

Implementing electric vehicles in urban distribution: A discrete event simulation

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Abstract

Urban freight transport becomes increasingly important with the development of cities. However, it generates also inefficiencies on social, economic and environmental aspects. A possible solution is the use of urban distribution centres in order to rationalise the deliveries and to operate the last miles with clean vehicles. Electric vehicles are gaining attention lately but some barriers remain. Since costs barriers were already investigated, the paper aimed at evaluating the difference of performances between a centre using a diesel truck and a centre using an electric vehicle. In order to do so, the operations of an urban distribution centre were modelled in a discrete event simulation and different scenarios were evaluated.

The results showed that replacing a conventional truck by an electric van generates more traffic due to the limited payload of the van. However, the limited range does not entail the daily operations of the vehicle since a single night charge is sufficient. Better, the depth of discharge is found to be limited to a minimum of 60%. The results on the battery are similar in the second scenario where the conventional truck is replaced by an electric truck. In that scenario though, no influences are identified on the logistics performances of the urban distribution center.

Keywords: city logistics, electric vehicle, discrete event simulation, urban distribution center

1 Introduction

In the future, cities will be increasingly important to the European economy. Today, they account for around 85% of the GDP in the EU [1] and the urbanization process will give an even more important role to the cities. Indeed, 75% of the European citizens already live in urban areas and population growth is expected to be absorbed only by cities [2].

A fundamental support of the urban economic vitality is freight transport [3]. Efficient urban logistics entail cheaper goods for the consumers and a more competitive production for businesses. Therefore, freight transport supports the accessibility and the attractiveness of the cities [4,5]. However, urban freight transport is

also recognised to generate strong economic, environmental and social inefficiencies [6]. As a result, the European Commission integrated urban freight transport in the white paper by setting an ambitious objective: city logistics should be CO₂ neutral in major urban environments by 2030 [7]. Urban distribution centres (UDC) are often regarded as a possible solutions for improving the sustainability of city logistics [8]. Browne *et al.* (2005) defines this concept as “*a logistics facility that is situated in relatively close proximity to the geographic area that it serves, be that a city centre, an entire town, or a specific site, from which consolidated deliveries are carried out in that area*”. The transfer of incoming freight from trucks to specific urban vehicles allows to rationalise the deliveries in the city as well as to

use environmentally friendly vehicles for the last miles in the city [10–12]. With regards to the European objectives of CO₂ free city logistics, electric vehicles (EVs) are increasingly gaining attention as their ecologic impact is lower compared to conventional vehicles [13]. Different European best practices in city distribution have already promoted electric vans in such a distribution model: London, Paris, Leiden, Bristol, La Rochelle and Malaga are examples of cities that combined the use of electric vehicles with an urban consolidation centre [14–17].

Even though the combination of an urban consolidation centre with electric vehicles represents a potential for sustainable city logistics [15], the attributes of electric vehicles might restrain their adoption by the operators of these centres; their high purchase and battery costs, the limited driving range and potential charging problems are considered as barriers for adoption in logistics [18]. To clarify the cost barriers of electric vehicles, a total cost of ownership analysis reveals that, in the segment of light commercial vehicles with a payload of less than a tonne, electric vehicles can be a financially attractive solution compared to conventional vehicles [19]. But their performances should also be comparable to conventional vehicles to convince transport operators to adopt them. Indeed, Macharis, Van Mierlo, & Van Den Bossche (2007) state that the price/performance ratio of electric vehicles should be set at least at the same level as internal combustion engine (ICE) equivalents in order to reach a breakthrough in logistics. However, assessing the impact of electric vehicles on the performances of logistics activities appears to be a challenge that scientific literature only scarcely addresses. The productivity of urban consolidation centres might indeed be affected because of the long charging times and limited range of electric vehicles. Since literature shows a gap, the objective of this paper is to evaluate the impact of electric vehicles on the performances of an urban consolidation centre.

To analyse the operations of an urban distribution centre, the case of the CityDepot in Hasselt is used to model the black box of a centre through a discrete event simulation. Then, the impact of different scenarios using EVs is evaluated in order to discuss their feasibility in logistics. Hence, the paper will first present the different simulation techniques available in operational research and explain why discrete

event simulation is the most appropriate approach. In a second step, the methodology used for building the discrete event simulation model based on the case of the CityDepot will be detailed. The results of the base scenario compared with the real performances will validate the model. The third section will then show the performance results of the different scenarios where EVs are introduced and these will be compared with the base scenario. Finally, the last section will discuss the results and conclusions.

