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

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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 6 years.

Keywords: Transportation; Emissions; Congestion; Freight; Distribution

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 which ensures compatibility with the present day passenger service. 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. 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. 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.

2. State of the art in urban logistics

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 [2].

Towards a sustainable transportation

From the 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 underground solutions are systems that shift goods from road to other transport modes as studied in Japan [3] and Netherlands [4]; or the development of a fully dedicated pipeline network with dedicated vehicles as researched in UK [5] and Germany [6].

3. Present day logistics in Lisbon

In Lisbon, the circulation of vehicles with a load capacity greater than 3.5 ton is not allowed in the city center, including in Historical Center. Usually the narrow roads have only one free lane for traffic and vehicles are frequently forced to park on the sidewalks. 54% of 604 establishments surveyed in Lisbon [7] 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 [7].

Underground transportation network:

Lisbon Metro has 4 different lines serving a total of 56 metro stations with 6 double stations (stations serving 2 different metro lines). Lisbon Metro is designed to cover important city areas as it is shown in Figure 1.

Figure 1: Diagram of Lisbon Metro Network.
Adapted from [8].

There is a train approximately every 5 to 8 minutes [8] but the frequency varies along the day. Each trip usually operates with 2 operational train units (each one with 3 passenger cars) semi permanently linked together. The average axis-depth of the metro network is 26 meters varying between 15 meters (e.g. Cais do Sodré section) and 48 meters (Baixa-Chiado section) [9].

4. Freight transportation 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. The wholesale business was not taken into consideration as well; 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 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).

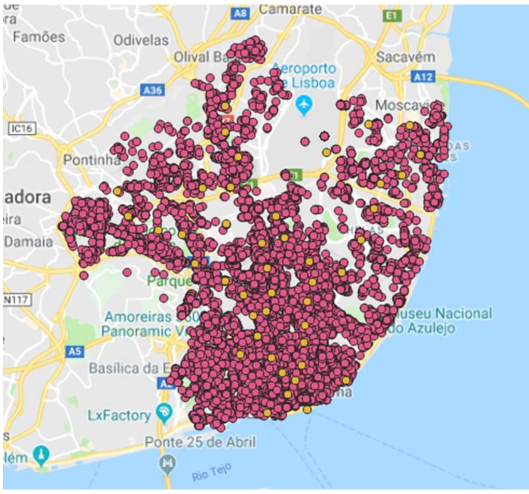

Figure 2: Allocation of establishments to the nearest station.

The methodology to convert economic sales volume to physical quantities (mass and volume) was different according to the type of goods:

- **Food 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. The reference values in the Portuguese Food Balance were used in conversion [10].

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

$$m_{i_{fg}} = \frac{(S_{sub})_{i_g}}{(C_{/kg})_{weight}} \times \frac{(m_{person/year})_{i_{fg}}}{(m_{person/year})_{i_{total}}} \quad (1)$$

where,

$$(C_{/kg})_{weight} = \sum_{i_{fg}}^{n} (C_{/kg})_{i_{fg}} \times \frac{(m_{person/year})_{i_{fg}}}{(m_{person/year})_{i_{total}}} \quad (2)$$

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; $(C_{kg})_{weigh}$ 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:

$$V_{i_{fg}} = \frac{m_{i_{fg}}}{\rho_{i_{fg}}} \quad (3)$$

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:**

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 and its average price.

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:

$$m_{i_{og}} = m_{av_{i_{og}}} \times N_{i_{og}} \quad (4)$$

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:

$$V_{i_{og}} = V_{av_{i_{og}}} \times N_{i_{og}} \quad (5)$$

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.

This project excluded some goods currently delivered by road transportation: the oversized goods and the perishable goods were not considered.

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 with an operational period from 06:30 until 12:00 (conservative approach to be able to accommodate any peaks in demand).

The number of trips available per day in a certain metro line to transport the goods is calculated using the equation (6):

$$No_{trip} = \frac{t_{tran}}{(f_s)_{av}} \quad (6)$$

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.

The freight mass and volume of goods to be transported in each trip of a metro line can be obtained by equations (7) and (8) respectively:

$$m_{trip} = \frac{m_{line/day}}{No_{trip}} \quad (7)$$

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.

$$V_{trip} = \frac{V_{line/day}}{No_{trip}} \quad (8)$$

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

Table 1: Freight to be transported per trip.

5. Design of 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 1200x800mm Euro-pallet (LxW). High Density Polyethylene (HDPE) was chosen for the material as it is a plastic commonly used in containers for goods transportation and an approved plastic by Food and Drug Administration (FDA) for storage of food products [11].

