Business Model of a Sustainable Transportation System for urban goods supply: Lisbon Case Study

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Resumo

Esta dissertação visa propor uma solução tecnológica para a distribuição de mercadorias usando a rede de metropolitano na cidade de Lisboa. Esta solução é projetada de modo a assegurar a compatibilidade com o atual serviço de passageiros e a satisfazer apenas alguns segmentos do mercado.

Atualmente a utilização de veículos rodoviários para o transporte de mercadorias causa vários constrangimentos quer a nível do desenvolvimento e qualidade de vida de uma área urbana quer a nível da qualidade de serviço do transporte. A necessidade de novas estratégias na logística advém de baixos níveis de eficiência, causados por crescentes restrições na circulação devido a congestionamento, e progressivas limitações nos níveis de emissões.

A solução proposta inclui o pré dimensionamento do sistema de transporte, sistema de distribuição e interligação das estações ao exterior; a análise da viabilidade do projeto e a comparação com a solução atual a nível de consumos energéticos e emissões.

O sistema para a distribuição de mercadorias usando a rede de metropolitano em Lisboa pode reduzir em cerca de 44% os consumos energéticos e 24% em emissões. O retorno financeiro previsto para o projeto é sensivelmente 5 anos.

Palavras-chave

- Transporte
- Emissões
- Congestionamento
- Mercadorias
- Distribuição

Abstract

This dissertation aims to propose a technological solution for the distribution of goods using the metro network in Lisbon city. This solution is designed to ensure compatibility with the current passenger service while satisfying only certain segments of the market.

Nowadays the use of trucks for transportation of goods is causing several constraints, affecting both the development and life quality of an urban area and the quality of the transportation service. The need for new logistics strategies comes from a low efficiency of the current system, due to traffic restrictions and congestion, and from an increase in limitations on emissions levels.

The proposed solution includes the design of the transportation and distribution system and connection of metro stations with the surface; a project viability analysis and a comparison with the current system in terms of energy consumption and emissions.

The underground system designed for freight transportation using the metro network in Lisbon may reduce energy consumption in around 44% and emissions 24%. The expected payback of the project is around 5 years.

Keywords

- Transportation
- Emissions
- Congestion
- Freight
- Distribution

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Acronyms list

HDPE - High-density polyethylene

HORECA - Hotels, Restaurants and Cafes

RFID - Radio Frequency Identification

TAB - Tunneling Auger Boring

CVC - Continuous Vertical Conveyor

HRC - Horizontal Roller Conveyor

WTT - Well to tank

TTW - Tank to Wheel

GDP - Gross Domestic Product

1 Introduction

The first objective of this dissertation is to study a technological solution for the distribution of goods using the subway network in Lisbon. The system should be fully compatible with the present-day passenger service and should address the demand of the establishments located within a certain range around each metro station. The solution developed in this report includes the design of transportation and cargo handling systems as well as the interconnection of the underground stations with the surface depots.

The second objective is to analyze the economical viability of the project and estimate the energy consumption and emissions as compared with the current truck-based system. Several economic and technical aspects related with the project implementation will also be considered such as construction methods and maintenance costs of the infrastructure.

This is important because one of the long-term objectives set by European Comission White Paper on Transport is to achieve at least a 60% reduction in 1990 greenhouse gas emissions from transportation by 2050. According to the European Environment Agency [1], EU increased the emissions due to transportation by 26% over the period 1990-2016 with road transport accounting for 72% of the emissions from the sector. Besides, road freight transport in cities also contribute to congestion and has an impact on the well-being of individuals and on urban development. The average speed loss in Lisbon is around 20 km/h due to the high traffic volume [2].

One of the solutions, highly promoted by European Comission, is the adoption of co-modal solutions in urban transportation. A modal shift from road transportation to a multi-mode model would lead to a more environmentally friendly and efficient freight logistics and an enhanced life quality in urban areas.

The second chapter contains a brief description on the opportunities for logistics. The current concerns in urban freight supply and several sustainable solutions are enumerated. Lisbon is characterized in terms of freight transportation, characteristics of establishments, metro network and geology framework.

The third chapter evaluates the present-day volume of freight in Lisbon with special attention to the establishments close to each metro station. The study investigates the market segments that are more suitable to be distributed by this system.

The fourth chapter contains the preliminary design of the transportation and cargo handling system and interconnection of the metro stations with the surface. The constraint of compatibility with the passenger service is taken into consideration.

The fifth and sixth chapters establish the investment and operational costs associated with the whole project.

The seventh chapter evaluates the viability of the project and the eighth chapter presents a comparison of energy consumption and emissions between the current transportation system and the proposed solution.

Finally, the main conclusions are highlighted and further developments are identified to understand possible indirect costs and impacts to be further studied in more detail.

2 State of art in urban logistics

2.1 Concerns regarding the urban freight supply chain

The attractiveness of a city relays on the range of resources it makes available to its community. Therefore, an efficient and effective transport system is an essential drive of the city's economy.

Over the years, road transportation has been the dominant inland transport mode, accounting for more than 75% of freight movements in 2015 [3]. Figure 1 shows the variation of inland transportation volumes and GDP of several cities in Europe between 2000 and 2015.

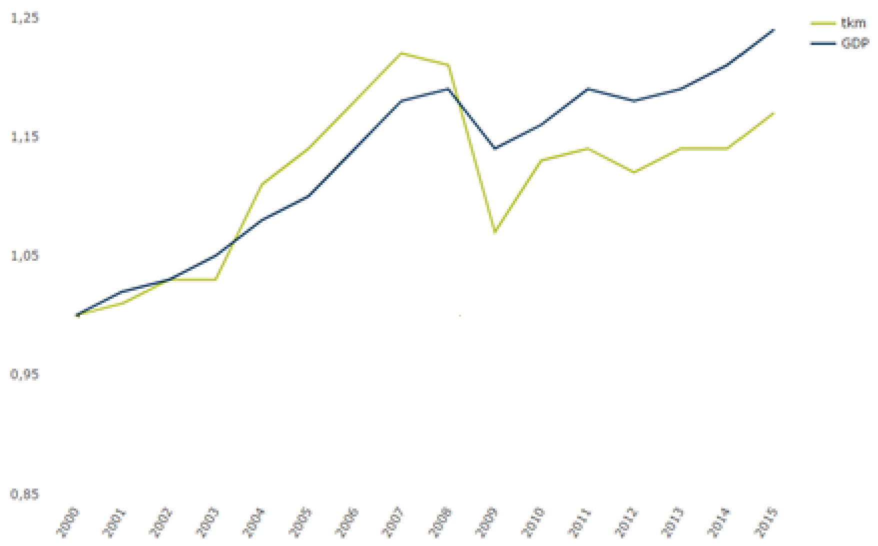

Figure 1: Growth of inland freight transport volumes and GDP relative to year 2000.

Adapted from [3].

The above growth rates are expected to increase in the coming years due to a clear improvement and consolidation of the e-commerce and home delivery concepts.

Half of the emissions concerned with road transportation are known to be generated in urban areas and are caused by a poor supply chain cooperation and efficiency of the transport systems[4].

Urban space is a scarce resource, limited in terms of capacity. The roads built in the past have not been able to absorb and handle the current load. Consequently, congested traffic leads to delays in goods delivery, noise, disruptions in passenger transportation flows and an inefficient use of fuel which translates into an increase in greenhouse gas emissions.

2.2 Towards a sustainable transportation system

Strategies currently adopted by governments tend to follow "segregated approach" as in what regards passenger and goods transportation. However, a key solution to develop a sustainable transport system in urban areas is to rethink the urban mobility as a "co-modality" to optimize the use of all transport modes.

The consensus of experts considers necessary to combine freight and passenger transportation and improve the network management. Cities should set a sustainable approach along three different axes [5]:

1) **Improve the sharing of road space** between road transport passenger flows and goods flows (*e.g.* multiuse lanes, night deliveries). This strategy would optimize the use of roads to avoid transportation peaks and guarantee a smoother operation.

2) **Shift passenger and/or goods flows** from road to other urban modes (*e.g.* shared metro/bus, pipeline network for goods supply). An increased use of public transportation could release cities from congestion while increasing revenues of public transport systems making them less subsidy dependent.

3) **Introduce distribution facilities** in urban areas already dedicated to passengers (*e.g.* urban delivery stations in car parks, good lockers in underground stations). Adopting this strategy could avoid unnecessary driving and parking.

In the recent years there has been initiatives leaded by governments, universities and even private companies in order to come up with this kind of sustainable solutions. In the next section it will be present some of these initiatives.

2.2.1. Netherlands: Tram-Integrated Transportation System

In 2007 a project was launched by the company CityCargo Amsterdam with the objective of reducing the traffic volume in the inner city. A testing phase was set on the tram network and trucks would supply 2 cargo trams at the last station of tram line. Cargo trams would not use passenger stations but instead two specific transfer points to avoid impact the passenger flow. The last mile delivery was done by small electrically powered vehicles which would deliver the goods from the two transfer points to the final address. After a successful trial phase, CityCargo estimated around 50 cargo trams and around 400 electric cars in order to supply the center of Amsterdam. This project was reported as cost efficient (1 cargo tram was replacing four 7.5ton-trucks), a reduction of up to 16% in emissions, less noise and higher efficiency during loading/unloading operations.

Despite the benefits and contributions from private companies, the cargo tram project went bankrupt in 2009 after the city refused to subsidize the expansion of the tram track network [6].

Figure 2: Tram-Integrated System. Adapted from [6].

2.2.2. Japan: Metro-Integrated Transportation System

The city of Sapporo in northern Japan has serious logistics problems caused by snow-confined roads. The city has studied the possibility of integrating goods transportation in the Sapporo city metro system. This strategy was tested during two weeks in 2010 and consisted in loading a 700x500x900 (LxWxH) hand cart with a maximum gross weight of 60 kg on a common passenger metro car. The results of the experience were quite positive with nearly 80% of the participants in the on-board monitoring survey stating not to feeling any discomfort in boarding the metro with freight goods. However, most has supported the idea of using a metro car exclusively for freight transportation. Since this study [7] it was not found any further developments.

Figure 3: Metro-Integrated System in Japan. Adapted from [7].

2.2.3. Underground Transportation Pipelines

Pipelines are already providing efficient and ecological solutions for transportation of liquid or gaseous materials. The main objective behind the initiatives described below is to replace freight trucks with capsules which will operate in an underground pipeline network connecting all logistics legs. Instead of a combination of different transportation modes, the following projects propose to segregate the transportation of freight from the passenger flow by moving freight underground without interfering with surface traffic.

- Foodtubes, Oxford University:

In 2008, the University of Oxford presented a project called Foodtubes [8]. Foodtubes consisted of lightweight food pipeline capsules (1-meter diameter by 2 meters long) powered by electric or pneumatic motors circulating in a 1,500 kilometers underground network connecting food producers and retailers in UK. These capsules would be loaded/unloaded at freight dockets and circulate underground at 100 kph. No further developments are known.

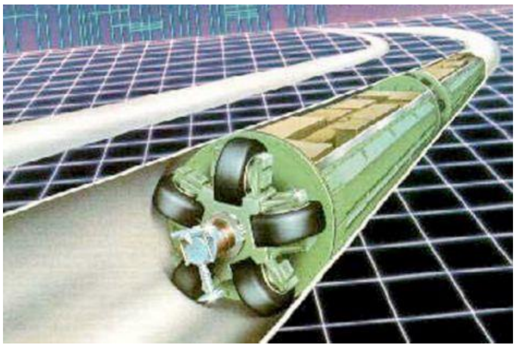
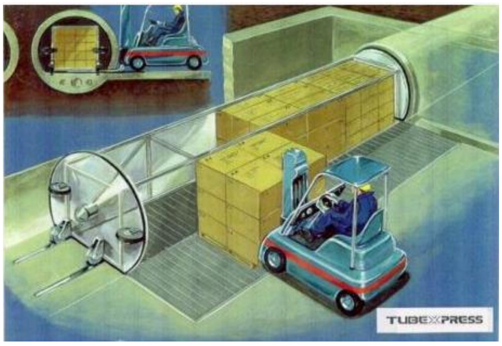

Figure 4: Foodtubes Project. Adapted from [8].

- CargoCap, Ruhr University:

CargoCap is a project carried out at the University of Ruhr. It consists of capsules designed for transportation of two euro-pallets across pipelines with a diameter of 2 meters. The pipeline network would connect suppliers, distributors and final retailers. The capsules would operate 24 hours a day at approximately 40 km/h and arrange themselves automatically into the station after loading/unloading at depots. Further transportation to the customer would be performed with the use of conveyors.

According to the autors [4], this project would decrease the emission of about 18% of carbon dioxide per year besides positive impacts on congestion. The theoretical research and development work on the CargoCap system has proceeded very far. A capsule prototype was built to be tested in a test track before further developments.