2 Simulation approaches

Operational research offers a large portfolio of techniques to assist decision making. An important technique are the simulation models. They represent real world systems through a set of rules that define their future evolution. They are particularly useful to understand how complex systems behave over time. For example, different conditions can be tested through a “what if” analysis in order to predict the performances on the system. This way, simulation models allow to optimize systems before their implementation.

When modelling a system, the challenge is to select the appropriate approach. In this section, we first give an overview of the three major paradigms in simulation models: system dynamics, discrete event simulation and agent based simulation [21]. Then, we discuss the state of the art of these paradigms used in logistics with a focus on urban distribution centres. Finally, the most appropriate technique is selected.

2.1 The three paradigms in simulation models

Discrete event simulation (DES) has been used since the very beginning of operational research in the 1950’s [22]. This approach is based on the concept of *entities* flowing across a system. Once an entity has entered the system, it travels through different steps representing the processes of the system before leaving [23]. The sequence of steps is typically pictured in a flowchart that conceptualises the system. Each one of these steps is a discrete point in time or *event* that changes the value of the entity. As a result, DES is considered as a global entity processing algorithm [21]. Stochastic behaviour can be introduced in the algorithms.

An important concept in DES models is queuing. Each event is described by its resources, its capacity or its efficiency. The rules of the system are concentrated on the events. On the contrary,

the entities are passive elements of the system. They are pushed across the flowchart. This implies that when an entity goes to the next step which is saturated, the entity will wait in a queue until it is his turn. This way, DES can discover the bottlenecks and evaluate which measures are the most efficient.

System dynamics (SD) is characterised by a higher degree of abstraction than DES. Forrester (1958) defined SD as “*the study of information-feedback characteristics of industrial activity to show how organisational structure, amplification, and time delays interact to influence the success of the enterprise*”. At first, system dynamics was applied to industrial processes, but it has then evolved to policy analysis.

Three elements are essential to characterise SD. First, the organisational structure of the system is based on a set of *stocks*. They represent the basic elements of SD like the entities in DES but their level of detail is less important. Second, the level of the stocks changes according to the *flows*. They link the different stocks in a network and their capacity is assessed. Finally, *delays* define the rapidity by which flows influence the stocks. System dynamics can hence be described as a network of stocks where a number of interacting feedback loops increases or decreases the stocks of the system [21].

However, SD is a deterministic model by nature and cannot integrate stochastic elements. Each simulation will therefore give the same results [23].

Agent based simulation (ABS) is a more recent approach which is gaining interest in operational research [25]. The main difference ABS brings compared to the traditional approaches of DES and SD is the decentralisation of the model [26]. In DES and SD, the system and the interactions are modelled first and then the behaviour of the elements within the model is observed. In ABS, it is the way around: the behaviour of the elements, called agents, is first modelled and then their interactions are observed. The goal of the modeller is to describe the process from the point of view of the agents. ABS relies on autonomous agents which follow a set of predefined rules corresponding to their own objectives [27]. In contrast with DES, the agents in ABS are active and not passive. Once the simulation of the model has been run, the global behaviour of the system emerges as a result of the interactions between many individuals [21]. Hence, ABS can be characterised as a bottom-up

approach, whereas DES and SD would be top-down.

ABS is particularly useful when there is little knowledge about the global interdependencies [21]. It is also considered to better address the modelling of complex structures and dynamics where lots of agents are involved [21]. On the opposite, agent based modelling can be harder to develop.

2.2 State of the art of DES, ABS and SD in logistics

In logistics and supply chain management issues, the traditional modelling approaches used for decision support tools are SD and DES [28]. Often, SD is considered more appropriate for modelling logistics problems at a strategic level that requires a high degree of abstraction. It can be used to understand the effects of freight policies considering the complex interactions among stakeholders [29]. Controversially, DES is better suited for operational/tactical levels because it models individual objects with a high degree of details. Tako & Robinson (2012) confirm that trend by conducting a literature review on the different applications of DES and SD in logistics and supply chain management issues. System dynamics and discrete event simulations can therefore be considered as complementary modelling approaches. Based on this observation, some hybrid simulation approaches have been developed by combining DES and SD [30,31]. They were particularly used for modelling supply chains. Nevertheless, these models remain marginal since they represent only 3% of the publications reviewed. DES remains the most popular approach in logistics and supply chain management issues with 68% against 30% for SD [28].

