An optimization approach for sustainable logistics

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Abstract: A development that considers the economy, together with environmental concerns has been increasingly adopted in order that a more sustainable future is secured. In this dissertation, sustainable development is related to the incorporation of alternatively fueled vehicles as a step forward into the reduction of harmful externalities generated by transportation activities within supply chains. The project concerns the development and implementation of a location routing problem to optimize an operational flow based on e-trucks and the potential siting of recharging stations. The model is based on the operations of a Portuguese retailer that still serves its stores using diesel trucks and assesses the feasibility of the transition from a diesel-truck based operation into an e-truck based one. And, according to the results, this transition is feasible, especially concerning the economic and environmental dimensions since the e-truck's higher upfront costs are compensated with lower maintenance and energy costs along with less emissions.

Keywords: Sustainable development, location routing problem, urban logistics, optimization, electric vehicles.

Introduction

In 1987, sustainable development was defined, (WCED, 1987), as the "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Over the recent years, a shift has taken place in order that sustainable development (SD) is effectively pursued.

SD is based on the respect for the sustainability pillars, represented by the triple bottom line (TBL), (Roca & Searcy, 2012). Pursuing a SD is, therefore, the way not to jeopardize the future generations' quality of life, as it promotes long-term sustainable growth, (Dubey et al., 2017).

In this sense, stricter environmental policies have been enacted, for instance, the ICE vehicles ban in some city centers and future bans on their sales, (Visser & Brundtland, 2013). Customers have also put pressure on regulators and companies in order that practices are improved, (Kumar & Alok, 2020).

The literature directly relates the companies' operations' impacts, namely their supply chains and the way they are adapting to this new environment, on whether a SD is effectively being pursued or not. As stated by (Nilsson & Göransson, 2021), the challenges of sustainable development require a close collaboration among the different stakeholders is put into action, towards a balanced economic activity, where environmental concerns are also addressed. However, most of the existing research on supply chains and optimization is on a company level, which mostly seeks short-term cost-reduction and/or profit maximization.

Thus, this dissertation aims to promote a more sustainable transportation system, where not only the economic aspect is considered, but also the environmental ones. In the context of Sustainable Supply Chains, (Barbosa-Póvoa et al., 2018), a major source of interest in the transition is the transportation of goods, which is the main thesis' focus and, therefore, the problematic to be addressed in the master thesis' model was the Location Routing Problem (LRP) of e-trucks from the depot and into several city center locations, since it will assess how charging infrastructure should be implemented in order that distribution operations, based on e-trucks, are not jeopardized. Thus, in the dissertation it will be necessary to consider, the interaction between the location of the depot and the demand points, along with the assessment of the to-be location and necessity for charging.

This, in order that it is possible to effectively operate a profitable and feasible distribution in urban environments using eco-friendlier vehicles which, in this case, are the e-trucks.

Literature Review

In the literature review that was performed, it was analyzed the models and research papers that developed LRPs incorporating e-trucks into the considered fleet. It were presented the main sustainable logistics characteristics as well as the challenges to be considered when modelling a LRP (that considers a fleet of e-trucks) and the main methods to solve it.

Regarding LRPs, besides extensive literature on classic LRPs, the case for the LRPs considering, specifically, electric vehicles (EVs), is still lacking a thorough research as stated by (Sar & Ghadimi, 2023). Thus, the inputs for the developed model were retrieved mainly from studies developed by Schiffer research papers (Schiffer & Walther, 2017), (Schiffer & Walther, 2018), (Schiffer et al., 2018) and (Schiffer et al., 2021). These research papers presented generic models and mainly two primary planning approaches for electric fleets were retrieved. The first approach prioritized routing decisions, considering the challenges posed by the limited driving range and lengthy charging times. The second approach was centered on the decision to place charging stations, or not, and if so, where. This aimed to define what was the necessary charging infrastructure considering the routing problem associated with electric vehicles. This simultaneous consideration allows to better support the decision-making process for logistics fleet operators, as it is the case for the retailers' distribution operation considered as a base case for the dissertation, (Figueiredo, 2009).

As a consequence, in this dissertation, it is aimed to optimize the recharging infrastructure together with the distribution operations, namely the delivery routes, also considering environmental concerns, which as previously mentioned were not yet considered, to the best of my knowledge, in the literature. A direct comparison between the Total Cost of Ownership (TCO) regarding e-truck and diesel-truck based operations with real-life base case parameters were also not considered so far.

Thus, the option to consider an LRP, regarded to the fact that, if these decisions were taken separately, the results that would be given by two separate models, one for location and another one for routing, would be suboptimal, when compared to the ones obtained by implementing a LRP.