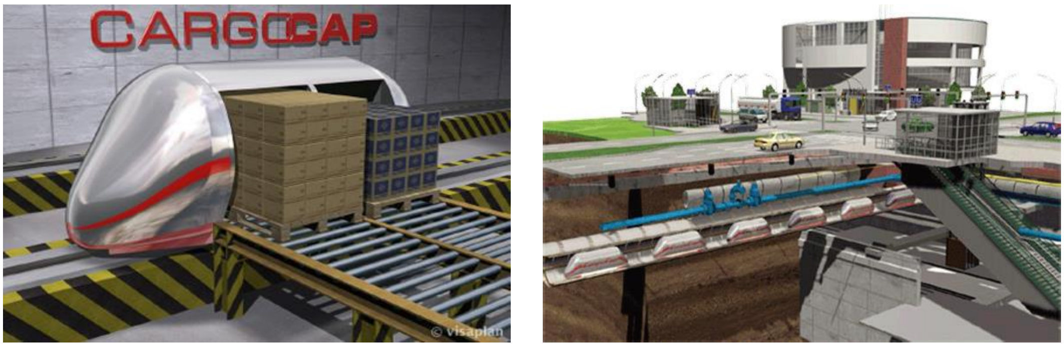

Figure 5: CargoCap Project. Adapted from [4].

2.2.4. Toyota e-Palette: New Ecosystem for Mobility Business

Private companies are also committed to develop new mobility solutions. The concept of an e-Palette Vehicle was already announced in 2018 by Toyota Motor Corporation to meet the demand of future multi-mode transportation applications [9]. The concept consists of a fully-automated, next generation battery electric vehicle designed to be customizable for a range of businesses. The interior layout will be open to the user's needs. The purpose would be to be flexible enough to support several business requirements and transitions.

In order to explore this concept, an alliance was created leaded by Toyota Motor Corporation and including partners such as Amazon, DiDi, Pizza Hut and Uber. The Alliance will explore various applications of this concept accoording to their business needs and focus on the development of the new vehicle. Toyota plans to conduct feasibility testing of the e-Palette Concept in various regions, including the United States, in the early 2020.

Figure 6: Toyota Project e-Pallete. Adapted from [9].

2.2.5. General Assessment

From the several projects developed over the recent years, underground transportation of goods is a promising direction to explore. Among the advantages are the optimization of the land use; significant reduction of the environmental effects caused by traffic volumes at surface level such as congestion or noise and increase in efficiency and flexibility of urban goods distribution. Among the possibilities for an underground system are a system that shifts goods from road to other transport mode such as the metro or the development of a fully underground pipeline network with dedicated vehicles. Both solutions will have aspects to consider during the planning and construction phase. A combination of freight and passenger transportation would impose some extra requirements to the system since it should not disturb the passenger transportation service. However, it would facilitate the implementation phase since a part of the network would be already operational. A fully underground pipeline network could offer an autonomous and completely flexible network for transportation of goods although the investment cost and effects from surface disruptions during construction phase would be substantially higher.

3 Present day logistics in Lisbon

3.1 Freight transportation process

The circulation of vehicles with a load capacity greater than 3.5 ton is not allowed in the Lisbon center, including the Historical Center. The typical narrow streets of Lisbon raise substantial problems to loading and unloading. Usually these narrow roads have only one free lane for traffic and the vehicles are frequently forced to park on the sidewalks to minimize the effects on circulation. 54% of 604 establishments surveyed in Lisbon [2] reported that vehicles are double parked on the road for over 75% of deliveries. Half of the establishments inquired considered the conditions for loading/unloading either very or somehow inadequate [2]. This represents a clear statement of disagreement regarding the current urban freight transportation.

The Logistics Platforms are located essentially in the “North Logistic Platform” and in Azambuja area. These distribution centers are distant from the Lisbon metropolitan area and there is no Center for Charging Orders (CCO) responsible for the urban distribution within the city center which creates difficulties in using trucks with smaller size.

As an example, we can mention the SUMOL+COMPAL 3.5 ton vehicles that serve the HORECA (Hotel, Restaurants and Cafes) sector in Baixa “Pombalina” of Lisbon. The delivery occurs before 10 am every day of the week with vehicles parking on Rua Augusta (a pedestrian street) and on the sidewalk of Rua de los Sapateiros [10].

Another example is the NOVADIS distribution of Sagres beer and Luso mineral water to establishments located in Rua Escolas Novas on the hill of Geaça [10]. This distribution route interferes with trams of line 28E which can lead to major blocking points in traffic.

Figure 7: Unloading in Historical Center of Lisbon. Adapted from [10].

3.2 Retail establishments characterization

According to an establishment-based survey of 604 establishments in Lisbon [2], 90% of the deliveries correspond to core goods and only 5% to postal deliveries and ancillary products. In terms of freight characteristics, more than 50% of the establishments classify their products as medium weight and medium volume (1 person per unit) and less than 15% as heavy weight and/or big volume (requiring more than 1 person or auxiliary equipment).

The number of deliveries to each establishment has a daily average of 8 and exhibits a low variation along the week. However, a significant variation exists along the day per establishment type. For instance, food and drinks have one peak only around 8AM but health and care products are distributed more frequently around 10AM and 4PM.

Around 90% of deliveries come from multiple shipping points and only 6% of establishments receive their goods in vehicles doing single trips. 60% of deliveries are done by a third-party logistic operator with the delivery day and time defined by the third-party company in 67% of these cases limiting the flexibility for the final customer. For about 65% of the deliveries, the goods are received the day after ordering. The light vehicles (gross weight <3.5 ton) used in these deliveries reported to take up to 5 min to unload in around 70% of the cases. The unloading operation is not done by the third party according to 30% of the establishments. For this reason, 90% of establishments mention not to accept deliveries off operational hours which is an obstacle to adopt night deliveries.

3.3 Underground subway network

As of 2017, Lisbon Metro has 4 different lines serving a total of 56 metro stations over 44.5 kilometers. 6 out of 56 are double stations which means that each one of these stations serves 2 different metro lines. Table 1 presents an overview of the Lisbon Metro Network:

Metro Lines	No. stations	Extension (km)
Blue Line	17	14
Yellow Line	13	11
Green Line	13	9
Red Line	12	10

Table 1: Overview of Lisbon Metro Network.

Figure 8: Diagram of Lisbon Metro Network. Adapted from [11].

As it can be seen from the network diagram in Figure 8, the Lisbon Metro is designed to cover important city areas with some suburban extension. The network is well integrated with other transportation modes such as plane, boat and train. The passenger service is operational every day from 06:30 until 01:00. There is a train approximately every 5 to 8 minutes [11] but the frequency varies along the day.

The rolling stock is composed by 111 operational train units. Each unit has 2 motorized cars and one trailer between them. Each trip usually operates with 2 operational train units semi permanently linked together. The series of cars mostly used are the ML95 and ML99, both assembled at Sorefame (Bombardier). The overall dimensions, transmission and brake systems have the same characteristics. The major difference between them is the maximum capacity of passengers. Table 2 presents the general specifications of a passenger car [12]:

Dimensions	
Length, $L_{passenger}$	16.224 m
Max. width, $W_{passenger}$	2.789 m
Height, $H_{passenger}$	3.523 m
Track gauge, G	1.435 m
Weight	
Tare, $T_{passenger}$	29.3 ton
With full capacity, $C_{passenger}$	40.6 ton
Performance	
Max velocity, V_{max}	72 km/h
Max acceleration, a_{max}	1 m/s^2
Supply voltage, $S_{voltage}$	750 V cc
Installed power, $P_{installed}$	4x175 kW

Table 2: General specifications of a passenger car (ML99 series).

The construction of Lisbon Metro Network started in 1955. The construction method at the time was open cut for most of the network and tunneling in some stretches [13]. The cross section of the galleries used in cut-and-cover method is illustrated in Figure 9.

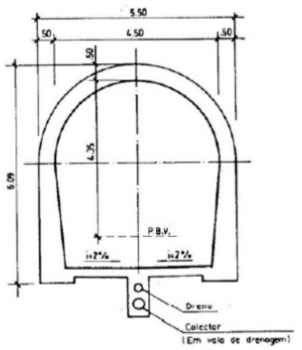

Figure 9: Open Cut Method - Shape of galleries. Adapted from [13].

This structural shape was chosen to allow compressive stresses to predominate. The construction material was simple concrete.

In later tunnels, the NATM (New Austrian Tunneling Method) was selected which uses shield boring machines. These machines are known as TBM (Tunneling Boring Machines). The shape of the galleries used in tunneling is represented in Figure 10.

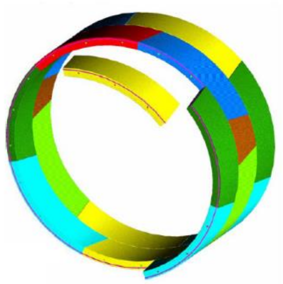

Figure 10: Tunneling Method - Shape of galleries. Adapted from [13].

The axis-depth of the metro tunnels varies between 15 meters (*e.g.* Cais do Sodré section) and a maximum of 48 meters (Baixa-Chiado section) [13]. It was estimated an average axis-depth of 26 meters although we were not allowed to access all details of the entire network due to “confidential reasons”.

A plan of expansion was announced by Lisbon Metro [14], which involves the construction of a circular line connecting the yellow line in Rato to the green line in Cais do Sodré. This new circular line would involve some modifications in the current network and the construction of two new metro stations: Estrela and Santos.

Although the Government is committed to pursue some major investments in the network, the Lisbon Metro reports consecutively negative results over the years. According to the 2018 financial report [15], in 2018 the loss amounted to 27.87 million euros and it was highlighted a debt in liabilities which amounted to 3.8 billion euros. Therefore, it would be beneficial for Lisbon Metro to find new opportunities to develop their network and consequently increase their profit and become more independent.

4 Freight transportation volume

4.1 Retail sales volume

The overall trade volume of the retail shops in 2016 was taken as a proxy for the maximum potential demand of the new transportation system. This is a conservative approach because it excludes the transportation of small parcells on behalf of individuals and all the transportation associated with e-commerce. Furthermore, the wholesale business was not taken into consideration; for the scope of this research, a metro-based system designed for the city of Lisbon would not reach easily most of the wholesale establishments, which are located outside the city.

The Lisbon retail sales volume in euros per year of a given group of retail goods i_g is described by expression 1:

$$(S_{lis})_{i_g} = (S_{pt})_{i_g} \times \left(\frac{S_{lis}}{S_{pt}}\right)_{total} \tag{1}$$

where S_{lis} is the retail sales volume of Lisbon in euros per year and S_{pt} is the retail sales volume of Portugal in euros per year. This expression assumes that the proportion between the retail sales volume of Portugal and retail sales volume of Lisbon is the same for all groups of retail goods.

The overall Lisbon sales volume was distributed by the metro stations on the assumption that the sales volume in the city is proportional to the number of retail establishments. The influence area of each metro station was estimated to allocate each retail establishment to the closest metro station (or to no one, if the establishment was not in the influence area of a station). A georreferenced map was created using the QGis tool. A GoogleMaps database was loaded with geodata references of the metro stations and information from the 2010 Census on commerce. By connecting each retail establishment to the nearest metro station, it was possible to determine how many retail establishments would be potential customers of a station.

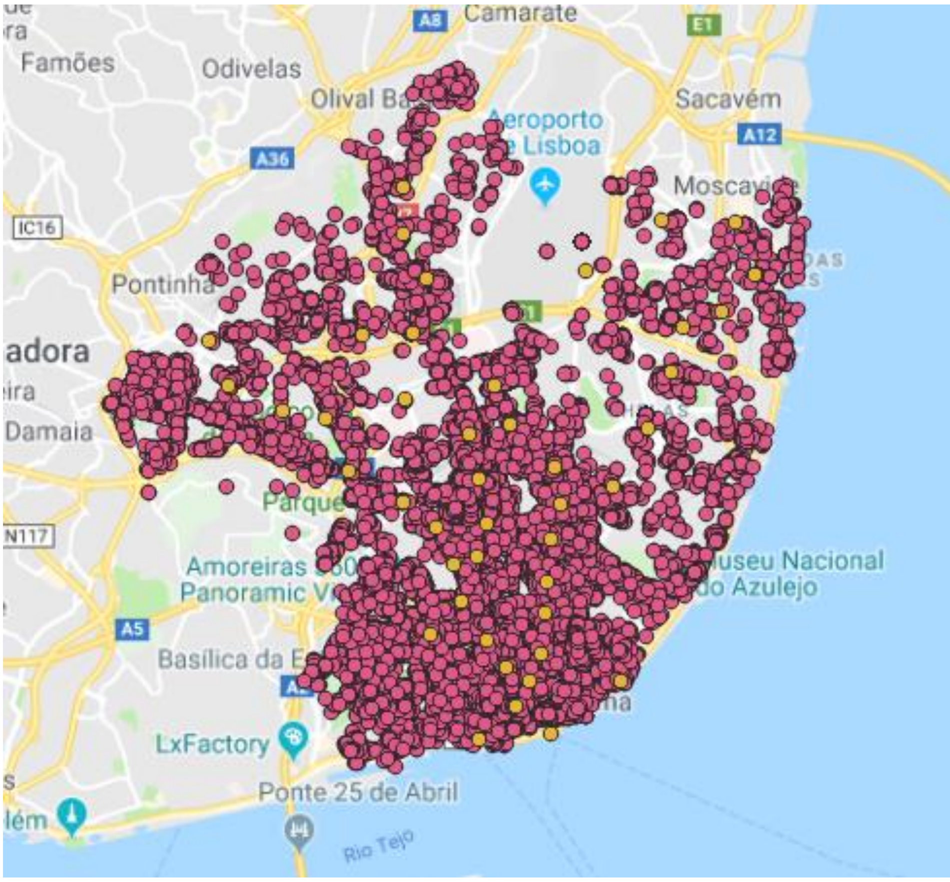

Figure 11: Allocation of establishments to the nearest station.

