almost entirely with cars and thus are exposed to the nearly the same risks as them, with the effect of being very sensitive to modifications in traffic conditions of the road network. To conclude, the value of resilience of the network during peak hour is poor.

Table 4.18 resumes the values chosen for the parameters used for the calculation of T_{Peak}, according to the indications provided in Table 3.6 and Table 3.7, presented in the paragraph of Chapter 3 dedicated to the peak hour analysis.

PARAMETER	MARK [1-5]
h	1
V_F	1
R	1
WEIGHT	**VALUE [0-1]**
γ	0.4
δ	0.3
ρ	0.3

Table 4.18: Assignment of parameters and weights for the calculation of T_{Peak}

For the definition of the first-trial values of the weights γ, δ and ρ, it is chosen to give slightly more importance to the frequency of the passage of trams during peak hours, which has a direct impact on the number of vehicles chosen and on the overall resilience of the service during this period. The value of T_{Peak} is calculated according to Equation (3.11) and the result for the case study of Line 4 of the city of Milan is presented in Equation (4.2)

$$T_{Peak} = 0.4 * 1 + 0.3 * 1 + 0.3 * 1 = \mathbf{1} \tag{4.2}$$

The value obtained for Line 4 is the lowest possible on a scale from 1 to 5, which indicates the worst grade of predisposition of the conditions for the implementation of the freight service of 2L-MLS for Line 4 during peak hours. The next step is the assessment of the situation in the other two time-bands considered, off-peak period and night hours operation.

4.5.2 Off-peak hours operation

The off-peak period considered for the case-study lasts for 8 hours and the headway between the vehicles is equal to 9 minutes. According to Table 3.8, the score attributed to this condition is equal to 4. This value of headway means that freight trams have to manage operation within 18 minutes without entering in contact with passengers' trams. This condition is certainly more relaxed than the one presented for peak hours. The defined value of headway allows for the circulation of 7 vehicles per direction per hour. Since passenger service is no more the focal activity of the line for the period indicated, more than one vehicle can be used for freight service at the expense of passenger service, depending on the demand of the service. Considering the case of Line 4 of Milan, which crosses zones amongst the most populated of the city, is still better not to overindulge with the number of freight vehicles in the network. So, the value chosen for the number of freight vehicles per direction per hour is equal to 2. The minimum and maximum number of freight vehicles allowed in the network during off-peak hours for Line 4, where 7 vehicles in total are circulating, is the following:

- Minimum: 1 freight vehicle;
- Maximum: 3 freight vehicles.

Through the linear interpolation, is simple to assess the score attributed to the condition of having two freight vehicles, being equal to 3 (mean value between 1 and

5). Figure 4.22 shows a representation of the sequence of vehicles operating on the network per direction per hour.

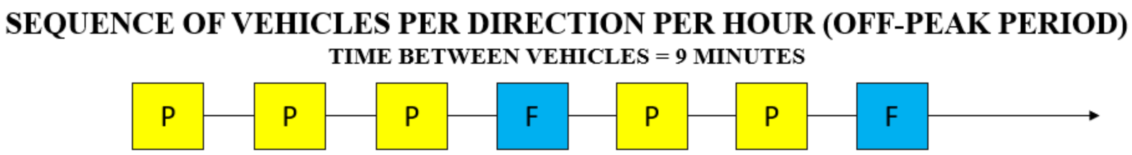


Figure 4.22: Situation of the 2L-MLS for Line 4 during off-peak hours

The total number of freight vehicles operating during off-peak hours, considering both directions, is equal to 32. Thus, this freight fleet has a full-load capacity of 2400 tonnes per working day.

The resilience R of the system is higher with respect to the one of peak hours, due to the less congested networks, both for trams and for cars, during this period. In case of faults of the tram network and traffic jams generated by cars, the integrity of the 2L-MLS system is still put at risk due to the small number of stations equipped with secondary rails presented along the line and for this reason is impossible to give the highest score to the condition of resilience during off-peak hours.

The values of the parameters chosen for calculating $T_{Off-peak}$ are reported in Table 4.19, together with their weights.

PARAMETER	MARK [1-5]
h	4
V_F	3
R	3
WEIGHT	**VALUE [0-1]**
γ	0.4
δ	0.3
ρ	0.3

Table 4.19: Assignment of parameters and weights for the calculation of $T_{Off-peak}$

As for the case of peak hours, higher consideration is given to the headway between trams, which influences the score of the other two parameters. The value of $T_{Off-peak}$ is assessed through Equation (3.12), and the calculation are reported in Equation (4.3):

$$T_{Off-peak} = 0.4 * 4 + 0.3 * 3 + 0.3 * 3 = \mathbf{3.4} \tag{4.3}$$

The result obtained shows a proficient level of predisposition of off-peak hours for the freight operations of 2L-MLS for Line 4.