Furthermore, (Schiffer & Walther, 2018) mentions that LRPs involving EVs involve conflicting aspects, which have to be balanced in order that a feasible operation is possible, especially if real-world conditions are considered. The aspects, to be considered, are: the routing planning requires that the limited range presented by EVs when compared to their ICE counterparts is accounted as well as the recharging times. Moreover, it has also to be considered what are the recharging points being used (conventional, fast or ultra-fast), since these plug-in recharges last longer when compared to the time required to fill an ICE vehicle's tank. Furthermore, it has to be considered other factors impacting last mile operations, (Melacini et al., 2018), especially within cities: the TCO, namely the higher purchasing costs when buying an EV, which are impacted by governmental incentives to the acquisition of EVs and the battery costs; also, the lower operation costs, in terms of energy and maintenance. Moreover, it also has to be considered that an ageing battery loses capacity in storage and increases the resistance to recharging, leading to higher recharging times. Furthermore, other factors impacting are the type of the product being transported, namely if it is refrigerated transportation or not, the area being covered, the battery decay, which has had little attention in the literature, (Dündar et al., 2021), as well as the lack of a publicly available recharging infrastructure, especially the ultra-fast charging stations (the ones suitable to recharging e-trucks), (Alarcón et al., 2023a).

Environmental concerns should also be considered, namely the impacts resulting from the lower emissions resultant from e-truck operations, but also the negative impacts of battery decay, (Schiffer et al., 2021).

Moreover, the main gap found on the literature concerns the inexistence, to the best of my knowledge, of LRP models considering other dimensions of the TBL, other than the economic one, together with an e-truck based distribution within urban areas.

Laslty, (Karaoglan et al., 2012) states that LRPs might be solved through formulating exact algorithms, namely, mixed integer programming (MIP) and mixed integer linear programming (MILP) and, therefore, getting an optimal solution. However, since this is a NP-hard problem, heuristics / metaheuristics might be appropriate methods as well. In the case of this dissertation, a MILP solution was considered and the mathematical formulation was implemented in GAMS software.

Model Formulation

This optimization model was created to address the LRP regarding the operation of a retailer's distribution into its stores with e-trucks, which helps to close the previously mentioned gaps.

This distribution process from the depot is still performed using diesel-trucks and the aim of this study is to model and discuss important tactical-operational planning considerations: whether, or not, it is feasible the transition from a diesel-based operation into an e-truck based one, this considering TBL dimensions of sustainable development; whether, or not, one or more, recharging stations need to be placed at the different stores in order that the operational flow is not compromised.

Moreover, the problem formulated is defined as static, single echelon, where each customer (vertex) is visited once, departing from a single depot located outside the city. The distribution will be performed by the most suitable type of e-truck from the existing two types (21 or 24-pallet EVs). They will leave the depot charged up to 80% and, when necessary, partial recharges, in the recharging points installed in the considered subset of the visited vertices, are possible. Lastly, it is also important to mention that no inventory decisions are relevant.

This mathematical model is based on three different works, in particular, the original dissertation in which this study is based on, (Figueiredo, 2009), as it formulates a model for the delivery into different stores, from a single depot, where demand must be met within the established time-windows, using the minimum number of trucks and routes possible. However, this model was not sufficient to develop this dissertation, since it did not consider the specificities of serving stores using e-trucks, namely: The equations for the battery balance, the associated recharging time and a limited range; and the equations for sitting recharging stations and to model the recharging process.

These were retrieved mainly from the models developed by (Schiffer et al., 2018, 2021). The models were more generic and, therefore, the need to use some restrictions for time-windows and trucks' capacity limitations from (Figueiredo, 2009). Furthermore, from the research papers, it were retrieved the equations that allowed to model the routing decisions (considering the constraints that e-trucks still face, as previously referred) together with the location of recharging stations.

Furthermore, it was also compared the results from the modelled e-truck based operation with what would be the results for the similar diesel-truck based operation. To this end, this model parameters and objective functions were based on the work developed by (Schiffer et al., 2021; Schiffer & Walther, 2017, 2018), where it was directly compared the TCO of an e-truck and a diesel-truck and, therefore, the economic dimension component of the objective function was based on the major cost drivers: investment, maintenance and operation.

The same author also mentions the environmental impacts of emissions generated from electrical production, diesel consumption and battery decay, all the components were monetized in order to have comparable results and a single-objective function that considered the two dimensions. To this end, it were considered the carbon emission costs, (Booto et al., 2021) to compute the emissions' impacts of both e-trucks and diesel-trucks.

The model notation includes the sets, presented in Table 1, the parameters, presented in Table 2 and the variables, presented in Table 3.