The sales volume in euros per year of a given group of retail goods i_g allocated to a metro station is calculated with the following expression:

$$(S_{sub})_{i_g} = (S_{lis})_{i_g} \times \left(\frac{N_{i_s}}{N_{total}}\right) \tag{2}$$

where $(S_{lis})_{i_g}$ is the Lisbon retail sales volume of a group of retail goods i_g in euros per year, N_{i_s} is the number of retail establishments linked to that metro station and N_{total} is the total number of retail establishments in Lisbon.

4.2 Physical characteristics of freight (mass and volume)

It was necessary to convert the economic retail sales volume to physical quantities such as mass and volume. The methodology was different according to the type of goods:

- Food products:

In order to calculate the mass and volume of food products, each category had to be classified according to a certain basket of products. It was assumed that the quantity and type of products sold by retail establishments was approximately equivalent to the quantity and type of products consumed by the population. Therefore, the type and quantity of products which comprise the Portuguese Food Balance were used as reference values for conversion [18].

The mass of a given food product i_{fg} to be transported to each metro station per year is given by the following expression:

$$m_{i_{fg}} = \frac{(S_{sub})_{i_g}}{(C_{/kg})_{weight}} \times \frac{(m_{person/year})_{i_{fg}}}{(m_{person/year})_{i_{total}}} \tag{3}$$

where,

$$(C_{/kg})_{weight} = \sum_{i_{fg}}^{n} (C_{/kg})_{i_{fg}} \times \frac{(m_{person/year})_{i_{fg}}}{(m_{person/year})_{i_{total}}} \tag{4}$$

where $(S_{sub})_{i_g}$ is the sales volume in euros of a given group of retail goods i_g allocated to a metro station in euros per year; $(C_{kg})_{weight}$ is the weighted cost per kilogram given by expression (4); $(C_{/kg})_{i_{fg}}$ is the cost per kilogram of a food product of index i_{fg}, $(m_{person/year})_{i_{fg}}$ is the average mass consumed per capita over one year of a food product of index i_{fg} and $(m_{person/year})_{i_{fgtotal}}$ is the total mass of all food categories consumed per capita over one year.

The volume of a given food product i_{fg} to be transported to each metro station per year is given by the following expression:

$$V_{i_{fg}} = \frac{m_{i_{fg}}}{\rho_{i_{fg}}} \tag{5}$$

where $m_{i_{fg}}$ is the mass of a food product of index i_{fg} to be transported per year and $\rho_{i_{fg}}$ is the density of a food product.

- Other products:

A different approach was considered to calculate the mass and volume of non-food products. Each category had to be classified also according to a certain basket of products. This estimate was based on informal surveys to an average of 3 retail establishments per product category. The purpose was to identify the core products sold within each category and be able to estimate a sales percentage of each type of product as well as its average price.

The quantity of a certain non-food product of index i_{og} to be transported per year is given by the following expression:

$$N_{i_{og}} = \frac{(S_{sub})_{i_g}}{(C_{/kg})_{weight}} \times W_{i_{og}} \tag{6}$$

where,

$$(C_{/kg})_{weight} = \sum_{i_{og}}^{n} (C_{av})_{i_{og}} \times W_{i_{og}} \tag{7}$$

where S_{sub} is the sales volume in euros of a given group of retail goods i_g allocated to a metro station in euros per year, $(C_{/kg})_{weight}$ is the weighted cost per kilogram given by equation (7); $(C_{av})_{i_{og}}$ is the average price of a non-food product of index i_{og} and the $W_{i_{og}}$ is the sales percentage of a non-food product of index i_{og}.

The mass of a certain non-food product of index i_{og} to be transported to each metro station per year is given by the following equation:

$$m_{i_{og}} = m_{av_{i_{og}}} \times N_{i_{og}} \tag{8}$$

where $m_{av_{i_{og}}}$ is the average mass of a non-food product of index i_{og} taking into account the best sellers of each product type and $N_{i_{og}}$ is the quantity of a non-food product of index i_{og} to be transported per year.

The volume of a certain non-food product of index i_{og} to be transported to each metro station per year is given by the following equation:

$$V_{i_{og}} = V_{av_{i_{og}}} \times N_{i_{og}} \tag{9}$$

where $V_{av_{i_{og}}}$ is the average volume of a non-food product of index i_{og} taking into account the best sellers of each product type and $N_{i_{og}}$ is the quantity of a non-food product of index i_{og} to be transported per year.

Table 3 presents a summary of the values obtained for the total mass and volume of freight that could be transported during one year to each metro station and through each metro line.

Mass/Volume per Metro Station	MASS (10^3 ton/year)			VOLUME (10^3 m^3/year)		
	Food Products	Other Products	$M_{total/year}$	Food Products	Other Products	$V_{total/year}$
Carnide	18	5	23	36	24	60
Colégio Militar/Luz	26	7	33	52	33	85
Alto dos Moinhos	9	2	11	17	11	28
Laranjeiras	6	2	8	12	8	20
Jardim Zoológico	8	2	10	17	11	28
Praça de Espanha	10	3	13	20	13	33
S. Sebastião	8	2	10	16	10	26
Parque	4	1	5	9	6	15
Marquês de Pombal	9	3	12	18	12	30
Avenida	12	3	15	24	16	40
Restauradores	13	3	16	25	16	41
Baixa-Chiado	23	6	29	45	29	74
Terreiro do Paço	9	3	12	18	12	30
Santa Apolónia	13	4	17	26	16	42
Blue Line	168	46	**214**	335	217	**552**
Ameixoeira	8	2	10	16	11	27
Lumiar	6	2	8	11	7	18
Quinta das Conchas	5	2	7	11	7	18
Campo Grande	3	1	4	5	4	9
Cidade Universitária	2	0.4	2	3	2	5
Entrecampos	6	2	8	11	7	18
Campo Pequeno	13	4	17	27	17	44
Saldanha	16	4	20	32	21	53
Picoas	12	3	15	24	15	39
Marquês de Pombal	9	3	12	18	12	30
Rato	55	15	70	108	70	178
Yellow Line	135	38	**173**	266	173	**439**
Telheiras	8	2	10	15	10	25

Campo Grande	3	1	4	5	4	9
Alvalade	15	4	19	31	20	51
Roma	14	4	18	28	18	46
Areeiro	13	4	17	25	16	41
Alameda	10	3	13	20	13	33
Arroios	22	6	28	45	29	74
Anjos	14	4	18	27	17	44
Intendente	12	3	15	24	16	40
Martim Moniz	19	5	24	38	24	62
Rossio	20	6	26	41	26	67
Baixa-Chiado	23	6	29	45	29	74
Cais do Sodré	21	6	27	41	26	67
Green Line	**194**	**54**	**248**	**385**	**248**	**633**
Aeroporto	3	1	4	5	3	8
Encarnação	3	1	4	7	4	11
Moscavide	3	1	4	6	4	10
Oriente	11	3	14	21	14	35
Cabo Ruivo	2	1	3	5	3	8
Olivais	5	1	6	10	6	16
Chelas	6	2	8	12	8	20
Bela Vista	8	2	10	17	11	28
Olaias	10	3	13	19	13	32
Alameda	10	3	13	20	13	33
Saldanha	16	4	20	32	21	53
S. Sebastião	8	2	10	16	10	26
Red Line	**85**	**24**	**109**	**170**	**110**	**280**

Table 3: Freight to be transported to each metro station per year.

It is important to mention that this analysis excludes some goods which are currently delivered by road transportation. For the scope of this study, the oversized goods and the perishable goods were not considered. The perishable goods represent around 40% of total mass of goods transported and can be included in future versions of this report if all transportation requirements are fulfilled in terms of the temperature, humidity and cleanliness.

Annex 1 presents more details on the mass and volume of goods not considered in this study for all metro stations.

4.3 Freight flow analysis

If freight is transported through the Lisbon Metro during normal service hours it has to be compatible with the current passenger service. The freight wagons will be carried as one more vehicle trailed by the current passenger trains. Therefore, the mass and volume to be delivered during each trip of a train was estimated based on the current frequency of passenger trains.

This freight transportation system was considered to be available during 251 days per year to exclude weekends. This is a conservative assumption to ensure it can accommodate any peak in transportation in case potential customers want to guarantee all stock delivered before the weekend comes.

It was also assumed that the transportation period per day would be concentrated in the morning, from 06:30 until 12:00. This design restrictions accommodates an allowance for potential customers that would prefer all goods to be delivered in the morning period rather than along the day (*e.g.* food products). This allowance also guarantees that the system is flexible when facing peaks in demand during short time periods like peak days during Christmas season. In case it is necessary to distribute greater volume more evenly along the day, the system could work along all day to meet the demand without major operation concerns.

The number of trips available per day in a certain metro line to transport the goods is calculated using the equation (10):

$$No_{trip} = \frac{t_{tran}}{(f_s)_{av}} \tag{10}$$

where t_{tran} is the duration of transportation period per day and $(f_s)_{av}$ is the average metro frequency of the current passenger service in that line.

To take a conservative approach the freight volume was assumed to be distributed in one direction (unidirectional flow) since most of the freight volume transported would be transported from wholesale facilities located outside the city. Since the worst-case scenario is a unidirectional flow of goods from the surroundings of the city to the retail establishments located in the center.

The freight mass and volume of goods to be transported in each trip of a metro line can be obtained by equations (11) and (12) respectively:

$$m_{trip} = \frac{m_{line/day}}{No_{trip}} \quad (11)$$

where $m_{line/day}$ is the mass of goods to be transported in a metro line per day and No_{trip} is the number of trips available per day in a certain metro line for freight transportation.

$$V_{trip} = \frac{V_{line/day}}{No_{trip}} \quad (12)$$

where $V_{line/day}$ is the volume of goods to be transported in a metro line per day and No_{trip} is the number of trips available per day in a certain metro line for freight transportation.

Table 4 presents a summary of values obtained for the mass and volume to be transported per trip in each line of Lisbon Metro.

Mass/Volume per trip	Blue Line	Yellow Line	Green Line	Red Line
Mass per year, $M_{total/year}$ (10^3 ton)	214	173	248	109
Volume per year, $V_{total/year}$ (10^3 m^3)	552	439	633	280
No. working days per year	251			
Mass per day, $M_{total/day}$ (ton)	853	689	988	434
Volume per day, $V_{total/day}$ (m^3)	2199	1749	2522	1116
Transport time per day, t_{tran} (h)	5.5			
Avg. metro frequency, $(f_s)_{av}$ (min)	6	6	6	8
No. Trips, No_{trip}	54	60	51	48
Mass per trip, m_{trip} (ton)	16	12	**19**	9
Volume per trip, V_{trip} (m^3)	41	29	**50**	23

Table 4: Freight to be transported per trip.

5 Design of the transportation system

5.1 Freight containers design

Most of the logistic chains in Europe use Euro-pallets so they represent a good standard unit for freight transport. Therefore, it was assumed that each container should transport a 1200 × 800 mm Euro-pallet ($L \times W$).

A full Euro-pallet can have a maximum height of 1800 mm and a maximum weight of 1000 kg. However, if these maximum dimensions are considered it would impose additional restrictions to the design and significant increase in infrastructure costs. Since the oversized goods were excluded, as previously explained, a maximum height (900 mm) and weight (500 kg) of a "half" Euro-pallet was taken as a reasonable value for the container dimensions without bringing extra difficulties to the design.

High Density Polyethylene (HDPE) is a plastic commonly used in containers for goods. It is also known as an approved plastic by the Food and Drug Administration (FDA) for storage of food products [19]. Besides it exhibits low weight; it is corrosion-resistant, it absorbs little moisture, does not leach chemicals over time and is resistant to impact and abrasion.

Table 5 presents a summary of the specifications for each container:

Freight Container Specifications	
Material	HDPE
Outer dimensions $(L_o \times W_o \times H_o)_{container}$	1290x890x1000 mm
Inner dimensions $(L_i \times W_i \times H_i)_{container}$	1250x850x900 mm
Tare ($M_{container}$)	20 kg
Cargo ($C_{freight}$)	500 kg

Table 5: Freigth container specifications.

The above specifications were validated through an assessment of similar containers currently available in the market.

Figure 12 shows an example of a HDPE container designed for goods transportation.

Figure 12: *e.g.* HDPE container for goods storage

(with similar dimensions although not exactly the same). Adapted from [43].

The number of containers to transport the freight volume per trip is given by equation (13):

$$No_{containers/trip} = \frac{V_{trip}}{V_{container}} \tag{13}$$

where V_{trip} is the volume of goods to be transported in each trip and $V_{container}$ is the volume of goods to be transported in each container.

Table 6 presents a summary of the number of containers required per trip in each line of the Lisbon Metro.

No. Containers per trip	Blue Line	Yellow Line	Green Line	Red Line
Volume per trip, V_{trip} (m^3)	41	29	50	23
Volume per container, $V_{container}$ (m^3)	0.956			
No. containers per trip, $No_{containers/trip}$	43	31	53	25

Table 6: Number of Freight Containers per trip.

The detailed value of the number of containers required per trip in each metro station of Lisbon Metro is shown in Annex 2.

5.2 Freight cars design

There are requirements on the overall dimensions to take into consideration in the design of a freight car compatible with Lisbon Metro. The maximum height, width and track gauge of the freight car must be the same as the current passenger cars to ensure it fully fits the Lisbon Metro.