Besides the traditional approach, ABS receives an increasing attention in logistics. Because it addresses both tactical/operational and strategic levels and can therefore combine the micro and macro environments in one integrated model, it is expected that agent based modelling will overthrow the two traditional approaches [25]. Closely related to the topic of this paper, we can mention the paper of Van Duin *et al.*, (2012) who used ABS for evaluating the performances of an urban distribution centre. The approach considers the urban distribution centre as an agent in order to see how it interacts with the other agents (freight carriers, truck drivers, retailers and municipality). ABS is indeed suited to understand the behaviour of stakeholders in UFT systems and simulate their

response to policy measures [29]. Many other initiatives aiming at solving urban freight transport problems were evaluated with ABS [27,32–35]. However, tactical/operational applications of ABS are less common in logistics. The absence of the queuing concept in ABS might be the reason for it being less applied for operational problems.

2.3 Selection of the best methodology

Given the research question of the paper on the evaluation of the introduction of electric vehicles in a UDC system, the model needs to describe how the logistic activities are organised within the centre. This is a purely operational problem which can only be enabled by ABS and DES.

There are few publications on modelling UDC to support the selection of ABS or DES [36]. However, UDC operations can be assimilated to terminal systems [37]. Even though ABS has been used to model this kind of systems [38,39], DES is the most relevant approach [40]. This can be explained by different advantages DES offers:

- The goal of DES is to find the optimal configuration of a system [41] whereas ABS is better to observe emergent pattern from a simulated scenario. In complex logistics system such as terminals or distribution centers, DES is more appropriate since the goal is to detect facility layout problems or bottlenecks of the system.
- The possibility to use the concept of queuing is unique to DES which makes it more adapted to the modeling of queues networks such as manufacturing and service industries [25].
- Finally, DES has more experience in modeling operational problems. It is indeed the most used technique in the literature for reproducing micro-logistics environments [28].

Given this advantages, DES is selected to be the most appropriate technique to model the operations of an urban distribution centre.

3 Methodology

In order to use adequately the DES approach, the paper will use the 8 step plan methodology developed by Manuj, Mentzer, & Bowers (2009). The first 5 steps are presented in the methodology section and the 3 last steps are presented in the results section.

3.1 Problem definition

As described in the introduction, the objective of the paper is to investigate the impact of electric vehicles on the performances of a UDC. To model these operations in a DES, the case of the CityDepot in Hasselt is used. Based on the model, the research question that needs to be addressed is the following: What is the impact of electric vehicles on the performances of an urban distribution centre? What is the difference on performances if using electric vehicles or conventional vehicle?

3.2 Variables definition

In order to model the system of an UDC, the different variables of that system need to be identified. Based on the observation of the CityDepot operations, the following groups of variables were identified:

- **Staff characteristics:** the number of people working, their schedule and their availability;
- **Infrastructure characteristics:** the space available for cross-docking and stock operations;
- **Vehicles characteristics:** the number of vehicles, the resources needed to operate them and their availability;
- **The demand characteristics:** the frequency of trucks arriving in the centre, the quantity of freight being delivered and their nature (small volumes or large volumes).

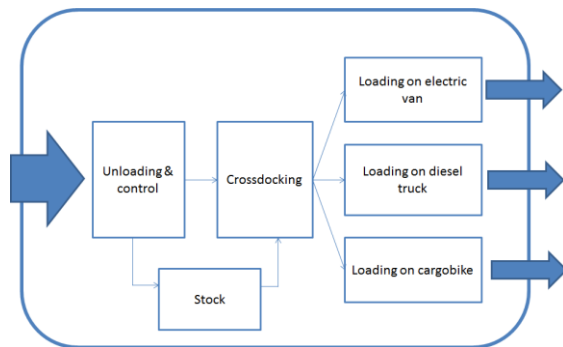
Based on the defined objective of the model, the dependent and independent variables have to be selected. Since this paper aims at investigating the differences of performance when changing the vehicle fleet, the dependent variables will be vehicles characteristics. The other variables will be independent and will describe the parameters of the system.