Table 1: Model Sets

Notation	Description
I	Set of all vertices indexed by i (i ∈ I)
J	Set defined as the set of choices after i is visited indexed by j (j ∈ J)
I_C	Subset of vertices I that corresponds to the depot indexed by i_c (i_c ∈ I)
I_D	Subset of vertices I that corresponds to demand nodes indexed by i_d (i_d ∈ I)
I_P	Subset of vertices I that are potential recharging points indexed by i_p (i_p ∈ I)
K	Set of electric vehicles' capacities indexed by k (k ∈ K)
S	Set representing the shift in which the operation takes place indexed by s (s ∈ S)
N	Set that represents the number of times the truck left the depot indexed by n (n ∈ N)

Table 2: Model Parameters

Notation	Description
evu	The e-truck unitary cost without batteries (€/unit)
buc	The cost of a set of batteries per truck (€/unit)
dvu	The diesel truck unitary cost (€/unit)
rpu	The unitary cost of setting up a charging station (€/unit)
ele	The cost of electricity (€/km) for the logistics' business
die	The cost of diesel (€/km) for the logistics' business
mae	The maintenance costs of an e-truck (€/km)
mad	The maintenance costs of a diesel truck (€/km)

Notation	Description
mar	The daily maintenance cost of a recharging station (€/day)
lr	The cost per employee and per day (€/day)
bcap	The initial battery capacity (kWh)
bmax	The maximum battery recharging level (%)
$fmax_k$	The maximum freight capacity of a truck k (number of pallets)
$cmax_i$	The capacity that a truck can have to be able to operate in vertex i (nr of pallets)
ea_i	The earliest arrival-time at the demand point i_c (min)
la_i	The latest arrival-time at the demand point i_c (min)
ts	The project's time span (min)
day	The duration (min) of the workday
dyear	The number of working days per year
rr	The recharging rate of the recharging station (kWh/min)
rrs	The recharging rate after 80% of battery capacity has been charged (kWh/min)
bdr	The battery degradation rate (€/km)
oek	The electricity consumption rate of an e-truck (kWh/km)
tx	The discount rate for the project evaluation
pco_2	The carbon price for emissions resulting from the trucks' operations (€/$gCO_{2\ equivalent}$)
carbe	The carbon intensity, in Portugal, of a km driven in an e-truck ($gCO_{2\ equivalent}$/km)
carbd	The carbon intensity of a km driven in a diesel truck ($gCO_{2\ equivalent}$/km)
d_{id}	The demand to be fulfilled at a given demand point id (nr of pallets)
dis_{ij}	The matrix representing the distance between vertices i and j (km)
tim_{ij}	The matrix representing the time between vertices i and j (min)
sf	The fixed duration to prepare the truck for the loading / unloading operations (min)
sv	The time required to load or unload a pallet at a demand point or depot (min/pallet)
num	The total number of vertices
bstr	The minimum battery level (%)

Table 3: Model variables

Notation	Description
X_{ijkns}	1 if the arc (i,j) is travelled by truck k that left n times the depot on shift s, 0 otherwise;
Y_{ip}	1 if a recharging station is located at vertex i_p, 0 otherwise.
A_{ik}	The arrival-time (min) of the truck k at the vertex i;
F_{ik}	The freight load (number of pallets) at a given vertex i, in truck k;
B_{jkns}	The battery load (kWh) at vertex i, in truck k that left n times the depot on shift s;
W_{ipk}	Amount of energy (kWh) charged at charging station ip, in truck k;
U_i	MTZ Variable
Z	Objective Function

The model presents a single-objective objective function that considers two of the three TBL dimensions. To make this possible, all the terms of the objective function were monetized. Such is done by computing the daily cost associated with each dimension, namely the economic and environmental dimensions. The reason to use daily values regards the fact that the route optimization is done on working day basis and, since the operation is similar throughout time, (Figueiredo, 2009), tactical decisions can be taken on the medium term (the project life span is five years, considering the average life span of a battery set, (Basso et al., 2022)), considering a day of operations.

The economic factor (EcoC) is computed by the sum of three different terms: the investment cost to acquire e-trucks (InvC), the operational cost of distribution process (OpC) and the maintenance costs of the e-trucks (MainC).