In order to increase flexibility, the design will be the same for all metro lines and it will take into consideration the maximum design capacity of 53 containers per freight car. The number of rows and columns of containers that fit into a freight car are:

$$Rows_{container} = \frac{W_{freight\ car}}{W_{container}} \tag{14}$$

where $W_{freight\ car}$ is the width of a freight car and $W_{container}$ is the width of a container.

$$Columns_{container} = \frac{L_{freight\ car}}{L_{container}} \tag{15}$$

where $L_{freight\ car}$ is the length of a freight car and $L_{container}$ is the length of a container. The length of a freight car was estimated through an iteration process. For a 1-deck freight car the length should be considerably higher than the length of a passenger car. To optimize the available space inside the freight car for containers storage, a 2-deck configuration was selected.

Since this transportation system must be compatible with the current passenger service, the containers must be loaded into the freight car during the boarding time of the passengers. An average dwell time of 30 seconds was considered [20] except for the stations at the end of a metro line where an average dwell time for boarding of 4 minutes was assumed.

The process for sorting, loading and organizing the containers in a freight car should be fully automated since the time for loading/unloading the containers is very limited and the weight of the containers is considerable. Besides, automation optimizes the available space.

A Radio Frequency Identification (RFID) system[1] would be installed to sort the containers according to their destination. An RFID reader would be mounted on the freight car door. Besides sorting the goods, all saved information could be used to track freight effectively and provide additional functionalities to customers.

Two different approaches were considered for a fully automated storage system:

1) Use fully automated containers powered by a lithium-ion battery. These vehicles would be autonomous.

2) Use passive containers supported on multi directional conveyors to move the containers in all horizontal directions and sort them.

Both options would use a puzzle-based organization system [21] to ensure the correct load is already located next to the exit door at arrival to the destination.

Design (2) was chosen since it is a less complex automated system being used in the industry (*e.g.* DHL with celluveyor). Multidirectional conveyors consist of power-driven transfer tables composed of several shafts with rollers with high impact resistance and load capacity.

Figure 13 represents products available in the market for power-driven transfer tables.

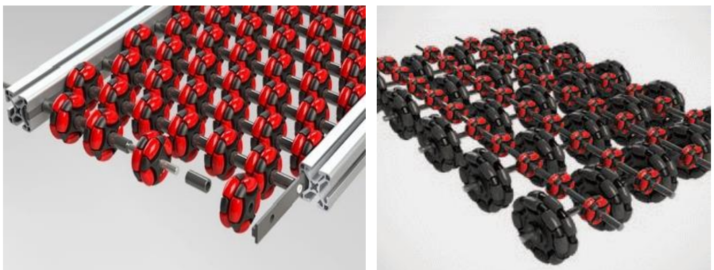

Figure 13: *e.g.* Power driver transfer tables. Adapted from [44].

[1] RFID systems have plenty of application[1]s in tracking goods along the supply chain (*e.g.* airport baggage logistics). This system uses electromagnetic fields to identify and track chips attached to the goods. Active chips have a local power source which can operate far from the RFID reader.

In order to design a power-driven conveyor table capable of moving a container, the velocity and power of each table must be computed evaluated. A demanding require was assumed: load up to 53 containers in a single station with a dwell time of 30 seconds. The velocity of each conveyor table is given by equation (16):

$$v_{table} = \frac{No_{containers/door} \times L_{container}}{t_{dwell}} \tag{16}$$

where $No_{containers/door}$ is the number of containers to load per each entry door of a freight car, $L_{container}$ is the length of a container and t_{dwell} is the average dwell time in a station. An initial approach showed it was not possible to achieve realistic velocities with only 1 unloading door and 1 loading door. Therefore, the freight car is designed with 2 decks, 1 unloading door and 1 loading door in each deck.

The maximum force to move a container is given by equation (17):

$$F_{max} = F_c + F_v \tag{17}$$

where F_c is the force to move the container at a constant speed and F_v is the force needed to accelerate the container which can be considered neglectable.

The maximum force to move each container must ensure the following condition:

$$F_{max} \cong F_c \ \leq \ N.\mu_{static} = \ m_{container} \times g \times \mu_{static} \tag{18}$$

where $m_{container}$ is the mass of a container, g is the gravity acceleration and μ_{static} is the friction coefficient of a container supported on commercial rollers. The static friction coefficient between a plastic container and the rollers was considered as 0.05 [22].

The maximum power of each conveyor table is:

$$P_{table} = \frac{F_{max} \times \ v_{table}}{\eta_{engine} \times \ \eta_{table}} \tag{19}$$

where v_{table} is the constant velocity of each transfer table, η_{engine} is the efficiency of the electric engine used in these conveyors and η_{table} is the efficiency of the table . An efficiency of 70% was taken as a reasonable value for the electric engine [23]. For the table an efficiency of 80% was considered.

Table 7 presents a summary of the design specifications of a freight car.

Freight car specifications	
No. decks	2
No. unloading/loading doors	4
Height, $H_{freight}$ (m)	3.523
Width, $W_{freight}$ (m)	2.789
Length, $L_{freight}$ (m)	13
Conveyor acceleration, $a_{conveyor}$ (m/s^2)	0.5
Maximum force of a conveyor table, F_{max} (N)	255
Velocity of a conveyor table, v_{table} (m/s)	1.14
Power of a conveyor table, P_{table} (W)	519

Table 7: Freight car design specifications.

It is important to mention that the overall dimensions presented in Table 7 allow a maximum of 56 containers to be transported on a freight car.

Figure 14 represents a sketch of a freight car and containers layout.

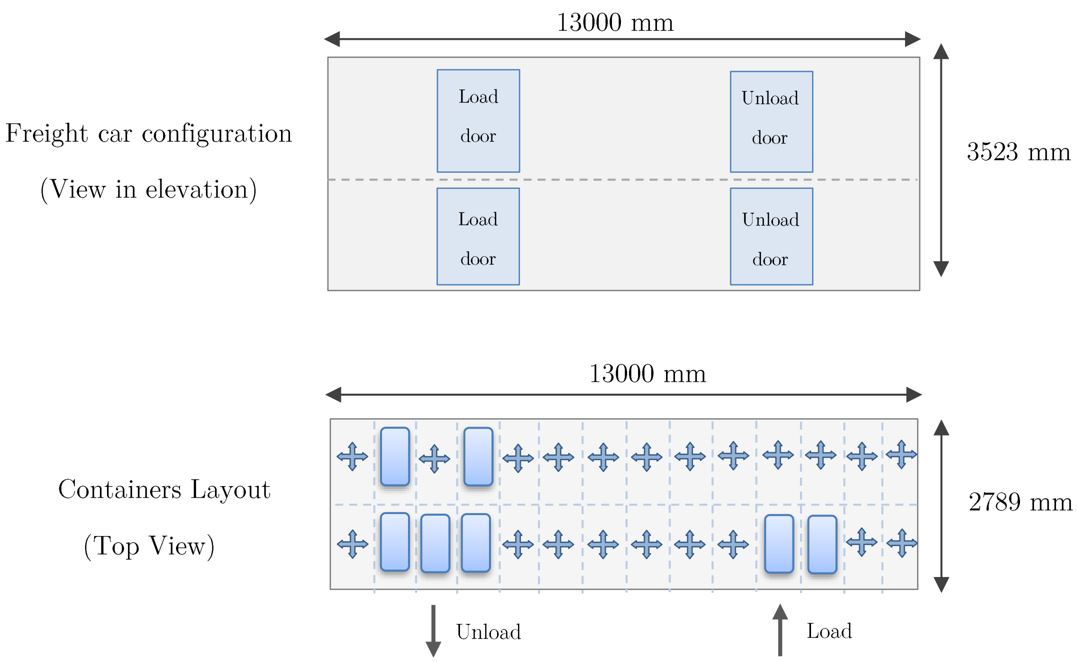

Figure 14: Sketch of a freight car configuration and containers layout.

In order to assess if the same motorization of a passenger car can be used in a freight car, the impact on the maximum acceleration of adding a freight car needs to be calculated. The additional mass of a freight car includes its tare mass, the mass of containers to be transported and the mass of conveyor tables. As a conservative approach, the tare mass of a freight car was assumed to be the same as a passenger car. Any additional electric or mechanical systems needed were not included in this study.

According to the chapter 2.3.3, the maximum acceleration of a passenger car in Lisbon Metro is 1 m/s^2 considering a maximum velocity of 72 km/h.

For the same traction force, the new maximum acceleration can be computed by equation (20):

$$a'_{metro} = a_{metro} \times \frac{m_{train}}{m'_{train}} \tag{20}$$

where a_{metro} is the maximum acceleration value, m_{train} is the mass of a current train (6 passenger cars) and m'_{train} is the mass of a new train with an additional freight car.

Table 8 presents the study on impact of an additional freight car on maximum acceleration of a train in Lisbon metro.

Impact on maximum acceleration of a Passenger + Freight Train	
Tare, $T_{passenger}$ (kg)	30400
Cargo, $C_{freight}$ (kg)	19000
Mass of a conveyor table, m_{table} (kg)	61
Total mass of conveyor tables, $m_{total\ tables}$ (kg)	3233
Mass of a freight metro car, $m_{freight}$ (kg)	52633
Mass of a passenger metro car, $m_{passenger}$ (kg)	41700
Mass of current train, m_{train} (kg) (6 passenger cars)	250200
Mass of new train, m'_{train} (kg) (6 passenger cars + 1 freight car)	302833

New maximum acceleration, a'_{metro} (m/s^2)	**0.83**

Table 8: Impact of a freight car on max. acceleration of a metro train.

The impact in the maximum acceleration is not significant thus the same motorization can be used in the freight car. The maximum velocity currently allowed in Lisbon Metro is 60 km/h [24] therefore the current maximum acceleration is lower than 1 m/s^2. Electromagnets can be installed both at the bottom of each container and at each table to guarantee the containers do not move once the freight car accelerates.

5.3 Underground Network Design

The first variable to take into consideration when designing the tunnels is its diameter. The container dimensions will influence the inner diameter of a pipeline since each container has to be transported through these channels.

Considering that these tunnels have to be constructed along Lisbon city, a trenchless method is preferred due to their suitability to urban areas. A trenchless method can provide lower social costs as surface disruption and environmental impact can be minimized. Moreover, a non-worker entry was assumed for the installation since it will considerably decrease the complexity of the construction process.

The literature suggests that for tunnels of similar characteristics, an increase of one unit in the tunnel diameter translates into twice the construction costs [25]. Therefore, a dedicated tunnel per container flow (entry/exit flow) with a smaller diameter was preferred over the construction of a joint tunnel with a diameter to include both flows. This intends to also minimize ground settlements which can impact the existent infrastructure. The inner diameter of a pipeline can be obtained by equation (21):

$$D_{pipeline} = \sqrt{2} \times H_{o_{container}} \tag{21}$$

where $H_{o_{container}}$ is the outer height of a container. Based on a container outer height of 1000 meters defined previously, an inner diameter of 1500 mm is enough for each pipeline. Figure 15 is a design sketch for the pipeline.

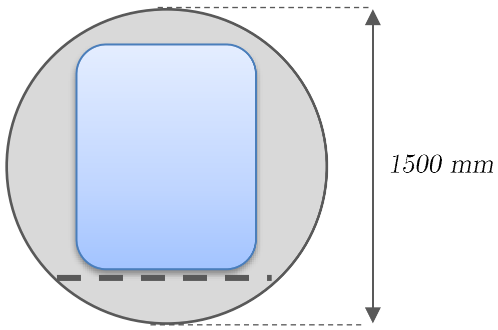

Figure 15: Pipeline design sketch.

In terms of network to transport the goods, 3 different flows must be considered:

1) Vertical movement from surface level to underground level
2) Horizontal movement from surface depot location to underground depot
3) Multidirectional movement and loading in underground depot

As explained previously in chapter 2.3.3., the average axis-depth of the tunnel network in Lisbon metro was considered to be 26 meters. For the tunnels on the vertical movement (ascending/descending), it was assumed an average depth equal to the average depth to the axis of metro tunnels.

It can also be considered an additional flow which would allow the containers to change direction in a metro line. In this case, the average depth of each tunnel would be equal to 5 meters (radius of a metro tunnel, 3 meters, plus an additional safety factor of 2 meters to avoid ground settlements near the metro structure).

Based on Lisbon geology and hydrology described on Annex 3, 2 construction methods were selected: thrust auger boring (TAB) and microtunneling. Both construction methods are suitable for terrains composed mostly of clays and limestones. Since it is a phased execution (drilling/crimping), both techniques avoid large settlements caused by the decompression of the ground in front of excavation. For metro stations above the groundwater level, thrust auger boring was chosen since it is a less complex construction method adaptable in case of unpredictable changes in terrain composition. For metro stations below the groundwater level, microtunneling was selected since it is an efficient technique which does not require any previous process to lower the water level. The axial forces applied to the pipelines during the installation are much higher than the compressive forces applied from the ground settlement. Thus, the axial forces as well as the pipeline material will influence the minimum thickness required.

A market study was done with the support of EuroAmbiente of the most suitable material and thickness for this type of application and construction method.

Based on the material and thickness advised by EuroAmbiente the maximum allowable compressive stress and the maximum jacking thrust force were analyzed.

For a jacking force applied with eccentricity (linear stress distribution) across the entire joint, the maximum allowable compressive stress across the pipe joint is given by equation (22) [26]:

$$\sigma_c = \frac{0{,}85.\,\varphi.\,\sigma'_c}{LF} \tag{22}$$

where $\varphi = 0.9$ is a strength reduction factor for compressive axial thrust, σ'_c is the design material strength and LF = 1.2 is a load factor for jacking thrust-eccentric load.