The number of containers to transport the freight volume per trip is given by equation (9):

$$No_{containers/trip} = \frac{V_{trip}}{V_{container}} \quad (9)$$

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 2 and table 3 present a summary of the specifications for each container and a summary of the number of containers required per trip in each line of the Lisbon Metro, respectively.

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

Table 2: Freight container specifications.

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

Table 3: Number of freight containers per trip.

5.2. Freight cars design

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.

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 [12] 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. A Radio Frequency Identification (RFID) system would be installed to sort the containers according to their destination. The system will use passive containers supported on multi directional conveyors to move the containers in all horizontal directions and sort them. The multidirectional conveyors consist of power-driven transfer tables composed of several shafts with rollers with high impact resistance and load capacity.

The velocity of each conveyor table is given by equation (10):

$$v_{table} = \frac{No_{containers/door} \times L_{container}}{t_{dwell}} \quad (10)$$

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. To achieve realistic velocities the freight car is designed with 2 decks, 1 unloading door and 1 loading door in each deck.

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

$$F_{max} \cong F_r \leq N.\mu_{static} = m_{container} \times g \times \mu_{static} \quad (11)$$

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 [13].

The maximum power of each conveyor table is:

$$P_{table} = \frac{F_{max} \times v_{table}}{\eta_{engine} \times \eta_{table}} \quad (12)$$

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 [14]. For the table an efficiency of 80% was considered.

Table 4 presents a summary of the design specifications of a freight car.

No. decks	2
No. unloading/loading doors	4
$H_{freight}$ (m)	3.523
$W_{freight}$ (m)	2.789
$L_{freight}$ (m)	13
F_{max} (N)	255
v_{table} (m/s)	1.14
P_{table} (W)	519

Table 4: Freight car design specifications.

The impact in the maximum acceleration of adding a freight car to the current train is not significant thus the same motorization can be used. Moreover, electromagnets can be installed to guarantee the containers do not move once the freight car accelerates.

Figure 3 represents a sketch of a freight car and containers layout.

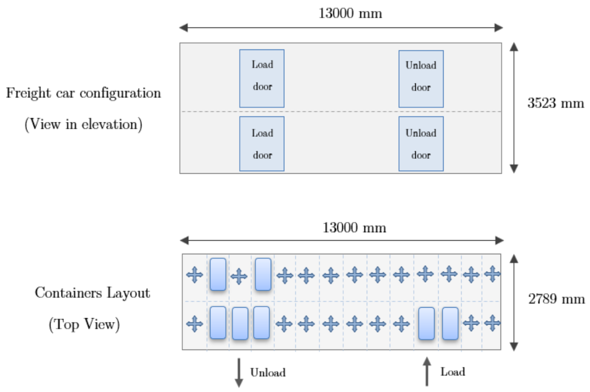

Figure 3: Sketch of a car configuration and containers layout.

5.3. Underground Network Design

The container dimensions influence the inner diameter of a pipeline since each container will be transported through these channels.

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 due to the difference in construction costs. This intends to also minimize ground settlements which can impact the existent metro infrastructure.

The inner diameter of a pipeline can be obtained by equation (13):

$$D_{pipeline} = \sqrt{2} \times H_{o_{container}} \quad (13)$$

where $H_{o_{container}}$ is the outer height of a container. An inner diameter of 1500 mm is enough for each pipeline.

Figure 4 is a design sketch for the pipeline.

A

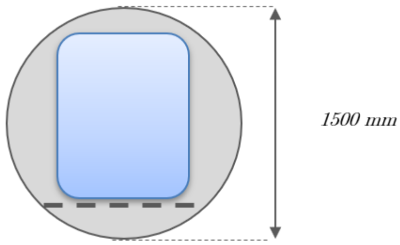

Figure 4: Pipeline design sketch.

trenchless method is preferred due to their suitability to urban areas. Two construction methods were selected: thrust auger boring (TAB) and microtunneling. Both construction methods are suitable for terrains composed mostly of clays and limestones. 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 influence the minimum thickness required. In TAB steel pipelines with 12mm thickness would be used and in microtunneling concrete pipelines with 152 mm thickness.

In terms of conveyor network, 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

Figure 5 represents a sketch of the underground network including the underground depots for containers storage. It is also shown the direction flow inside the network.

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 (26 meters).