The environmental factor (EnvC) that equals to the sum of two different terms, the environmental penalty due to carbon emissions associated with the network's transport activities (CarbC) and the battery degradation cost (DegC).

$$\begin{aligned} Min\ Z &= EcoC + EnvC \\ &= InvC + OpC + MainC + CarbC + DegC \end{aligned} \tag{1}$$

$$\begin{aligned} InvC &= \text{Actualization Constant} \\ &\times \left(\sum_{i_c} \sum_{j} \sum_{k} \sum_{n} \sum_{s} \times (evu + buc + rpu) \times X_{i_c jkns} \right. \\ &\qquad \left. + rpu \times \sum_{i_p} Y_{i_p} \right) \end{aligned} \tag{2}$$

$$Actualization\ Constant = \frac{\frac{tx}{dyear} \times \left(1 + \frac{tx}{dyear}\right)^{dyear \times ts}}{\left(1 + \frac{tx}{dyear}\right)^{dyear \times ts} - 1} \tag{2.1}$$

$$OpC = \sum_{i} \sum_{j} \sum_{k} \sum_{n} \sum_{s} ele \times oek \times dis_{ij} \times X_{ijkns} \tag{3}$$

$$\begin{aligned} MainC &= \sum_{i} \sum_{j} \sum_{k} \sum_{n} \sum_{s} mae \times dis_{ij} \times X_{ijkns} \\ &+ mar \times \left(\sum_{i_p} \sum_{k} Y_{i_p k} + \sum_{i_c} \sum_{j} \sum_{k} \sum_{n} \sum_{s} X_{i_c jkns} \right) \end{aligned} \tag{4}$$

$$CarbC = \sum_{i} \sum_{j} \sum_{k} \sum_{n} \sum_{s} carbe \times pco_2 \times dis_{ij} \times X_{ijkns} \tag{5}$$

$$BatC = \sum_{i} \sum_{j} \sum_{k} \sum_{n} \sum_{s} buc \times bdr \times dis_{ij} \times X_{ijkns} \tag{6}$$

Subject to:

$$\sum_{k} \mathrm{fmax}_k \times X_{i_c i_d kns} \geq \mathrm{d}_{i_d}, \qquad \forall i_d, i_c, n, s \tag{7}$$

$$\sum_{i} \sum_{k} X_{i i_d ks} = 1, \qquad \forall i_d, n, s \tag{8}$$

$$\sum_{i} X_{i i_p ks} \leq 1, \qquad \forall i_p, k, n, s \tag{9}$$

$$\sum_{i} \sum_{k} X_{ijnks} = \sum_{i} \sum_{k} X_{jikns}, \qquad \forall j, n, s \tag{10}$$

$$X_{iikns} = 0, \qquad \forall i, k, n, s \tag{11}$$

$$\begin{gathered} U_i - U_j + \mathrm{num} \times X_{jikns} \leq \mathrm{num} - 1, \\ \forall k, n, s \wedge 2 \leq \mathrm{i} \neq \mathrm{j} \leq num \end{gathered} \tag{12}$$

$$W_{i_p k} \leq bmax \times bcap \times Y_{i_p}, \qquad \forall i_p, k \tag{13}$$

$$Y_{i_p} \leq W_{i_p k}, \qquad \forall i_p, k \tag{14}$$

$$W_{i_p k} \geq 0, \qquad \forall i_p, k \tag{15}$$

$$B_{ikns} \geq bstr, \qquad \forall i, k, n, s \tag{16}$$

$$B_{i_c kns} \leq bmax \times bcap, \qquad \forall i, k, n, s \tag{17}$$

$$B_{i_p kns} + W_{i_p kns} \leq bmax \times bcap, \qquad \forall i_p, k, n, s \tag{18}$$

$$\begin{gathered} B_{jkns} \geq B_{i_d kns} - oek \times dis_{i_d k} \times X_{i_d jkns} \\ +bcap \times bmax \times \left(1 - X_{i_d jkns}\right), \\ \forall i_d, j, k, n, s \end{gathered} \tag{19}$$

$$\begin{gathered} B_{jkns} \geq B_{i_p kns} - oek \times dis_{i_p k} \times X_{i_p jkns} + W_{i_p k} \\ +bcap \times bmax \times \left(1 - X_{i_d jkns}\right), \\ \forall i_p, j, k, n, s \end{gathered} \tag{20}$$

$$A_{ik} \geq\ ea_i, \qquad \forall i, k \tag{21}$$

$$A_{ik} \leq\ la_i, \qquad \forall i, k \tag{22}$$

$$ea_i <\ 240\ \Rightarrow s \leq 1, \qquad \forall i \wedge\ s \leq 1 \tag{23}$$

$$ea_i \geq\ 240\ \Rightarrow s \geq 2, \qquad \forall i, k \wedge s \geq 2 \tag{24}$$

$$\begin{gathered} A_{jk} \geq A_{i_d k} + \left(tim_{i_d j} + \left(sf + sv \times d_{i_d}\right)\right) \times X_{i_d jkns} \\ -\left(1 - X_{i_d jkns}\right) \times \left(la_{i_c} + \times \left(bmax - bstr\right)\right. \\ \left. + \left(\ sv \times d_{i_d}\right) + rr \times bcap\right), \\ \forall i_d, i_c, j, k, n, s \end{gathered} \tag{25}$$