The maximum jacking thrust force for a linear stress distribution can be computed by equation (23) [26]:

$$P_c = 0{,}5.\,\sigma_c.\,A_p \tag{23}$$

where A_p is the contact area between the joint packing and pipeline surface with no joint separation and σ_c is the maximum allowable compressive stress across the pipe joint.

Table 9 presents a summary of the selected construction methods for the tunnel network and pipelines specifications.

Pipeline inner diameter (D)	1500 mm
Thrust Auger Boring Method (TAB)	
Material pipeline	Steel
Thickness pipeline ($t_{steel\ pipeline}$)	12 mm
Boring diameter (D_{TAB})	1524 mm
Design steel compressive strength ($\sigma'_{c_{steel}}$)	172 MPa

Contact area ($A_{p\ steel}$)	0,06 m^2
Max allowable compressive stress ($\sigma_{c_{steel}}$)	110 MPa
Max jacking thrust force ($P_{c_{steel}}$)	3125 kN
Microtunneling Method	
Material pipeline	Concrete
Thickness pipeline ($t_{concrete\ pipeline}$)	152 mm
Boring diameter ($D_{Microtunneling}$)	1804 mm
Design steel compressive strength ($\sigma'_{c_{concrete}}$)	28 MPa
Contact area ($A_{p\ concrete}$)	0,79 m^2
Max allowable compressive stress ($\sigma_{c_{concrete}}$)	18 MPa
Max jacking thrust force ($P_{c_{concrete}}$)	7041 kN

Table 9: Tunnel construction methods and pipeline specifications.

Jacking forces usually range between between 1200 and 7000 kN [27]. Therefore the specifications considered for both pipelines are reasonable and common machinery can be used.

Both construction techniques use the drilling/crimping method which do not require to bitumen the annular surface of the tunnel. Thus, the tunnel diameter is obtained considering the thickness of the pipelines.

The average length of each tunnel must be defined as well since it can be limited by the construction methods and influence the design of the transportation system. Depending on the business model the length will vary. If the surface depot is inside or nearby the metro station, then the length will be less than in case the connection is directly to the delivery point. For this study an average length of 50 meters was considered which is a reasonable distance for selecting a depot area for goods delivery. This average length can be changed in future investigations and depending on the customer adherence it can be higher in special cases such as shopping centers with higher flow of goods or existent warehouses.

Considering the extensive loading movement from the surface depot until the entry in the freight car (26 meters vertical movement + 50 meters horizontal movement) and a short dwell time of 30 seconds, an underground depot connecting the loading tunnels to the metro tunnel has to be built in each direction of a metro line to allow the storage of goods until the arrival of a metro car. This underground depot has to be built with 2 decks to allow for loading/unloading through 4 doors. Therefore, the height of the underground depot was set as 3 meters to allow for the storage of 2 floors of containers. Knowing that this depot must store a maximum of 53 containers, the length of a quadrangular underground depot is given by equation (24):

$$l_{depot} = \sqrt{\frac{No_{containers} \times A_{container}}{2}} \tag{24}$$

where $No_{containers}$ is the number of containers to be loaded and $A_{container}$ is the area of a container.

In the additional flow which allows the containers to change direction in a metro line, the average length of each tunnel is given by the equation (25):

$$l_{tunnel\_dir} \cong D_{metro} + 2\ (l_{depot} - 2 \times l_{cont}) \tag{25}$$

where D_{metro} is the diameter of the metro tunnel, l_{depot} is the length of the underground depot and $L_{container}$ is the length of a container.

Table 10 presents a summary of the tunnel network specifications:

Tunnel Network for movement 1/2 (surface level-underground depot)	
Average axis-depth (H)	26 m
Average length (L)	50 m
Tunnel Network for changing direction in a metro line	
Average relative* depth (H_{rel})	5 m
Average length (L)	20 m
Underground Depot Network for movement 3 (store and load goods)	
Overall dimensions (L×W×H)	6 x 6 x 3 m

No. floors	2

* Relative depth to the axis of the metro tunnel.

Table 10: Tunnel network specifications.

Figure 16 represents a sketch of the underground network including the underground depots for containers storage. It is also shown the direction flow inside the network.

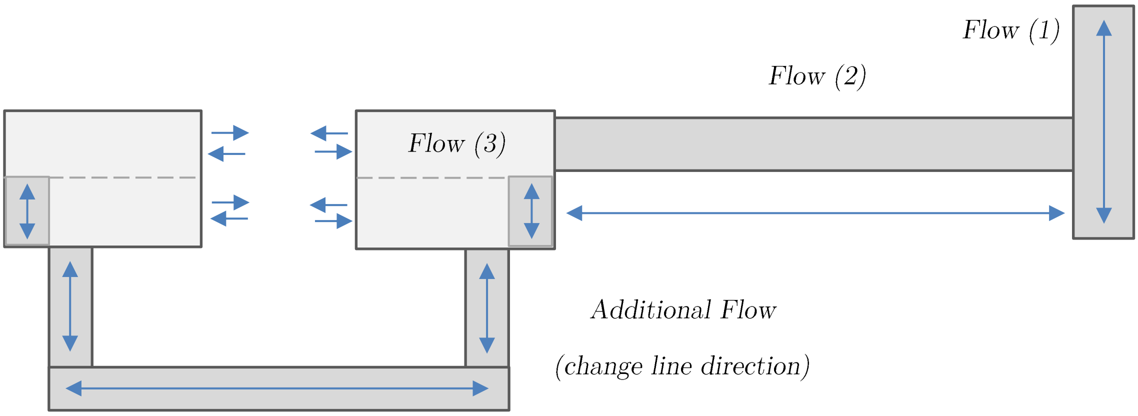

Figure 16: Sketch of network configuration including direction flows.

The constant velocity at which the containers have to be loaded to guarantee the loading occurs before the arrival of a freight car is given by the equation (26):

$$v_{conveyor} = \frac{(No_{containers} \times L_{container}) + H_{tunnel} + L_{tunnel}}{t_{load}} \tag{26}$$

where $No_{containers}$ is the number of containers to be loaded, $L_{container}$ is the length of a container, H_{tunnel} is the axis-depth of a tunnel, L_{tunnel} is the length of a tunnel and t_{load} is the loading/unloading time which is equal to the average frequency of a metro car.

The vertical movement (ascendant/descendent) can be achieved with the use of continuous vertical conveyors (CVC). The continuous vertical conveyors would be used to lower containers from surface to underground level through automatic loading platforms consistently at a high capacity.

The number of containers that each CVC is able to transport at once is given by equation (27):

$$No._{container/CVC} = \frac{H_{tunnel}}{H_{container}} \tag{27}$$

where H_{tunnel} is the axis-depth of a tunnel and $H_{container}$ is the height of a container.

The maximum force to move the CVC is given by equation (28):

$$F_{max} = F_r + \ F_g - F_{cg} \tag{28}$$

where F_r is the resultant force to accelerate the CVC, F_g is the force exerted by the total weight of containers and F_{cg} is the force applied by the counterweight.

The force to accelerate the CVC is given by equation (29):

$$F_r = \ No._{container/CVC} \, (m_{container} \times \frac{dv_y}{dt}) \tag{29}$$

where $No._{container/CVC}$ is the number of containers that each CVC is able to transport at once, $m_{container}$ is the mass of each container and $\frac{dv_y}{dt}$ is the acceleration of each platform. A value of 0.5 m/s^2 was considered for the CVC acceleration.

The force exerted by the total weight of containers in a CVC is given by equation (30):

$$F_g = \ No._{container/CVC} \ \ m_{container} \times g \tag{30}$$

where $No._{container/CVC}$ is the number of containers that each CVC is able to transport at once, $m_{container}$ is the mass of each container and g is the acceleration of gravity .

The force applied by the counterweight, assuming a counterweight equal to the weight of 4 containers is given by equation (31)

$$F_{cg} = 4 \times m_{container} \times g \tag{31}$$

where $No._{container/CVC}$ is the number of containers that each CVC is able to transport at once, $m_{container}$ is the mass of each container and g is the acceleration of gravity .

The maximum power to move the CVC is given by equation (32):

$$P_{max} = \frac{F_{max} \times v_{conveyor}}{\eta_{eng} \times \ \eta_{conveyor}} \tag{32}$$

where F_{max} is the maximum force to move the CVC, $v_{conveyor}$ is the conveyor velocity and η_{engine} is the efficiency of the electric engine used in these conveyors. An efficiency of 70% was taken as a reasonable value for this application [23]. For the conveyor an efficiency of 80% was considered.

Table 11 presents the values used to obtain the power to operate a CVC:

Continuous Vertical Conveyors (CVC)	
t_{load} (s)	240
v_{cons} (m/s)	0.602
$No._{container/CVC}$	26
$\frac{dv_y}{dt}$ (m/s^2)	0.5
F_r (N)	6760
F_g (N)	132496
F_{cg} (N)	20384
F_{max} (N)	118872
P_{max} (W)	127787

Table 11: Maximum power to operate a CVC

In case of the small CVC to be installed in the underground depot to move half of the 53 containers from the ground level to the upper level located one meter above, the conveyor velocity required would be 0.8 m/s and the maximum power 7651 W.

The horizontal movement to move the containers from the location of the surface depot until the underground depot can be achieved with horizontal roller conveyors (HRC). These driven conveyors are typically composed by steel rollers which are generally looped together through chains. These conveyors are flexible enough to handle heavy loads.

The maximum force to move the HRC is given by equation (33):

$$F_{max} = F_c + F_v \tag{33}$$

where F_c is the force to move the container at a constant speed and F_v is the force needed to accelerate the container which can be considered neglectable.

The maximum force to move the HRC must ensure the following condition:

$$F_{max} \cong F_c \ \leq \ No._{container/HRC}\,(N.\,\mu_{static}) \\ = \ No._{container/HRC}\,(m_{container} \times g \times \mu_{static}) \tag{34}$$

where $No._{container/HRC}$ is the number of containers that each HRC is able to move at once, $m_{container}$ is the mass of a container, g is the gravity acceleration and μ_{static} is the friction coefficient of a container supported on commercial rollers. The static friction coefficient between a plastic container and the rollers was considered as 0.05 [22].

The number of containers that each HRC is able to move at once is given by equation (35):

$$No._{container/HRC} = \frac{L_{tunnel}}{L_{container}} \tag{35}$$

where L_{tunnel} is the length of a transportation tunnel and $L_{container}$ is the length of a container.

The maximum power to move the HRC is given by equation (36):

$$P_{max} = \frac{F_{max} \times v_{conveyor}}{\eta_{eng} \times \eta_{conveyor}} \tag{36}$$

where F_{max} is the maximum force to move the HRC, $v_{conveyor}$ is the conveyor velocity and η_{engine} is the efficiency of the electric engine used in these conveyors. An efficiency of 70% was taken as a reasonable value for this application [23]. For the conveyor an efficiency of 80% was considered.

Table 12 presents the values used to obtain the power to operate a HRC:

Horizontal Roller Conveyors (HRC)	
t_{load} (s)	240
$v_{conveyor}$ (m/s)	0.602
$No._{container/HRC}$	38
F_{max} (N)	9682
P_{max} (W)	10408

Table 12: Maximum power to operate an HRC

Finally, the multidirectional movement is not only used inside the metro cars as explained in chapter 4.2 but also inside the underground depot. The design of a multidirectional conveyor table is the same as well as the number of tables required to move all containers. It is important to mention that the conveyor design for the network branch to change the direction on a metro line was not included in this study since the admissible dwell time will depend on the customer's requirements. This portion of the transportation network will not be fully compatible with the passenger service. If a container is required to change metro line direction, it will not be ready to load in the following freight car. Nevertheless, it provides additional flexibility to the customer and that is why it should be considered.

6 Investment Cost

6.1 Freight Cars Cost

The cost of a freight car without any storage system was assumed approximately as 2.62 M€. This value was estimated based on the cost of a passenger car for Lisbon metro in 2018 [28]. The additional cost from the storage system (multidirectional conveyors) was obtained from a quotation of 2 companies (*Adept* and *Rotacaster*) based on design requirements from chapter 4.2. The cost of the conveyor system including the entire network of 53 multidirectional conveyor tables per freight car is around 146 m€. Thus, the total cost of each freight car is approximately 2.77 M€.

The number of freight cars needed in operation for each metro line circuit was computed based on the equation (37):

$$No_{freight\ car} = 2.\frac{t_{sl}}{(f_s)_{av}} \tag{37}$$

Where t_{sl} is the travelling time from the first to the last station in a metro line and $(f_s)_{av}$ is the average metro frequency of a metro line. Since it is being considered the same number of metro cars operating in both directions of a metro line a factor 2 was included in the equation.

Table 13 presents the values used to obtain the total cost of freight cars.

Cost of Freight Cars	Blue Line	Yellow Line	Green Line	Red Line
t_{sl} (min)	22	16	19	20
$(f_s)_{av}$ (min/train; each direction)	6.33	5.83	6.17	7.67
$No_{\text{freight } car}$ per circuit (both directions)	8	6	6	6
Total freight cars per circuit	26			
Unit cost freight car (M€)	2.77			
Total cost (M€)	72			

Table 13: Cost Estimative for Freight Cars.

6.2 Freight Containers Cost

Quotations were obtained for the container cost based on design requirements from chapter 4.1. An average cost of 276€ for each container was assumed although the unit cost might be lower if a purchase order is made for a large number of containers.