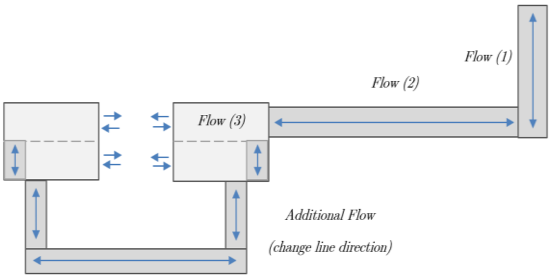

Figure 5: Sketch of network including direction flows.

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. However, the conveyor design for the network branch to change the direction on a metro line was not included in this study.

Depending on the business model the length will vary. For this study an average length of 50 meters was considered which is a reasonable distance for selecting a depot area for goods delivery.

Considering the extensive loading movement from the surface depot until the entry in the freight car and the 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 would be built with 2 decks. Therefore, the height of the underground depot was set as 3 meters. Knowing that this depot must store a maximum of 53 containers, the length of a quadrangular underground depot is given by equation (14):

$$l_{depot} = \sqrt{\frac{No_{containers} \times A_{container}}{2}} \qquad (14)$$

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

Table 5 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	
Average relative* depth (H_{rel})	5 m
Average length (L)	20 m
Underground Depot 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 5: Tunnel network overall dimensions.

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 (15):

$$v_{conveyor} = \frac{(No_{containers} \times L_{container}) + H_{tunnel} + L_{tunnel}}{t_{load}} \qquad (15)$$

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 number of containers that each CVC is able to transport at once is given by equation (16):

$$No._{container/CVC} = \frac{H_{tunnel}}{H_{container}} \qquad (16)$$

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 (17):

$$F_{max} = F_r + F_g - F_{cg} \tag{17}$$

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 (18):

$$F_r = No._{container/CVC} \left(m_{container} \times \frac{dv_y}{dt}\right) \tag{18}$$

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 applied by the counterweight, assuming a counterweight equal to the weight of 4 containers is given by equation (19):

$$F_{cg} = 4 \times m_{container} \times g \tag{19}$$

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 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). The number of containers that each HRC is able to move at once is given by equation (20):

$$No._{container/HRC} = \frac{L_{tunnel}}{L_{container}} \tag{20}$$

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

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

$$\begin{aligned} F_{max} &\cong F_r \\ &\leq No._{container/HRC} \left(N \cdot \mu_{static}\right) \\ &= No._{container/HRC} \left(m_{container} \times g \times \mu_{static}\right) \end{aligned} \tag{21}$$

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 [13].

The maximum power to move the CVC and HRC is given by equation (22):

$$P_{max} = \frac{F_{max} \times v_{conveyor}}{\eta_{eng} \times \eta_{conveyor}} \tag{22}$$

where F_{max} is the maximum force to move the CVC/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 [14]. For the conveyors an efficiency of 80% was considered.

Table 6 presents the CVC and HRC preliminary design specifications.

Vertical and Horizontal Conveyors	
t_{load} (s)	240
$v_{conveyor}$ (m/s)	0.602
$No._{container/CVC}$	26
$CVC\ F_{max}$ (N)	118872
$CVC\ P_{max}$ (W)	127787
$No._{container/HRC}$	38
$HRC\ F_{max}$ (N)	9682
$HRC\ P_{max}$ (W)	10408

Table 6: CVC and HRC preliminary design.

6. Viability Analysis

In order to analyze the economical viability of this project, it was necessary to calculate the investment and operational costs. The investment costs were estimated based on the design requirements from the previous chapter. The yearly operational costs considered include the energy consumption, maintenance and labor costs. Besides, the yearly revenues were calculated using the 2011 transportation cost by light trucks of 6,114 €/t.km [36]. This value excluded profit margins and was taken as base price for future customers using the metro.

Table 7 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 7: Overall cost analysis.

By plotting the above values, a financial return is obtained within approximately 5 years and 4 months for this project.

7. Comparison to truck transportation

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.

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.

Table 8 presents a comparison in terms of energy consumption between a truck-based system and a metro-based system.

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 8: Energy Consumption (MJ/Vehicle)

In terms of mass of emissions, for a truck freight transportation system, the well-to-tank (WTT) and tank-to-wheel (TTW) phases are considered. On the other side, if a metro freight transportation system is considered, there are only emissions during the well-to-tank phase.

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 9: Emissions per vehicle (kgCO2e/vehicle).

8. Conclusions

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 6 years with an investment cost of 185 M€ and yearly revenues of around 41 M€/year.

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.

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