$$\begin{gathered} A_{jk} \geq A_{i_c k} + \left(tim_{i_c j} + sf + sv \times d_{i_d}\right) \times X_{i_c jkns}, \\ \forall i_d, i_c, j, k, s \wedge\ n \leq 1 \end{gathered} \tag{26}$$

$$\begin{gathered} A_{jk} \geq A_{i_c k} + tim_{i_c j} \times X_{i_c jkns} \\ +rr \times \left(bcap \times bmax - B_{i_c kns}\right), \\ \forall i_d, i_c, j, k, s \wedge\ n \geq 2 \end{gathered} \tag{27}$$

$$\begin{gathered} A_{jk} \geq A_{i_p k} + tim_{i_p j} \times X_{i_p jkns} + rr \times W_{i_p k} \\ -\left(la_{i_c} + rr \times bcap \times \left(bmax - bstr\right)\right) \\ \times \left(1 - X_{i_p jkns}\right), \qquad \forall i_p, j, k, n, s \end{gathered} \tag{28}$$

$$F_{ik} \geq 0, \qquad \forall i, k \tag{29}$$

$$F_{ik} \leq fmax_k, \qquad \forall i, k \tag{30}$$

$$\begin{gathered} F_{ik} \geq F_{i_d k} - d_{i_d} \times X_{i_d jkns} \\ +\left(fmax_k\right) \times \left(1 - X_{i_d jkns}\right), \qquad \forall i_d, j, k, n, s \end{gathered} \tag{31}$$

$$\left(cmax_j - fmax_k\right) \times X_{ijkns} \geq 0, \qquad \forall i, n, s \tag{32}$$

$$X_{ijkns} \in \{0; 1\}, \qquad \forall i, j, k, n, s \tag{33}$$

$$Y_{i_p} \in \{0; 1\}, \qquad \forall i_p \tag{34}$$

Constraints (8) to (12) are the constraints commonly used in deterministic LRP models for a robust model formulation, namely by securing that all customer demand is served, along with single assignment for customer vertices. Nevertheless, relaxation for recharging vertices is also modelled by constraint (11). The MTZ constraint (13) is used to eliminate sub-tours. The charging station location decision is linked to the routing and recharging decisions by constraints (14) to (16), avoiding that charging stations are placed in stores unless they are used. Range limitations due to battery capacity and recharging limitations are modeled by constraints (17) to (21). The first 3 constraints limit the battery capacity and recharging, in the lower bound, to the "anxiety level" and, in the upper bound, to 80% in order to increase the battery life span. Moreover, constraints (20) and (21) obtain the energy balance throughout the day. Constraints (22) to (29) are time related. While constraints (22) and (23) obtain time window feasibility for all vertices, constraints (24) and (25) allow the model to ensure that intervals and shifts are considered into the model and constraints (26) to (29) ensure the time flow of the model. Freight constraints are given by equations (30) to (33), ensuring that limits for each truck k are respected along with the capacity restrictions of the stores and the material flow throughout the day. Lastly, binary variables are defined in (34) and (35).

Case Study and Data Collection

The data in which the dissertation was based on, regards both to the base case, (Figueiredo, 2009), which was based on a Portuguese retailer's distribution operations, along with research developed by (Schiffer & Walther, 2017), (Schiffer & Walther, 2018), (Schiffer et al., 2018) and (Schiffer et al., 2021), since this author presented the generic mathematical formulation for a Location Routing Problem, along with the required data to run the model and also the data required to compare the e-truck and diesel-truck operations. In the base case, (Figueiredo, 2009), it was done an optimization regarding the duration and distance covered in the distribution process and, therefore, few parameters for a TCO analysis could be retrieved. This is the main reason for the need of additional data.

(Figueiredo, 2009) study is based on the logistic difficulties posed by carrying out the distribution of goods in densely populated areas. This is because many small and medium supermarkets, from the retailer's chain, are located in buildings that were not built with commercial uses in mind and do not have designated unloading docks.

As a result, it was studied by (Figueiredo, 2009) the characteristics that would enable to create a group of representative stores in the Lisbon area. As a consequence, it were chosen 40 stores, that could be served by either 21 or 24-pallet trucks. Moreover, the services could take place in two distinct time periods which enabled that the model could be run for the entire working day.

Furthermore, from the base case it was possible to retrieve some cost, operational and bound parameters. The remaining parameters in the previously mentioned categories and also on vehicle characteristics and costs (for both diesel and electric trucks), along with parameters regarding battery characteristics, recharging stations and carbon emissions were retrieved from the literature, most notably from (Schiffer et al., 2018, 2021) research papers.