4.5.3 Night hours operation

The night hours period considered for the case study lasts for 8 hours, from 10 P.M. to 6 A.M. For this period there are no issues of congestion of the tram network, since passengers service is halted until 7 A.M. One of the main drivers for the choice of the night hours as period designated for freight delivery is the presence of one (or more) DC, useful as depot for freight while the 2nd level of the 2L-MLS is paused. As explained in the paragraph dedicated to the nightly operations in Chapter 3, not every customer is able to receive the freight ordered during night hours, thus the items need to be temporarily stored in DCs, smart lockers and cargo wagons until the 2nd level operations starts again or until the customers retrieve their order with their private vehicles. One DC can be installed in the middle of the loop infrastructure of Niguarda Parco Nord, with the concrete possibility of implementing new ones in the zones of the lines situated in the northern section of the line, for which some space is available for construction. Near hospital Niguarda it should be also possible to install a new DC in terms of space available, if the municipality of Milan gives its permission. The score assigned to the presence of DCs along the line is equal to 5, since at least one DC will be implemented along the line.

Regarding the number of vehicles per direction per hour in service, a compromise between the fulfilment of the demand and the safety and noiselessness of the operations must be found. If 4 vehicles per hour per direction are chosen, the capacity of the freight service is twice the one presented in case of off-peak operations, thanks to the number of vehicles on the network at night, equal to 64, which is twice the value of 32 obtained during off-peak service. Thus, the capacity of the network is equal to 4800 tonnes per day. By adopting this scheduling, the headway between trams is equal to 15 minutes, which could be considered adequate for performing freight management operations smoothly. The sequence of vehicles per hour per direction is reported in Figure 4.23. It is possible to see that passengers service are not operating along the line during this period.

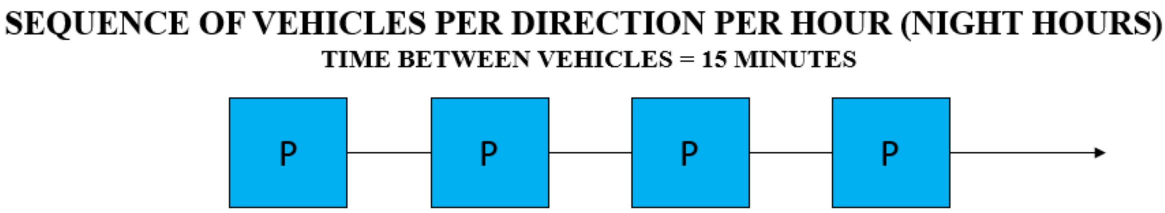


Figure 4.23: Situation of the 2L-MLS for Line 4 during night hours

The level of resilience of the network during night hours assumes a value higher than the one assigned to peak and off-peak period, but still the configuration of Line 4 does not ensure that some obstacles could be present also during night, since the line crosses the most populated zones during night-time. The value assigned to the parameters for the calculation of T_{Night} are reported in Table 4.20.

PARAMETER	MARK [1-5]
DC	5
V_F	3
R	4
WEIGHT	**VALUE [0-1]**
ϵ	0.6
δ	0.2
ρ	0.2

Table 4.20: Assignment of parameters and weights for the calculation of T_{Night}

For the assignment of the weights, the focus of the nightly operations is the availability of DCs, so it has been decided to attribute greater importance on the presence of DCs over the number of vehicles and the resilience, according to the following proportion 3:1:1. The calculation performed for the assessment of the value of T_{Night}, according to Equation (3.13), are reported in Equation (4.4).

$$T_{Night} = 0.6 * 5 + 0.2 * 3 + 0.2 * 4 = \mathbf{4.4} \quad (4.4)$$

The value attributed to the predisposition of the night hours for performing the freight service is the highest one for Line 4 amongst the period considered, so the better solution for the case-study is to implement freight service during night-time.

Since the value of predisposition of the off-peak period is still to be considered sufficiently high, some hybrid configurations of the service can be implemented. One solution could be to split the 8 hours of service in proportion between night and off-peak hours, e.g., 6 hours during night-time and 2 during off-peak period. In alternative, the total amount of hours of service could be extended from the 8 belonging to both the off-peak and night period, deploy a freight service which runs on the network for up to 12-14 hours. This last solution could be the most indicated when the demand for freight is impossible to fulfil within the 8 hours of the period. The last consideration that can be made according to the results obtained in this paragraph is that the idea to deploy the freight service during peak hours is to be avoided, due to the configuration of the line itself and the situation of the time-schedule utilised for passenger service during peak hours.