3.3 Conceptual model building

In order to show how the different variables interact within the system, a general flowchart was drawn. Figure 1 shows the organisation of the system. First, the parcels are unloaded from the truck and are controlled: the supplier and the responsible of the centre exchange a receipt as a proof that the parcel was transferred. Then, the responsible of the centre places the parcels either in stock or on the cross-docking platform. If the parcel goes in the stock, it will go in the cross-

docking later, when the parcel will be asked by the customer. Next, a decision is made to transport the parcel either via a cargo bike, a diesel truck or an electric van. Finally, the parcels are loaded on the different vehicles and the parcels quit the distribution centre for their deliveries.

Figure 1: General flowchart of the operations in the CityDepot



The centre receives parcels between 8h and 12h00. Afterwards, parcels can be delivered at the centre but on demand. For the simplicity of the model, parcels are assumed to arrive only between 8h00 and 12h00.

3.4 Data collection

To estimate the parameters of the system, data were collected based on two days of observations at the centre on the 28th of June and the 9th of July 2013.

3.5 Computerized model building

By using the ARENA software (version 14), the conceptual model is computerized with the associated parameters estimated with the data collection. The simulation is run during 120 hours which represents the five working days of the week.

4 Results

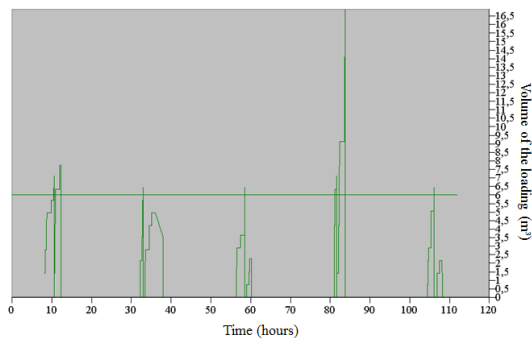
Based on the developed model, the three last steps of the methodology developed by Manuj et al. (2009) are presented in this section. First, the base scenario will be simulated in order to validate the model by comparing the results with the real operations. Then, the simulation of the different scenarios implementing electric vehicles in the centre will be tested. Finally, the discussion will comment these results.

4.1 Model validation

Before using the model for the purpose of the paper, the current operations of the centre are simulated and the results are compared with the real observations in order to test the accuracy of the output of the model.

Figure 2 shows the evolution of the loadings for the truck during the simulated week: once the loading of the truck is ready for the delivery (the volume reaches the horizontal line or it is the end of the day), the queue for the next loading drops back to zero. The number of deliveries is therefore depicted by the number of peaks. Figure 2 shows therefore that the truck makes two deliveries per day. The results of the simulation are similar to our observations since the truck was used each time twice a day starting around 10 o'clock.

Figure 2: Evolution on one week of the loadings of the truck in base scenario



The cargo bike and the electric van were observed to be used once a day around noon. However, employees informed us that sometimes only one of them is used. These observations are confirmed by the results of the simulation shown in Figure 3 and Figure 4. Indeed, they are both used every day, once a day. However, Figure 3 shows that the loading of the cargo bike has such a small volume on Wednesday that, in the real world, the parcels would have been transferred into the electric van that has some remaining capacity available (total capacity of 4,5m³), saving an unnecessary trip. Therefore, the cargo bike would not have been used that day which confirms the possible exceptions. It is true in the other directions: the volume of the electric van on Friday could be transferred to the cargo bike.

Figure 3: Evolution on one week of the loadings of the cargo bike in base scenario

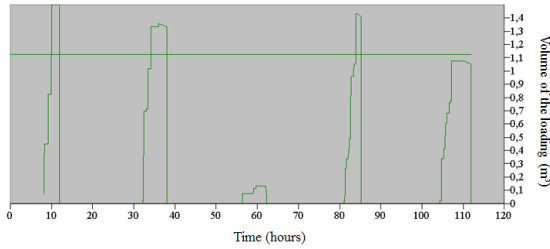
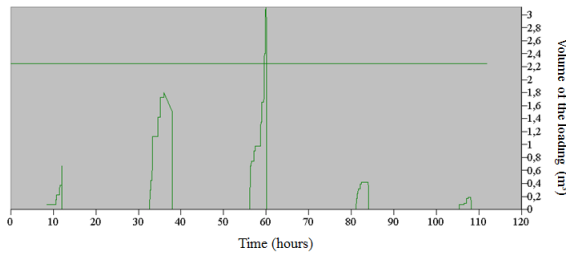