It were also considered actualization parameters in order that all costs were in 2023 equivalent values and also to include the opportunity costs into the equation, as it was computed a discount rate of 7,56% per year of the project, based on (Banco de Portugal, 2023), mostly concerning the required upfront investment to deploy e-truck based operations, instead of diesel-based ones.

Thus, the main factors impacting the transition feasibility are: the total costs, in 2023, to operate e-trucks instead of diesel trucks and, also, the environmental impacts of having an e-truck based operation instead of a diesel-based one are presented in the Table 4 below.

Table 4: Cost drivers comparison (2023 values)

Parameter	E-truck	Diesel-Truck
Vehicle	152.882€	81.901€
Battery pack	61.425€	-
Recharging Station	47.446€	-
Energy	0,14€/km	0,20€/km
Vehicle Maintenance	0,14€/km	0,28€/km
Recharging Station Maintenace	1,02€/day	-
Carbon Emmissions	0,015€/km	0,06€/km
Battery Decay	0,008€/km	-

Results and Discussion

The results returned by the model make it clear that for the considered conditions, it is indeed feasible to switch from a diesel-truck based operation and into an e-truck based one. This is because, for the current battery maximum capacities (450kWh), quick recharges up to 80% and battery levels that never go below the anxiety levels (at 13%) are possible without major impacts in daily operations, at least when batteries are new, (Guo et al., 2018). Nevertheless, even when batteries are not new, at least for the simulation performed, it is possible to charge up to 90% of the new maximum battery level and still run the operation always above the minimum level of battery that prevents the anxiety to the driver, this for a project lifespan of 5 years. The major impact that this creates regards the extended recharging time in some routes, where recharging above 80% is necessary to run the operation, namely this will create for the studied case an increment of 7,2 minutes to one of the drivers' total working time in a given day.

According to the results retrieved from the model run, in-store charging is not required in normal operating conditions for this type of operation (small radius of operation and regulars returns to the depot), as the bulk of the recharging can be performed during idle periods, for instance, during the lunch or other breaks, along with the waiting time for loading at the depot.

Nevertheless, for operational resiliency, if no publicly available options for fast charging are available and, given that conditions are never perfect, it would be advisable to locate a single charger at a central point within each cluster of stores in case unexpected events occur (such as roadwork, accidents, or other situations that may lead to considerably longer routes or extended waiting times and higher electricity consumption for the truck, than modelled), (Booto et al., 2021).

In addition, the model enabled to conclude that for the considered case study, the primary constraint is the truck's capacity rather than battery capacity. This is because trucks need to return to the distribution center before any recharging becomes necessary, as they run out of goods and therefore a new loading of products is required before the battery runs-out.

Moreover, for the considered characteristics, a truck, if charged up to 80% is able to serve stores within a 84km radius from the distribution center. However, stores located farther away will require in-store recharging with dedicated charging stations in order to be served efficiently with e-trucks.

As previously mentioned, the costs to operate e-trucks instead of diesel trucks were also assessed and summarized in Figure1 below:

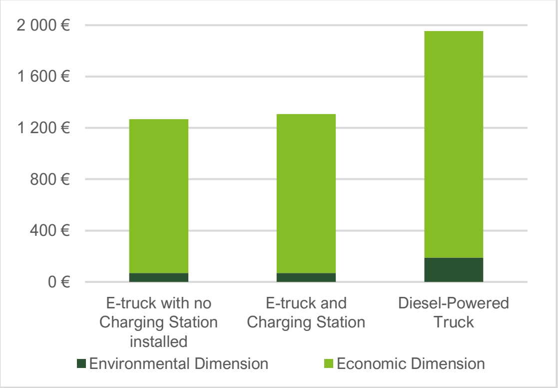

Figure 1: Break-down on the assessed BTL pillars

The values associated with the graph mean that there is an overall cost reduction (when considering charging stations' costs) of 32% and a cost reduction (not considering charging stations) of 34% when comparing to the as-is operations. It is worthwhile to mention that this distinction derives from the fact that, to the best of my knowledge, no ratio has been assessed in the literature regarding the number of e-trucks vs the number of charging stations to be deployed at the depot and, therefore, a conservative assumption was taken, as it was considered that each e-truck required 1 charging station at the depot. Furthermore, no recharging stations at the stores were needed in this set-up and, as a consequence, the recharging stations' costs considered only refer to those set-up at the depot.

Moreover, the model run results enabled to learn that the major driver is the economic dimension, since it corresponds to 91,2% of the total costs, on average, for the three scenarios that were assessed.