It is necessary to guarantee the system is runs smoothly when estimating the number of containers. Therefore, the minimum number of containers should guarantee that:

1. There are empty containers available to load in freight cars during 1st circuit of the day;
2. There is placement of the number of containers unloaded in each metro station in transport to return to a main metro station of each line.
3. There is unloading of all containers in main metro station of each line to be available for a next transport;

It was assumed the worst-case scenario in which the 53 containers would have to return to a main metro station in each metro line selected by the customers according to their preferred point of discharging. The other stations would only have to load the containers which were unloaded in the previous discharge and could be considered as minor stations. The minimum number of containers required is given by equation (38):

$$No_{containers} = No_{containers/trip} \cdot \left(\underbrace{No_{freight\ cars}}_{1st\ circulation} + \underbrace{No_{freight\ cars}}_{place\ in\ transport\ on\ minor\ stations} + \underbrace{No_{freight\ cars}}_{unload\ on\ main\ stations} \right) \tag{38}$$

where, $No_{containers/trip}$ is the number of containers to be transported per metro trip, $\underbrace{No_{freight\ cars}}_{1st\ circulation}$ is the number of freight cars operating in each metro line during the first circuit of the day (both directions), $\underbrace{No_{freight\ cars}}_{place\ in\ transport\ on\ minor\ stations}$ is the number of freight cars that will have to be loaded while containers from previous trip are being placed in transport in minor stations and $\underbrace{No_{freight\ cars}}_{unload\ on\ main\ stations}$ is the number of freight cars that have to be loaded while containers from previous trip are being unloaded in main stations.

The number of freight cars operating in each metro line during the first circuit of the day was calculated in chapter 5.1.

The number of freight cars that will have to be loaded while containers from previous trip are being placed in transport in minor stations and that will have to be loaded while the containers from previous trip are being unloaded in main stations are given respectively by equation (39):

$$\underbrace{No_{subway\ cars}}_{place\ in\ transport/unload\ on\ minor/main\ stations} = \frac{t_{minor/main\ stations}}{(f_s)_{av}} \tag{39}$$

where $t_{minor/main\ stations}$ is the average time for placing in transport/unloading all containers from previous trips in minor/main stations respectively and $(f_s)_{av}$ is the average metro frequency.

The average time for placing all containers from previous trip in transport in minor stations per metro line is given by equation (40):

$$t_{minor\ stations} = \frac{\sum_{i=0}^{n} No_{unload/trip} \times t_{place/container}}{No_{metro\ stations}} \tag{40}$$

Where n is the index of each metro station, $No_{unload/trip}$ is the number of containers to unload per trip per metro station, $t_{reload/container}$ is the time to place a single container from previous trip in transport and $No_{metro\ stations}$ is the number of metro stations per metro line.

The time to place one container from previous trip in transport in minor stations is given by equation (41):

$$t_{place/container} = t_{unload\ depot} + \frac{d_{place\ network}}{v_{conveyor}} \tag{41}$$

where $t_{unload\ depot}$ is the average time required to unload a container in the surface depot [29], $d_{place\ network}$ is the distance a container takes to be placed again in transport and $v_{conveyor}$ is the velocity of the conveyors in the network.

The time for unloading the containers in the main stations is given by equation (42):

$$t_{main\ stations} = \frac{No_{containers/trip}}{No_{workers}} \times t_{unload/container} \tag{42}$$

where $No_{containers/trip}$ is the number of containers to unload per trip per metro station, $No_{workers}$ is the number of workers needed to unload all containers at the surface depot and $t_{unload/container}$ is the time to unload a container from previous trip. The number of workers was ca by iteration until obtaining a reasonable value for a time to unload at main stations.

The time to unload one container in main stations is given by equation (43):

$$t_{unload/container} = t_{unload\ depot} + \frac{d_{unload\ network}}{v_{conveyor}} \tag{43}$$

where, $d_{unload\ network}$ is the distance that a container takes to be unloaded in the network. Table 14 presents a summary of the values used to obtain the number and total cost of containers required:

Cost of Containers	Blue Line	Yellow Line	Green Line	Red Line
$No\ _{containers/trip}$	45	38	53	25
$No_{\text{freight } cars}$	8	6	6	6
$t_{unload\ depot}$ (s)	240			
$d_{place\ network}$ (m)	164			
$d_{unload\ network}$ (m)	82			
$v_{conveyor}$ (m/s)	0.602			
$t_{place/container}$ (min)	8.52			
$t_{unload/container}$ (min)	6.27			
$t_{minor\ stations}$ (min)	28.68	32.46	34.92	16.14
$t_{main\ stations}$ (min)	56.43	47.65	66.47	31.35
$(f_{sl})_{av}$ (min)	6.33	5.83	6.17	7.67
$\underbrace{No_{freight\ cars}}_{1st\ circulation}$	8	6	6	6
$\underbrace{No_{subway\ cars}}_{place\ in\ transport\ on\ minor\ stations}$	4	5	5	2
$\underbrace{No_{subway\ cars}}_{unload\ on\ main\ stations}$	9	9	10	5
$No_{containers}$	956	748	1128	315
Unit cost container (€)	276			
Total cost (M€)	0.87			

Table 14: Cost Estimative for Freight Containers.

6.3 Underground Network Cost

With the support of *Euroambiente* (company specialized in trenchless construction in Portugal) it was possible to obtain an estimate for the cost per meter of tunnels and pipelines as well as mobilization associated costs for Thrust Auger Boring (TAB) and Microtunneling.

In order to calculate the network costs, each metro station has to be linked with a construction method based on Annex 3. Annex 2 presents a table with details on the construction method associated to each metro station.

Taking into consideration the design specifications for the tunnel network mentioned in chapter 4.3 it was possible to calculate an estimative for the total cost.

The cost of an underground depot was assumed to be similar to the cost of expanding a metro station since similar construction methods can be used. Therefore, the cost of expanding Arroios metro station was taken as a reference [30].

Table 15 presents a summary of the values used to obtain the total cost of the tunnel network:

Cost of Tunnel Network + Underground Depots	
Thrust Auger Boring Method (TAB)	
Mobilization (€)	3000
Drilling DN 1500mm (€/m)	800
Pipeline steel DN 1500mm (€/m)	950
No. metro stations (2 tunnels)	28
No. metro stations w/ joint lines (4 tunnels)	4
TAB network drilling length (m)	6336
TAB network pipeline length (m)	2592
Drilling cost (€)	5152800
Pipeline cost (€)	8481600
Microtunneling	

Mobilization (€)	35000
Drilling DN 1500mm (€/m)	2000
Pipeline concrete DN 1500mm (€/m)	1200
No. metro stations (2 tunnels)	10
No. metro stations w/ joint lines (4 tunnels)	2
Microtunneling drilling length (m)	2464
Microtunneling pipeline length (m)	1008
Drilling cost (€)	5278000
Pipeline cost (€)	4166400
Total tunnel network construction cost (M€)	23.08
Underground Depots	
Cost of expanding a metro station (€/m)	32444
No. metro stations (2 depots)	38
No. metro stations w/ joint lines (4 depots)	6
Underground depots construction cost (M€)	16,22

Table 15: Cost Estimative for Tunnels + Underground Depots.

In what regards the conveyors network, quotations were obtained from different companies based on design requirements stated in chapter 4.3. The cost estimative considered for Continuous Vertical Conveyors was provided by *NERAK Systems* while the cost estimative for Horizontal Roller Conveyors was provided by *Cisco-Eagle*. Both values were assumed as reasonable when compared to quotations given by similar companies.

In terms of the quotation for Multidirectional Conveyors for the underground depots, it was explained previously in chapter 5.1 and remains applicable for this case.

Table 16 presents a summary of the values used to obtain the total cost for the conveyor systems in the tunnel network:

Cost of Conveyor Network	
CVC to load/unload depot-metro car (€)	350 000
CVC to change levels in underground depot (€)	60 000
HRC to load/unload depot-metro car (€)	61 100
HRC to change direction (€)	46 436
Multidirectional conveyors in underground depot (€)	146 000
No. metro stations (2 tunnels)	38
No. metro stations (4 tunnels)	6
No. underground depots per metro station	2
Cost CVCs to load/unload depot-metro car (M€)	35
Cost CVCs to change levels in underground depot (M€)	12
Cost HRCs to load/unload depot-metro car (M€)	6.11
Cost HRCs to change direction (€)	4.64
Cost multidirectional conveyors in underground depot (M€)	14.62
Total conveyors cost in tunnel network (M€)	72.37

Table 16: Cost Estimative for the Conveyor Network.

7 Operational Costs

7.1 Energy Consumption

The energy to move a freight car is given by equation (44):

$$E_{mov} = \frac{\underbrace{F_{R_{acel}} \times d_{acel}}_{E_{acel}} + \underbrace{F_{R_{cons}} \times d_{cons}}_{E_{cons}}}{\eta_{trans}} \tag{44}$$

where $F_{R_{acel}}$, v_{acel} are the resultant force and velocity during the acceleration period; $F_{R_{cons}}$, v_{cons} are the resultant force and velocity during the period at constant speed and η_{trans} is the power supply transmission efficiency. According to the literature [31], it was assumed an efficiency for a 750V DC third rail system of approximately 92%.

Equation 45 represents the balance of forces on the freight car:

$$F_R = F_{rr} + F_g + F_D \tag{45}$$

where F_{rr} is the rolling resistant force, F_g is the grade resistance force and F_D is the aerodynamic drag force.

The rolling resistance force F_{rr} is a resisting force to the metro motion on the tracks and it is defined by equation (46):

$$F_{rr} = 9{,}8.\, m_{sub}.\, c_{rr} \tag{46}$$

where m_{sub} is the mass of a freight car and c_{rr} is the rolling resistance coefficient. This coefficient is dependent on the type of material combination. For a passenger rail car with contact between a steel wheel on steel rail a rolling resistance coefficient of 0.001 can be assumed [32].

The grade resistance force F_g is a resisting force to the movement of the metro in the tracks if a slope is considered. This force is computed by equation 47:

$$F_g = 9{,}8.\, m_{freight}.\sin\alpha \tag{47}$$

where $m_{freight}$ is the mass of a freight car and α is the ruling gradient which according to the literature [33] can be assumed to be around 1% for a common metro structure.

The aerodynamic drag force F_D is calculated based on equation 48:

$$F_D = \frac{\rho_{air}.\, v^2.\, c_D.\, S}{2} \tag{48}$$

where ρ_{air} is the density of the air, v is the velocity during the acceleration and constant period respectively, c_D is the coefficient of drag and S is the reference area. The air density can be assumed to be 1.225 kg/m^3 (standard atmospheric pressure and temperature at sea level). The coefficient of drag for a freight car in Lisbon was obtained considering a flow around a cube with velocity parallel to its horizontal axis (c_D=1). A rectangular shape was considered for the reference area S.

The distance made by a freight car during acceleration period can be computed using equation 49:

$$d_{acel} = \frac{No_{ave\ stations}.\, v_{acel}^2}{a} \tag{49}$$

where $No_{ave\ stations}$ is the average number of stations of a metro line, v_{acel} is the average velocity in the acceleration period and a is the acceleration.

Most of the distance made by a freight car occurs at constant velocity and is obtained by equation 50:

$$d_{cons} = d_{ave} - 2.\, d_{acel} \quad (50)$$

Where d_{ave} is the average distance made by a metro car during one trip (including return) and d_{acel} is the distance made by a freight car during acceleration period.

Table 17 has all values used to compute the energy to move a freight car:

Energy for movement of a freight car	
Mass of a freight car, $m_{freight}$ (kg)	52633
c_{rr}	0,001
Rolling Resistance Force, F_{rr} (N)	1032
Metro grade	0,01
Grade Resistance Force, F_g (N)	5158
ρ_{air} (kg/m^3)	1,225
c_D	1
S (m^2)	9,8
v_{cons} (km/s)	60
v_{acel} (km/s)	30
Aerodynamic Force in constant period, $F_{D_{cons}}$ (N)	1672
Aerodynamic Force in acceleration period, $F_{D_{acel}}$ (N)	418
d_{ave} (m)	12000
$No_{stations}$	11
a (m/s^2)	0,8
d_{acel} (m)	955
d_{cons} (m)	10090
E_{acel} (MJ)	6.3

E_{cons} (MJ)	79.3
η_{trans}	0.92
E_{mov} per trip (MJ/freight car)	93

Table 17: Energy for movement of a freight car.

The total yearly energy for movement and operation of freight cars is given by equation 51:

$$E_{freight\ car} = \underbrace{E_{mov}.\sum_0^n(2.\, No_{trips/day}\,.\, No_{days/year})}_{Energy\ to\ move\ the\ freight\ cars} + \underbrace{No_{tables/car}.\, P_{table}.\sum_0^n(2.\, No_{hours/trip}.\, No_{trips/day}\,.\, No_{days/year})}_{Energy\ to\ operate\ the\ multidirectional\ conveyors} \quad (51)$$

where n represents the number of metro lines, E_{mov} is the energy required to move a freight car per trip, $No_{trips/day}$ is the number of trips per day, $No_{days/year}$ is the number of operational days per year, No_{tables} is the number of conveyor tables per freight car, P_{table} is the power to operate a conveyor table and $No_{hours/trip}$ is the number of operational hours per trip.