4.6 Discussion on the results obtained for the case-study applied to Italian cities

In this paragraph the results obtained through the analysis of the case-study are commented and further considerations are discussed, giving a general report on the validity of the model proposed for the assessment of the preliminary technical analysis of the 2L-MLS focusing on tram vehicles. The outcome of the decision of the city in which implementing 2L-MLS is represented by the city of Milan, one of the most advanced and organized Italian cities regarding LPT operations and management. The assessment of the predisposition of the city of Milan considering a different pool of candidates could be an interest topic for further research works. For example, it could be interesting to evaluate the marks assigned to the four parameters used for the assessment of the predisposition of the cities in case of European candidates instead of Italian ones, for which Milan has the maximum score for any parameter considered. One of the most difficult actions to perform when considering European cities is the gather of data comparable within cities located in different countries, which is difficult to outline especially for freight flows.

The next part of the analysis of the case study shifts towards the assessment of the physical characteristics of Line 4, which is a well-known tramway line which crosses the most central zones of the city. The outcome of this analysis gives a high level of predisposition of the line towards the implementation of the project, which allows the procedure of the preliminary assessment to reach further levels, heading towards the definition of the number and location of mixed stations along the line. Line 4 has been chosen as case-study mainly because of the zones it crosses, which are among the most populated and trafficked of the city of Milan, continuously attracting people and freight. Regarding the stations along the line to be converted, it is chosen to set the value of S_0 equal to 5, based on the result of the possible indications coming from the municipal authorities in the discussion phase of the project between decision-makers, stakeholders and municipality. For the demand analysis, the customers considered in the case-study presented are gastronomy activities, big retailers and hospitals. After having performed the demand analysis for each zone covered by the stations of Line 4 and the feasibility analysis regarding the possibility to install secondary rails and storage facilities, 8 stops of Line 4 are declared suitable for the conversion into mixed operation stations. In this case, the first 5 out of the 8 feasible stations ranked according to the demand generated by the potential customers of the project are chosen to be converted.

The last thing that has been covered by the model is the definition of the time period in which offer delivery services. Peak hours are strongly discouraged for their consistent interference with the passenger service, due to the conformation of the line and to the low value of headway between vehicles on the light rail network. Night hours operation gives better results in terms of favourability with respect to off-peak periods, in addition to an increase in the capability of the system due to the higher number of vehicles moving freight if the operation would be carried out at night-time, where no passenger vehicles are circulating. Hybrid configurations can also be exploited, and further research studies could be aimed at optimizing the most suitable period of the day for maximizing the efficiency of the passengers and freight service, considering varied factors not exploited in the model presented, like the difference in costs between the three periods considered and the quantity of pollution avoided. The analysis of the time period presented in the model is useful to have a general idea on the most favourable period, but in case of real implementation of 2L-MLS a more focused analysis of time scheduling needs to be performed according to LPT operators and municipal authorities. Moreover, surveys for assessing the preference of the customers over the period of delivery could result useful for guaranteeing a better efficiency of the service. The most important parameters referred to the case-study of tramway Line 4 of the city of Milan are presented in Table 4.21.

PARAMETER	DEFINITION	VALUE [1-5]
C	Predisposition of the city of Milan towards the implementation of 2L-MLS over a national horizon	5
L	Mark assigned to the physical characteristics of tram service of Line 4	3.5
S	Number of freight stations along Line 4	5
T_{Peak}	Value attributed to peak hours operation	1
$T_{Off-peak}$	Value attributed to off-peak hours operation	3.4
T_{night}	Value attributed to night hours operation	4.4

Table 4.21: Result of the preliminary technical analysis for the case study of Line 4 of Milan

After having obtained the outcomes of the preliminary analysis on the 1st level of 2L-MLS presented in the table, is possible to proceed to the next phase of the assessment of the feasibility of the project of 2L-MLS, which is the preliminary technical analysis of the 2nd level. Only after all this phase has given positive results in terms of feasibility, Multi-Criteria Analysis is used to assess the financial and economic assessment of the proposed 2L-MLS implementation.

5. Conclusions and further research

The aim of the thesis work is to provide an instrument able to define the feasibility of the 1st level of the 2-Level Mixed Logistics System using trams. The work is focused on the technical and physical characteristics that an existent tramway line must have for participating to the 2L-MLS framework.

2L-MLS is a shipment modality which combines the benefits of a decomposition of the delivery chain of products into multiple sections with the capillarity provided by tram systems. Both topics are exploited in detail in the literature review presented in Chapter 2, where also insights of Multi-Criteria Analysis, which represents the last action to be carried out for the implementation of the project, are presented. By using 2L-MLS, is possible to provide Last-Mile Delivery services using electrical vehicles for both levels of operation, having less impact on the quality of air, which is an important topic when talking about municipalities. Electric vehicles also ensure an advantage in terms of avoided congestion, since the delivery network generated by 2L-MLS is a multimodal process, able to replace Heavy-Duty Vehicles that perform the delivery operation emitting more pollutant and with longer distances to cover.