This is because the economic cost of operating a diesel vehicle, under the considered model is 1.764€ per day, while the cost of operating an electric vehicle is 1.200€, per day (a 564€ difference), which implies that, from an economic point of view, operating a diesel-truck entails a 47% higher cost.

If one charging station for every truck is considered, then the cost of operating an e-truck increases by 3% to 1.239€ per day.

The economic factor analysis was further divided to assess the impact of the different factors within the economic dimension: investment, operation and maintenance. This break-down can be stated in Figure 2, below:

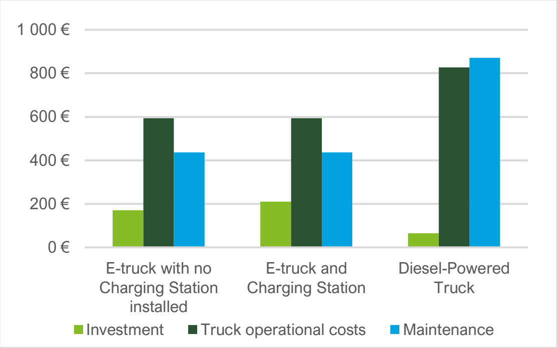

Figure 2: Break-down on the three costs drivers

This analysis demonstrates that the maintenance and the operational costs (i.e., energy) are the major costs drivers for diesel trucks (representing on average 13 times more daily expenses than the amount that the investment represents), whereas the different cost drivers for an e-truck based operation are more balanced amongst the different drivers (investment, maintenance and operation).

Nevertheless, the daily cost of operating the e-truck is 3,47 times higher when compared with the investment driver and the cost to maintain the e-truck is 2,55 times higher. Thus, these two factors represent the main reasons why the e-truck operation is, economically, more attractive than the diesel based one.

Regarding investment, if a truck is driven at least 229km per day, the upfront investment is paid off in the considered 5-year period, considering the mentioned operating conditions. Which is significantly lower than the value, on average for the trucks' routes for this simulation, which stands at 415 km/day, 81,2% above the minimum threshold for economic break-even of the project.

This enables to conclude that, for the presented model, it can be quite advantageous this transition, since the distribution center is on average 59,23km away from the stores and, therefore, two daily routes (to the store and back) are sufficient for break-even.

Regarding the operational costs, these entail the lowest relative difference between e-truck and diesel truck. Since the diesel costs are 827€/day, which represent a 39% higher daily expense when compared to the 593€/day to pay for the electricity required for the e-truck operation, which is a result of the subsidized "professional" diesel, which is still not the case for a potential "professional" electricity for logistics operations, according to (Schiffer et al., 2021). Another factor that could positively impact operational costs would be the electrical production at the distribution center, for instance through the installation of solar panels.

Lastly, within the economic dimension, maintenance is also a major driver for the e-truck total cost of ownership advantage since it is significantly lower for e-trucks than for diesel trucks. This is because the maintenance costs for the e-truck (including the recharging station maintenance) are half of the costs required to maintain the typical diesel-truck. And, therefore, the daily estimated cost for e-truck service is 437€, whilst this cost for diesel trucks is of 871€/day.

Another dimension assessed in this study was the environmental cost of the transition. This is quite favorable to e-trucks, since operating a diesel-truck in Portugal is 177% more impactful when compared to operating an e-truck.

The main driver is the Portuguese electrical mix, since it is based mostly in renewable energy, then the daily cost associated with carbon emissions of an e-truck is 46€, whilst for a diesel truck this value is 317% higher, at 190€ per day, (Alarcón et al., 2023b; Governo de Portugal, 2021). Moreover, battery degradation entails a daily cost of 23,17€, lowering the difference, in environmental terms, between operating an e-truck and a diesel-truck to 121€, as the total environmental cost of an e-truck increases to 69€ per day. Moreover, some facts might actually limit the real-life decay of the battery, namely: not charging the battery above 80%, except when required to complete a trip and also not letting the battery the battery discharging completely, (Guo et al., 2018).

In order to further analyze the feasibility of the transition from diesel-trucks towards electric trucks, it was also performed a sensitivity analysis on different factors impacting the overall sustainability of the proposed e-truck adoption: Investment, operational costs, maintenance and environmental impacts of the operation, which can be stated in Figure 3.