On the other hand, the energy to operate a certain conveyor type can be generally computed by equation 52:

$$E_{conveyor\ type} = No_{conveyor\ type}[P_{conveyor\ type}.\, t_{ope}] \quad (52)$$

where for a certain conveyor type, $No_{conveyor\ type}$ is the total number of conveyors, $P_{conveyor\ type}$ is the power required to operate it and t_{ope} is the operation time per year. All these values were mentioned in previous chapters.

Table 18 presents the total energy per year to operate this system:

Energy Consumption per year	
$E_{freight\ car}$ (kWh/year)	4649534
E_{CVC} (kWh/year)	19753436
E_{HRC} (kWh/year)	1436824
$E_{underground\ depot}$ (kWh/year)	3797341
$E_{distribution\ system}$ (kWh/year)	24987601

Table 18: Yearly Energy Consumption.

The illumination and other items related to the operation of a surface depot were not included in this analysis.

7.2 Energy and Maintenance Costs

The energy cost per quilowatt in Lisbon metro was considered to be approximately 0.0875 €/kWh [34]. Therefore, knowing the yearly energy consumption from the previous chapter, the yearly operational costs can be computed.

There are elements of the transportation system that require a regular maintenance activity such as the conveyors and freight cars in order to control the wear and guarantee a smooth operation. According to CEMA Guidelines, it is reasonable to assume that the yearly maintenance costs for these conveyors are approximately 2% of the capital cost. Regarding the maintenance of the freight cars, a 2014 report from Lisbon metro [35] shown a maintenance cost of 0.36 €/km/metro car.

Table 19 presents the operational costs related with energy and maintenance:

Operational Costs (Energy and Maintenance)	
$E_{freight\ car}$ (€/year)	406834
$E_{distribution\ system}$ (€/year)	2186415
$M_{freight\ cars}$ (€/year)	447644
$M_{distribution\ system}$ (€/year)	1514844

Table 19: Yearly Operational Costs (Energy and Maintenance).

The maintenance costs for other elements such as tunnels and underground depots were considered neglectable since the wear is considerably lower.

7.3 Labor Costs

The number of employees necessary at a surface depot was considered to be 5 for the main stations and 3 for the minor stations. These employees will not only support the loading and unloading of containers but also control the goods delivery.

The yearly labor costs can be estimated based on equation 53:

$$C_{Labor} = (No_{W_{main\ stations}}.\,No_{main\ stations} + No_{W_{minor\ stations}}.\,No_{minor\ stations}).\,[No_{months}.\,S_{month}\ 1 + SS\ \ + (LS_{day}.\,No_{work\ days/year})] \quad (53)$$

where $No_{W_{main\ stations}}$ and $No_{W_{minor\ stations}}$ is the number of workers in main and minor stations respectively; $No_{main\ stations}$ and $No_{minor\ stations}$ is the number of main and minor stations respectively; No_{months} is the number of paid months, S_{month} is the monthly salary, SS is the social security share, LS_{day} is the daily lunch subsidy and $No_{work\ days/year}$ is the number of working days per year.

Table 20 presents the estimated operational costs related with labor.

Operational Costs (Labor)	
$No_{W_{major\ stations}}$	5
$No_{W_{minor\ stations}}$	3
$No_{major\ stations}$	4
$No_{minor\ stations}$	40
No_{months}	14
S_{month} (€/month)	750
SS (%)	23.75
LS_{day} (€/day)	4.77
$No_{work\ days/year}$	251

C_{Labor} (€/year)	1986743

Table 20: Yearly Operational Costs (Labor).

8 Viability Analysis

The capital cost was estimated in chapter 5 and yearly operational costs in chapter 6. In order to analyze the economical viability of this project, it is necessary to calculate the yearly revenues.

The 2011 transportation cost using light trucks was 6,114 €/t.km [36] (excluding profit margins added to the cost by the transportation companies). This value was considered as base price for future customers using the metro.

Therefore, the revenue of the metro-based system per year is calculated using equation 54:

$$Revenue/year = c_{transport}.\, d_{ave}.\, m_{year} \tag{54}$$

where $c_{transport}$ is the base price, d_{ave} is the average distance made by a freight car per trip (including return) and m_{year} is the total freight mass transported per year.

In order to cover the risk in the interest rate fluctuation, it is advisable to take a fixed interest rate for the entire duration of the project. According to the literature [37], the annual average interest rate was 1.92% on February 2019. Based on a 7-year estimative for the project duration, an euro swap rate of 0.39% [38] was added to a spread of 2.0828% (after the removal of an Euribor indexation of -0.108% [39]) and a final fixed interest rate of 2.418% was assumed.

Table 21 presents a summary of the values used in the cost analysis.

Cost Analysis	
Interest Rate	0.02418
Investment Cost (M€)	185
Freight cars	72

Containers	0.87
Tunnel network	23.08
Underground depots	16.22
Conveyors	72.37
Negative Cash Flows (M€/year)	6.54
Energy	2.59
Maintenance	1.96
Labor	1.99
Positive Cash Flows (M€/year)	48.12

Table 21: Overall Cost Analysis.

Figure 17 shows the financial return for this project along the years.

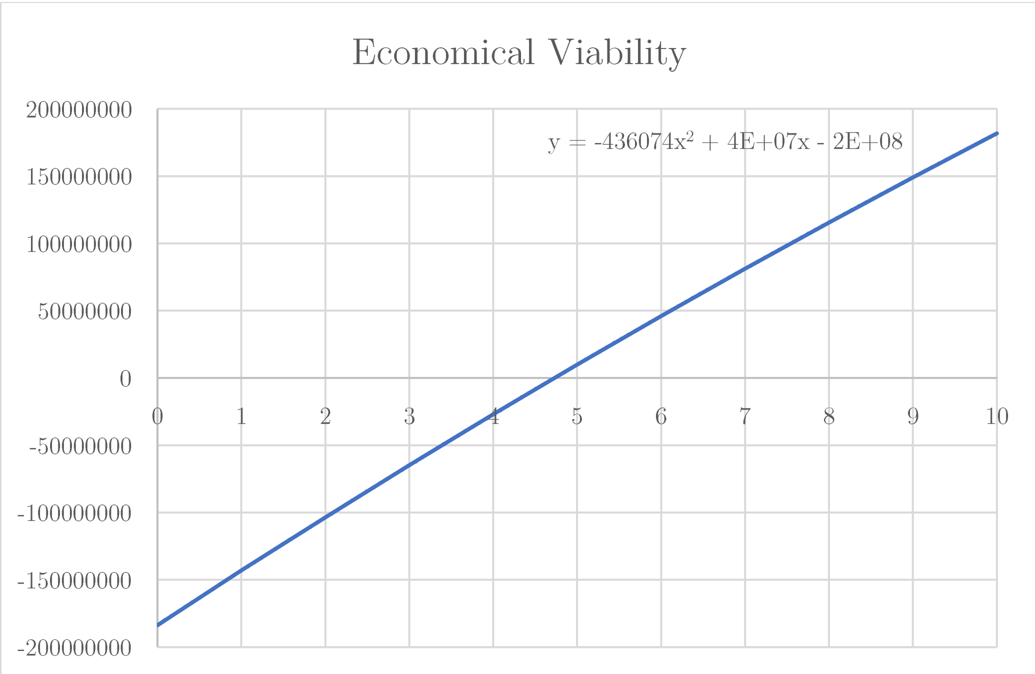

Figure 17: Project Financial Return.

By solving the equation above a payback of approximately 5 years is obtained.

9 Comparison to Truck Freight Transportation

This chapter compares the current truck freight transportation with the proposal of a metro freight transportation system at both energy and emissions levels.

A comparison was done considering just the transportation method (truck/metro) from one point to another, excluding the energy required for loading/unloading, sorting the freight and the portion loss due to traffic.

The energy consumption of a metro-based system was described previously in chapter 6.1. In order to compare both systems in terms of transportation process from point A to B, the energy consumed by the metro-based system includes not only the energy to move the freight cars but also the energy required to transport the goods from the surface to underground level.

In case of a truck-based system the total energy consumed is the energy required by trucks to transport a mass transported by a freight car. The total energy consumed by a truck-based system is given by equation (55):

$$E_{truck\ equivalent} = No_{trucks\ (goods/freight\ car)} \cdot E_{truck} \tag{55}$$

where $No_{trucks\ (goods/subway\ car)}$ is the number of trucks required to transport the equivalent mass transported by a freight car and E_{truck} is the energy consumed by a truck.

As mentioned in the chapter 2.3.1., the transportation in Lisbon has been restricted to the use of light duty trucks.

Table 22 presents an example of a light duty truck commonly used:

Mercedes Benz Sprinter Specifications	
Tare weight (kg)	2010
Total weight (kg)	3550
Max. freight weight (kg)	1540
Consumption (l/100km)	10.5

Table 22: Example of a light duty truck (Mercedes Benz Sprinter).

Table 23 presents a comparison in terms of energy consumption between a truck-based system and a metro-based system.

Energy Consumption per vehicle (MJ/vehicle)	
Metro Freight Transportation System	
E_{mov} (MJ/freight car)	93
E_{extra} (MJ/freight car)	332
$E_{metro\ equivalent}$ (MJ/freight car)	425
Truck Freight Transportation System	
E_{truck} (MJ/truck)	45
$No_{trucks\ (goods/subway\ car)}$	17
$E_{truck\ equivalent}$ (MJ/truck)	765

Table 23: Comparison of energy consumption truck vs metro system.

From the results it is possible to achieve around 44% decrease in energy consumption by using the metro to transport the goods. It is important to mention that this estimative does not consider the traffic effects in the consumption so in reality savings could be higher.

For a truck freight transportation system, the mass of emissions during the well-to-tank (WTT) and tank-to-wheel (TTW) phases are considered.

The well-to-tank (WTT) emissions using a truck-based system is obtained using equation (56):

$$m_{WTT\ truck\ equivalent} = E_{truck\ equivalent}.WTT_{CO2e} \tag{56}$$

Where $E_{truck\ equivalent}$ is total energy consumed by a truck-based system and WTT_{CO2e} is the CO2 equivalent well-to-tank emission index considering a pathway from crude oil to diesel. The literature [40] suggests a well-to-tank emission value of 0.01534 kgCO2e/MJ.

The tank-to-wheel (TTW) emissions using a truck-based system is calculated using equation (57):

$$m_{TTW\ truck\ equivalent} = No_{ave\ km/truck} \cdot No_{trucks\ (goods/subway\ car)} \cdot TTW_{CO2e} \quad (57)$$

where $No_{ave\ km/truck}$ is the average number of kilometers that a truck travel to deliver the goods and TTW_{CO2e} is the CO_2 equivalent tank-to-wheel emission indexes for a diesel engine. A commonly used light truck such as Mercedes Benz Sprinter has an emission index of 0.222 kgCO2e/km [41].

On the other side, if a metro freight transportation system is considered, there are only emissions during the well-to-tank phase which can be obtained by equation (58):

$$m_{\ metro\ equivalent} = E_{metro\ equivalent} \cdot I_{CO2eq} \quad (58)$$

where I_{CO2eq} is the equivalent CO2 emission factor for electricity and $E_{metro\ equivalent}$ is total energy consumed by a metro-based system. According to the literature [42], the emission index for Portuguese electricity consumption in 2013 was 0.368 kgCO2e/kWh. Table 24 presents a comparison in terms of mass of emissions between a truck-based system and a metro-based system.

Emissions per vehicle (kgCO2e/vehicle)	
Metro Freight Transportation System	
I_{CO2eq} (kgCO2e/kWh)	0.368
$m_{\ metro\ equivalent}$ (kgCO2e/vehicle)	43.5
Truck Freight Transportation System	
WTT_{CO2e} (kgCO2e/MJ)	0.01534
TTW_{CO2e} (kgCO2e/km)	0.222
$m_{WTT\ truck\ equivalent}$ (kgCO2e/vehicle)	11.7
$m_{TTW\ truck\ equivalent}$ (kgCO2e/vehicle)	45.3
$m_{truck\ equivalent}$ (kgCO2e/vehicle)	57

Table 24: Comparison of mass of emissions truck vs metro system.

It is clear from the results the benefit in terms of emissions of using a metro-based freight transportation system. Around 24% reduction in emissions is achieved which can contribute positively to the EU 2050 low-carbon economy objective.

10 Conclusions and further considerations

The proposed solution of using the metro network for freight transportation in Lisbon has shown clear positive results. Reductions of 44% in energy consumption and 24% in emissions are achievable when shifting from road transportation to an underground system enhancing the environmental benefit. The project has a payback of around 5 years with an investment cost of 185 M€ and yearly revenues of around 41 M€/year. The freight analysis made to Lisbon establishments demand within the range of each metro station has shown that freight will be more than 60% food products. This high percentage would be higher if perishable products were included and it allows to characterize the potential customers and market segment for this project: primary products that require on-time, fast and flexible delivery. A critical design factor of the proposed solution is the cargo distribution system. From a financial point of view, the investment in freight cars and conveyors represent 80% of the capital cost. In terms of energy, 84% of total consumption corresponds to the energy required by the distribution conveyor network. The biggest contribution corresponds to the operation of vertical conveyors (67%). This was expected and it is related with the estimated average depth of each metro station which leads to a higher power required in the descending movement considering a maximum load during operation hours. From the maintenance viewpoint, there is a similar trend with the conveyor network representing 80% of total maintenance cost.