Figure 4: Evolution on one week of the loadings of the electric van in base scenario



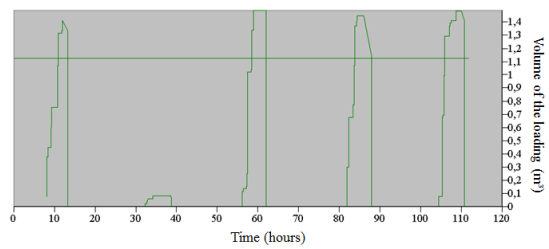
As the results of the base scenario correspond to the observations, the model can be validated and the impact of introducing another electric vehicle in the UDC of Hasselt can be simulated.

4.2 Simulation

Different options are available to introduce EVs in the centre. Since the cargo bike and the electric van are already used in the centre, no change will be simulated on these two vehicles. Our interest is on changing the 16m³ diesel truck into an electric vehicle and on the evaluation of their impact on the UDC performances.

As electric vehicles with a payload below one tonne are recognised to be competitive with diesel vehicles, the first simulation tests the replacement of one diesel truck by another electric van of 4,5m³ loading capacity. The results of the simulation shown in Figure 5 illustrate that no major changes are seen on the cargo bike: it is also used almost once a day since the small volume of Tuesday would be probably transferred on the electric vans.

Figure 5: Evolution on one week of the loadings of the cargo bike in scenario 1



However, Figure 6 and Figure 7 show that the change of the diesel truck into an electric van also impacts the operations of the original electric van. Because the new electric van has a more limited payload than the truck, both electric vans are used more intensively and generate more trips: the two electric vehicles achieve 28 trips per week compared to the 16 trips achieved by the electric vehicle and the truck in the base scenario. It is important to stress that a slight increase of the demand will show that the centre is almost saturated under this scenario. Additional vehicles and human resources would be needed given the limited payload of the electric vans.

Figure 6: Evolution on one week of the loadings of the original electric van in scenario 1

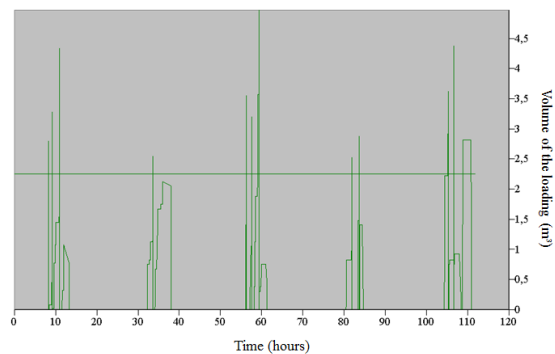
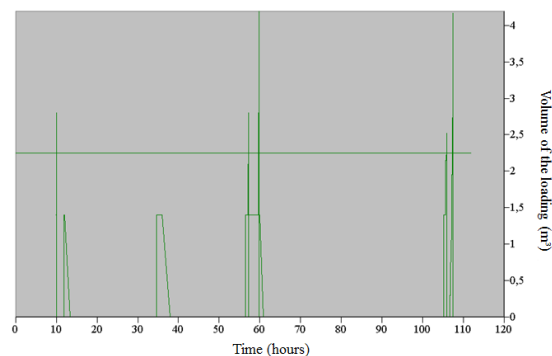


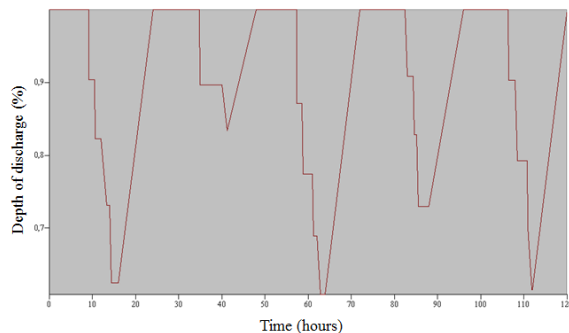
Figure 7: Evolution on one week of the loadings of the replacing electric van in scenario 1



Because the electric vans are used more intensively, it is interesting to see the impact on the