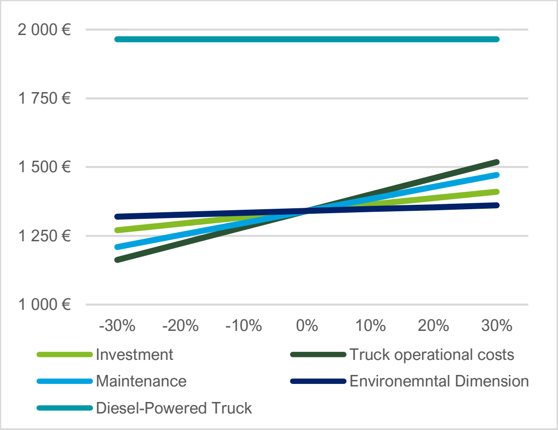

Figure 3: Sensitivity analysis of the transition into e-trucks

This graph presents the ownership and operational costs of e-trucks (also considering the cost of owning and operating one charging station per e-truck) and, it can be stated that, for the considered variations, the model proves to be feasible, when compared to the diesel-based operation. This is because, the total daily costs for operating a distribution operation with e-trucks are, at most, 77% of the diesel-based operation costs.

For this result, the most impactful domain is the truck operational costs. This is also aligned with the model results previously presented. Thus, incremental changes in the operational costs (namely, the cost of electricity), will be the most impactful in the total e-truck daily operating costs. This is because, as stated, the difference between electricity cost and diesel cost in €/km is relatively low, at 39% (comparatively to maintenance cost difference, at 100%), but its overall weight on the total cost (the relative weight on the total operating costs for the values considered for electricity consumption costs in the model is 44%), makes it the most impactful factor for the sensitivity analysis.

This factor is also something to be considered in strategic level, since the renewable production at the distribution center, as previously suggested, could mean a much lower cost to operate e-trucks, allowing a faster payback of the upfront costs. For instance, a 30% decrease in the electricity acquisition costs, would mean that the total daily costs, considering recharging stations, would stand at 57,2% of the cost to operate diesel trucks.

Moreover, the maintenance costs remain as the second most impactful factor. However, to the best of my knowledge, no further information, on the forecasted evolution of maintenance costs over the next years, exists.

Regarding the environmental dimension, it is expected that the overall carbon intensity of the Portuguese electrical mix will gradually reduce over the coming years, since it is forecasted that by 2030, 80% of the electric mix will be composed by renewables and by 2045 it will be totally neutral on carbon emissions, (Governo de Portugal, 2021). For instance, this value stood at 64,9% in 2021, (Pordata, 2023). Furthermore, the renewable energy as share of the electricity consumed can be higher, at an earlier stage, if, as previously mentioned, the distribution center produces its own electricity from renewable sources such as solar energy.

Lastly, it is worthwhile to mention that, both the environmental dimension and the investment required in batteries (as their acquisition costs are expected to drop by 37,5% until 2030, (Schiffer et al., 2021)) are set to improve the overall position of the e-trucks, when compared to diesel-powered vehicles. Thus, these factors will likely positively impact the transition towards e-truck adoption and mitigate possible negative impacts coming from the investment (on the e-trucks and recharging stations) along with maintenance, where less certainty on a positive evolution exists, according to the same author.

Conclusions and future research

To conclude, this simulation is validated for the considered case study, as the transition is feasible, especially concerning the economic and environmental dimensions.

Economically, the financial payback of the investment is achieved in 3,5 years and this return on investment is possible without endangering efficient and effective operations. This is possible due to the lower maintenance and operational costs that outweigh the higher upfront investment required by the e-truck based operation. In addition, the location of recharging station in stores is not required for the considered operational set-up, this means that only placing recharging stations at the depot would be required.

Environmentally, the solution is less impactful than the as-is situation, especially considering that over 69% of the electricity, currently produced in Portugal, is renewable. The battery decay is more difficult to assess. However, in terms of the costs entailed by battery disposal, together with carbon costs regarding the emissions from the electricity production, they are clearly outweighed by the emissions resulting from diesel consumption in a comparable operation.

Nevertheless, it is also worthwhile to note that, despite economically viable, a relatively long distance must be covered in order that, economically, the transition with the current e-truck operations' characteristics makes sense. This is because, the minimum distance for break-even, according to my results, is not covered by, at least, 21% of the EU trucking operations, (Eurostat, 2023).

Another situation where the economic feasibility should be further assessed is when different paths are taken every day and returns to the depot are not frequent, since the driver might have to be frequently looking for publicly available charging options, which are still sparse at the moment.

Lastly, for future analysis, more topics could be subject to assessment in order to improve the model and have a more real-life like scenario for discussion, namely: including the battery decay as a variable of the model; the influence of batteries' weight on the operations; an improved formulation to include a better approximation to real-life charging rates and usual uncertainties associated with this type of models, such as: traffic; wider distribution areas, namely in non-metropolitan regions where distances between depots and stores as well as among stores are bigger. Lastly, the distribution with a similar radius but with smaller products could be also considered, particularly parcel delivery, since en-route recharging would likely be needed due to a smaller number of returns to the depot.

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