The main goal of this study was to obtain an overview on the feasibility and environmental benefits of an underground freight transportation system. Several steps where included to increase the reliability of this project such as (i) initial surveys to collect further details on market characteristics; (ii) discussions with several companies on the construction techniques most suitable for Lisbon geology framework; (iii) design parameters adapted to worst case scenario including peak conditions and maximum flexibility towards the customer; (iv) avoid eventual impacts of the solution on the passenger service during design phase.

Further developments

In terms of future developments, this study does not contemplate the design of last mile delivery (from surface depots to final customers). A surface depot can be located nearby or within each metro station and last mile delivery operated by private smaller vehicles or an electric fleet; or a surface depot can be located in existent warehouses from establishments with higher demand. The impact of last mile delivery process on this project viability should be evaluated and possible limitations addressed.

A detailed information on the geology and hydrology framework near each metro station would allow to foresee all possible constraints during the construction phase and confirm the construction methods.

This study does not include the design of electric control systems responsible to organize the goods and track them along the chain.

Moreover, a detailed study on the maintenance costs provide a better view on the likelihood of a failure and support to ensure the reliability of this transportation system. It should also be investigated the process to overcome disturbances in metro lines which may stop operation for hours. The forecast of the disturbances and constraints during implementation phase (traffic diversions, congestion and possible effects on the area nearby) should also be studied and any additional costs included.

From an environmental point of view, it should be included the energy consumed and mass of emissions from loading/unloading operations; the impact of the current speed loss due to traffic congestion and the evolution in the energy mix for electricity in Portugal which can improve the comparison between both systems.

The impact of the tourism growth in recent years should be taken into consideration as well due to an increase in demand.

For further developments, it could also be analyzed the possibility of including perishable goods and consider any extra requirements to accommodate these goods.

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Annexes

A) Annex 1

Mass and Volume of goods not considered in the study for all metro stations.

Perishable goods		**Mass Metro**	**Volume Metro**
Fruits and vegetables	Apple	172	614
	Pear		
	Peach		
	Grapes		
	Another fresh fruits		
	Oranges		
	Nuts		
	Tomato		
	Another vegetables		
Meat and meat-based products	Beef meat	87	94
	Pork meat		
	Poultry meat		
	Sheep and goat meat		
	Another meat		
	Edible offal		
Fish, crustaceans and mollusks	Fish (fresh, chilled, frozen or pickled)	38	44
	Cod and other dried fish, salted, smoked or in brine		
	Crustaceans and molluscs (fresh, chilled, frozen or in brine)		
Bread and pastry products	Pastry	52	23
Milk and derivatives; eggs	Yoghurt and other acidified milks	41	74
	Cheese		
	Other milk products		
	Eggs		
Olive oil, oil and other fats	Butter	11	12
	Margarines and similar products		
	Lard, bacon and other fats		
Other products		**Mass Metro**	**Volume Metro**
Home Appliances	Large Home Appliances	25	124
Building materials/tools	Heavy materials & big tools	21	88
Furniture and lighting	Large Furniture	21	299

B) Annex 2

Number of containers and tunnel construction method in all metro stations.

Metro Station	No. containers	Tunnel Construction Method
Carnide	5	TAB
Colégio Militar/Luz	6	TAB
Alto dos Moinhos	2	TAB
Laranjeiras	2	TAB
Jardim Zoológico	2	TAB
Praça de Espanha	3	TAB
S. Sebastião	**2**	TAB
Parque	1	TAB
Marquês de Pombal	**2**	TAB
Avenida	3	TAB
Restauradores	3	Microtunneling
Baixa-Chiado	6	Microtunneling
Terreiro do Paço	3	Microtunneling
Santa Apolónia	3	Microtunneling
TOTAL BLUE (incl. double stations)	43	TAB (10) Microtunneling (4)
Ameixoeira	2	Microtunneling
Lumiar	1	Microtunneling
Quinta das Conchas	1	Microtunneling
Campo Grande	**1**	Microtunneling
Cidade Universitária	1	TAB
Entrecampos	2	TAB
Campo Pequeno	3	TAB
Saldanha	4	TAB
Picoas	3	TAB
Rato	11	TAB
TOTAL AMARELA (incl. double stations)	31	TAB (7) Microtunneling (4)
Telheiras	2	Microtunneling
Alvalade	4	TAB
Roma	4	TAB
Areeiro	3	TAB
Alameda	**3**	TAB
Arroios	6	TAB
Anjos	3	TAB
Intendente	3	TAB
Martim Moniz	5	Microtunneling
Rossio	5	Microtunneling
Cais do Sodré	5	Microtunneling
TOTAL VERDE (incl. double stations)	53	TAB (7) Microtunneling (6)
Aeroporto	1	TAB
Encarnação	1	TAB

Moscavide	1	TAB
Oriente	3	TAB
Cabo Ruivo	1	TAB
Olivais	2	TAB
Chelas	2	TAB
Bela Vista	2	TAB
Olaias	3	TAB
TOTAL VERMELHA (incl. double stations)	**25**	**TAB (12)**

C) Annex 3:

Geology and hydrology at Lisbon

A general knowledge on the geological characteristics and hydrological at Lisbon will be necessary at different stages of this project. An assessment of the underground conditions around each location of a metro station will guide the choice of construction methods during preliminary studies of this project and influence the cost evaluation.

The city of Lisbon belongs to the Western Meso-Cenozoic Basin. From the oldest layers to the recent ones, the formations of Lisbon soil are described in the following sequence [16]:

- Cretaceous:

Oldest layers composed of limestones and marls and predominantly located in the areas of Monsanto, Ajuda and Vale de Alcântara. This formation is part of the Lisbon bedrock.

- Lisbon Volcanic Complex:

Volcanic formations composed of basalts and pyroclasts fissured due to the movements suffered after their formation. This soil type is mainly located in the north of Lisbon and it can reach 300 meters.

- Paleogene (Benfica Complex):

Essentially a mixture of sedimental deposits such as conglomerates, marly clays and clayey sandy gravels. This formation can be found on depths greater than 300 meters and it becomes thicker north and westwards.

- Miocene:

Combination of clays, limestones, clay sands and sandstones formations in different proportions and interlayered. The thickness of this formation can reach approximately 300 meters and it becomes thicker in the East direction. According to [13], this soil type was the formation most intersected by the construction works of the Lisbon Metro.

- Pos-Miocene:

Superficial recent layers which are still in formation. It is a composition of alluvia, sands, sandy gravels and heterogeneous fills.

Figure 11 represents a sketch of Lisbon geological map with its main characteristics.

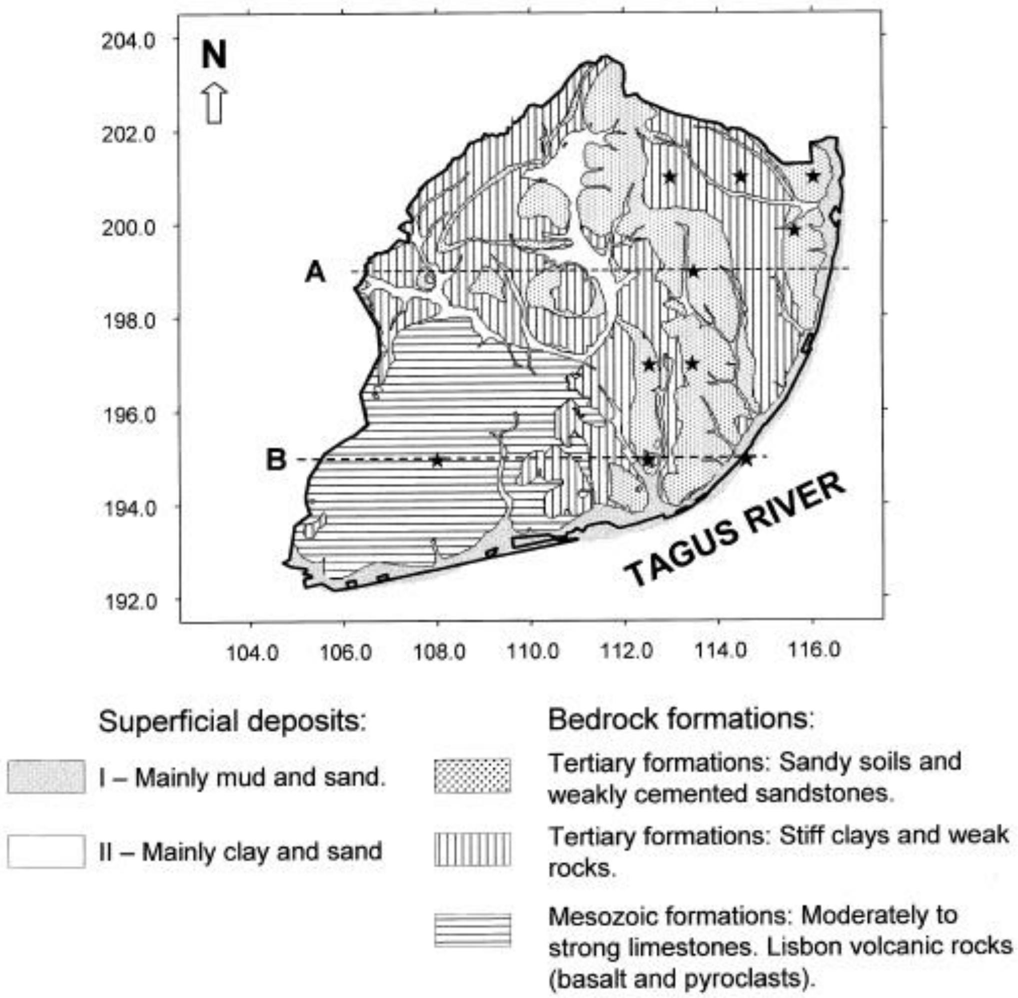

Figure 1: Sketch of Lisbon Geological Map. Adapted from [16].

The previous formations can be divided into two groups according to their hydrogeological characteristics: formations with primary porosity (sedimentary rocks with spaced grains) and formations with second porosity (metamorphic and igneous rocks with fissures). The heterogeneity of the lithology is responsible for a difference in permeability across the city. The hydrological framework is influenced not only by the geological conditions of the formations but also by the urbanization level.

Areas with high permeability are more favorable to form and feed groundwater bodies. According to a recent hydrogeological study published for the Lisbon Drainage Plan [17], Lisbon cretaceous sedimentary formations and alluvial formations stand out with high permeability; Miocene formations present a medium to high permeability and the remaining lithologies are classified from low to medium.

Based on the figure 12 and on several groundwater levels documented, it is possible to estimate the groundwater depth in each location of a metro station.

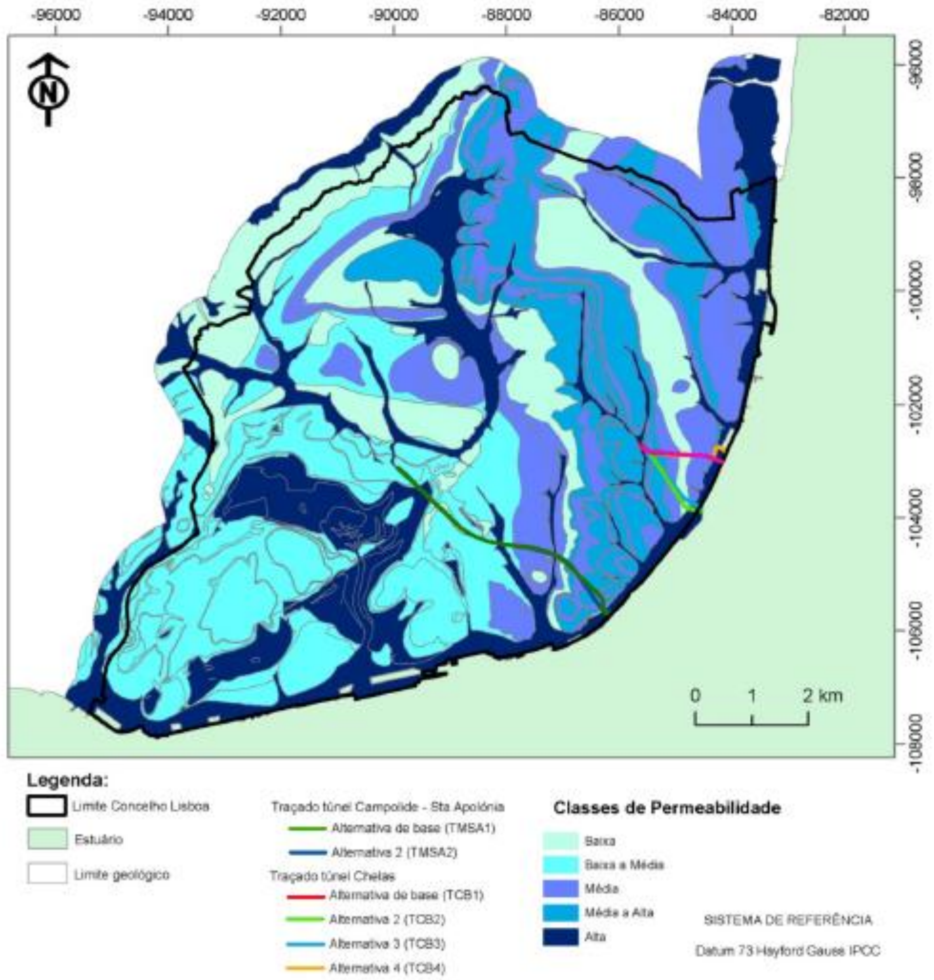

Figure 2: Permeability levels across Lisbon. Adapted from [17].