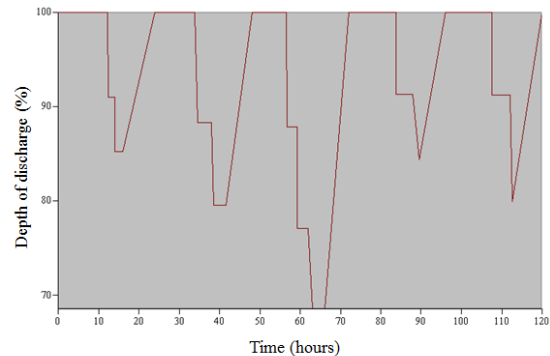
battery in order to see if specific charging schemes are needed to keep the electric vans productive. Knowing that distance of the delivery turns have a minimum of 5 kilometres, a maximum of 15 and a mean of 10, Figure 8 shows the evolution of the battery capacity of the original electric van which is the most intensively used. It assumes that the vehicle is charged at night and that range is limited to 100km. The results highlight that, even though the vehicle is used at full capacity, the electric van would not need to be charged during the day. Indeed, the depth of discharge of the battery does not fall under 60%.

Figure 8: Evolution on one week of the depth of discharge of the original electric van



An alternative scenario is to simulate the substitution of the diesel truck by an electric. The results show that the operations of the centre remain slightly the same than in the base scenario. The electric vehicle is used once a day as well as the cargo bike except for Friday. The truck operates also two deliveries per day except on Wednesday when three deliveries are achieved. However, the performances should remain similar since the loading capacity of the electric truck is the same than for the diesel and the limited range does not influence the truck since its depth of charge does not fall under 60% as shown on Figure 9. As a result, the differences between the base scenario and scenario 2 are attributed to the variability of the demand generated by the simulation.

Figure 9: Evolution on one week of the depth of discharge of the electric truck



4.3 Analysis & documentation

The results of the simulation show that the difference of the UDC performances when using an electric or a conventional vehicle can be summarised by a trade-off: either the diesel truck is replaced by an electric van which is competitive but entails the centre with more delivery turns (scenario 1), either the diesel truck is replaced by an electric truck which keeps the same performances than the diesel truck but is uncertain from costs aspects (scenario 2).

In the first case, replacing a diesel truck by an electric van might be a financially attractive solution according Lebeau, *et al.* (2012). But the more limited payload of the van doubles almost the number of delivery turns. Browne *et al.*, (2011) already noticed an increasing traffic due to the use of electric vehicles in a demonstration in London. Hence, introducing electric vans in urban distribution centre might not be the optimal solution as the objective of a UDC is to rationalise and group the deliveries. Introducing electric vans should be more interesting for transport operators using conventional vans. Their performances would not be affected due to equivalent constraints on the payload and the financial situation would be improved.

In the second case, replacing a diesel truck by an electric truck does not influence the performances of the centre. The capacity of the battery is big enough to ensure the daily operations. For this reason, no additional charging schemes were investigated since they are not needed. However, the costs of an electric truck remain uncertain. As a result, electric trucks do not satisfy the price performance ratio of conventional trucks. Logistics performances are similar but the costs make today the electric alternative not competitive. Though, the situation could change in the future. Costs of batteries are expected to lower in the next years

[43], which could improve the price performance ratio. Moreover, the results show that the depth of discharge is particularly limited when using a truck in a UDC, ensuring a higher lifetime for the batteries [44] and resulting decreased costs.

5 Conclusions

The paper evaluated the difference of performances of an urban distribution centre using a conventional truck and an electric vehicle. It simulated two scenarios: the first one simulated the replacement of the truck by an electric van and the second scenario simulated the replacement of the truck by an electric truck. The results of the first scenario showed that the limited loading capacity of the van compared to the truck generated more traffic than the base scenario. However, it is interesting to notice that no special infrastructure needs to be introduced to support the limited range of the batteries since their capacity are enough to operate daily operations on a single night charge.

The results of the second scenario showed that the electrification of the truck does not have an influence on the logistics performance. The capacity of the battery is again sufficient for daily operations and the loading of the truck obey to the same constraints than the conventional truck.

Interesting future research can link the costs aspects to the operational aspects in order to assess more precisely the price performance ratio. Indeed, the paper showed that the limited depth of discharge is directly linked to the operations of the electric vehicle. However, Omar (2012) showed that depth of discharge influences the costs since a limited depth of discharge improve the lifetime of the battery, decreasing significantly the costs of the electric vehicle. Other operational aspects were recognised to influence the batteries like temperature and the charging method. Integrating the different dimensions would give a more comprehensive situation of electric vehicles in logistics.

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