2L-MLS is currently considered an innovative delivery methodology, as there are little implementations to be referred to. The works reported in literature about this topic generally exploit multimodal freight distribution systems as a tool for applying mathematical algorithms to test their applicability and reliability for solving VRPs. Hence, the results obtained in literature are usually referred to the minimisation cost functions and definition of the fleet for 1st or 2nd level activities, with scarce information about the technical and physical characteristics of the tram systems. The thesis work presented aims to fill the gap between the theoretical implementation of a multilevel mixed logistics system and the economical outcomes of the project in terms of minimization of costs, proposing a technical analysis of the already installed tram infrastructure for the definition of optimal conditions for the implementation of 2L-MLS.

The future success of 2L-MLS implementation is based on the premises founded by the tram-based delivery systems born in the central zone of Europe in the first decade of XXI century. Even in those cases, the main uncertainties for the implementation are related to the economical features of the system. It is indeed not clear which are the actors of the systems and how to manage the redistribution of the income between participants of the project. The financial uncertainties evolve into organization issues when the delivery through tram vehicles represents only a section of the Last-Mile Delivery activity, which is the case described in the thesis work, coping with two levels of delivery of freight. Synchronization between levels is one of the most concerning issues when talking about multilevel delivery systems, as well as the definition of optimal routes for the last section of the delivery chain. These problems are mentioned in the thesis work and left to other studies totally dedicated to solving these issues.

The economic and financial analysis is a procedure which needs to be exploited only after the technical analysis has given satisfying results in terms of feasibility of the project. The key issues arousing from the economical point of view are the definition of regulations between stakeholders participating in the project, with agreement on the payment and on the ticket fees for passengers and freight service. Moreover, fixed costs are difficult to address because they depend on the characteristics of the line in which the implementation of 2L-MLS is conducted, leading to detailed economic analysis related to the particular case-study analysed, without the possibility of establishing a global generalization. The lack of economical information has driven the thesis work towards the assessment of the feasibility of the project in terms of technical characteristics of the context in which 2L-MLS is performed. The economic and financial benefits generated by the project will be assessed in the Multi-Criteria Analysis that is programmed afterward the technical analysis of the 1st and 2nd level of the 2L-MLS.

The strongest characteristic of the model proposed, explained along Chapter 3, resides in its level of applicability. The model can affirm whether a city can be considered for the implementation by comparing it with other candidates, then is able to select the suitable tramway line of the city which has the sufficient conditions for the implementation of 2L-MLS, regardless of economic and financial parameters. One of the keys of the application of the model proposed is the presence of a reliable source of data able to address for different characteristics of the cities and the tramway lines using parameters that can be compared between different alternatives. The gather of data represents a crucial activity for the model, since in absence of a consolidated source of data able to classify parameters for any of the city considered in the analysis, is impossible to assess the predisposition of the cities considered.

To conclude, the validation of the model can be appraised from the results obtained throughout the analysis of the case-study of the Italian situation. The comparison shows off that Milan is the best solution to implement the tram-based 2L-MLS, and a detailed analysis on one specific tramway line of the city, Line 4, is carried out to understand whether the model is able to deal with the location optimization of the mixed activity stations along the line. The outcome of the application of the model is that, considering the 1^{st} level of 2L-MLS using trams as vehicles for performing the delivery activities, Line 4 of the city of Milan represents a good candidate, and five stations can be converted into mixed stations. In case the results coming from the technical analysis of the 2^{nd} level of the 2L-MLS implementation and from MCA analysis turn out to be positive as well, the realization of the project along Line 4 of the city of Milan can become reality.

Further studies on the topic can be the assessment of the 2L-MLS from the point of view of wholesalers instead of considering final customers. In this approach, 2L-MLS could represent an interesting vector for bringing goods from factories located in the outbound of the cities into the inner core, building a demand analysis no more based on final customers but on freight producers. Another interesting in-depth analysis could be carried out on the integration of the 2L-MLS implementation considering the whole tram network of a city instead of a single line, investigating how the parameters to take in consideration will change by adopting this prospective. Furthermore, a sensitivity analysis on one or more parameters involved in the model proposed for the technical assessment can be performed, to address the resilience of the model to modifications on the relative weights assigned to the parameters considered. Thanks to these deepening research works on the topic, a complete assessment on the Two-Level Mixed Logistics System implementation can be accomplished.

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