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Abstract: Public authorities have been issuing strict measures to decrease the pollutant emissions over the last years. Thus, hybrid and electric vehicles are more and more attracting the attention of the automotive industry. In such a context, batteries are the key elements for the propulsion of these vehicles. Therefore, the related Supply Chain (SC) appears to be crucial and many studies focus their attention on it. This SC has to be examined thoroughly due to the concentration of raw materials in limited areas, and the transportation and storage conditions that have to maintain the initial performance. In this field, there is a lack of studies considering the SC organization from battery manufacturers to car makers. In order to contribute to such a stream of research, the proposed paper presents a case study aimed at defining a suitable battery SC configuration to produce a hybrid vehicle. In particular, the purpose of the study is the assessment of the SC operations for batteries to ensure that the process is effective and efficient. In order to achieve this objective, four scenarios are defined to represent possible logistics flows from the battery supplier to the car assembly line, differing in battery warehouse location. For every scenario the main logistics cost are considered under different demand levels for identifying the most effective one. The results show that the configuration with a direct shipment from supplier to plant without a halfway warehouse is the best solution in terms of cost, even if the risk of supply increases. The proposed study could support automotive companies to design their SC through the implementation of efficient solutions, by taking into account the logistics inbound costs. The development of this case study might encourage future research to highlight the importance of the SC for low impact vehicles.

Keywords: low-impact vehicles, supply chain, battery, warehouses, car maker

1. Introduction

Concerns for environmental issues have been recently growing and they are changing the way consumers perceive low impact vehicles (Chowdhury, Salam and Tay, 2016; Nilsson, Sternberg and Klaas-Wissing, 2017). The market share of such kinds of vehicles is still limited but the situation is expected to change in the next years, as they are going to pave the way for cleaner technologies in transportation (Al-Alawi and Bradley, 2013; Glock and Kim, 2015). In fact, these low impact vehicles driven by energy stored in batteries play an important role in sustainable development with reduced greenhouse emissions from the transportation sector, less air pollution for citizens, and new job opportunities with positive social impacts (Günther, Kannegiesser and Autenrieb, 2015). As a consequence of battery and automotive technology improvements over the last two decades, the new generations of electric and hybrid vehicles are likely to become more and more a suitable choice around the globe (Wilberforce et al., 2017). Electric cars just relying on batteries as a source of power typically have a limited range of 30-50 miles only. On the contrary, hybrid vehicles are designed to use both an electric engine and a traditional internal combustion one. This configuration allows vehicles to travel longer distances compared with the pure electric ones.

Thus, for electric and hybrid vehicles batteries are key elements since they are responsible for giving power to wheels. Furthermore, they are the *de facto* cost-determining component of these vehicles (Nykvist and Nilsson, 2015). Additionally, there are a number of issues contributing to define battery relevance. First, raw materials for producing batteries are concentrated in limited areas around the world, which brings supply reduction, concentration, and political risks (Helbig et al., 2018). Second, batteries are particularly sensitive to external conditions and they can easily lose their designed performance (Kouchachvili, Yaïci and Entchev, 2018). Finally, due to their components, which are likely to negatively impact pollution, batteries need a careful end of life management. Therefore, for such items the related supply chain (SC) assumes a crucial importance (Jaffe, 2017) since it requires appropriate transportation and storage conditions.

On the one hand, the organization of the SC for producing electric and hybrid vehicles is still poorly studied by literature. In fact, the available works are usually just focused on the diffusion of low impact vehicles and their production strategies (Gu, Liu, and

Qing, 2017). On the other hand, contributions about the SC of vehicle propulsion batteries are mainly addressed to raw material procurement, manufacturing, storage, transportation, and reverse logistics (Ciez and Whitacre, 2017; Li, Dababneh and Zhao, 2018; Pelletier et al., 2017). In such a context, still few papers explore the procurement phase of those components that largely influence the successful production of low impact vehicles. In particular, the logistics network underpinning traction batteries on their way from manufacturers to car makers and the choice of the location of the associated warehouses (Hamidi et al., 2017) deserve further attention. With the aim of bridging this research gap, the present paper addresses the selection of the most efficient logistics configuration to deliver batteries from a supplier to the manufacturing lines of a European car maker. In particular, the analysis focuses on the best organization of the transportation of finished batteries from the battery supplier to the car manufacturer plant that can be considered the last part of a battery SC within the new automotive hybrid and electric vehicle SC. To this end, a case study is analysed: based on the characteristics of the production and logistics network of the focus company, several scenarios are developed and assessed in order to find the best location of warehouses and buffer areas involved in the procurement of batteries for a hybrid car model. The primary objective is to provide a contribution for enhancing literature on logistics systems associated with low impact vehicle production. To this end the authors aim to support both researchers and practitioners in designing suitable logistics networks for battery procurement by vehicle manufacturers.

The paper is structured as follows. First, an overview of the existing literature on the topic is carried out. Second, the research methodology and different scenarios description are defined. Then, results are presented and discussed. Finally, implications and conclusions are drawn.

2. Literature Review

SCs of electric and hybrid vehicles are significantly different from the SCs for the production of diesel and petrol cars (Schaltegger and Burritt, 2014). Although they share with conventional vehicles many components in the bill of material, the electrified powertrain system poses peculiar issues such as a relevant increase in the manufacturing costs, which reflects in the vehicle selling price (Heinicke and Wagenhaus, 2015), a complex traction battery procurement process as well as end of life management. Unlike the SC of traditional vehicles, which has been studied for several decades, the electric/hybrid vehicle production SC is currently investigated in a very limited way. In fact, most of the works address the adoption dynamics of such vehicles together with the associated benefits and marketing mechanisms (Cagliano et al., 2017a; Hagman et al., 2016), thus focusing on the last SC part after the vehicle has been completed. By looking at the upstream portion of the SC, one relevant topic is production strategy, which is key in order to foster a quick diffusion of electric and hybrid vehicles. At the other end of the spectrum, battery recycling is a quite well discussed topic regarding the downstream SC. Among the different authors, such an aspect is for instance considered by Gu and others (2017), who prove that an increased battery recycling rate promotes optimal production volume.

Lithium-ion batteries (LIBs) are currently the most popular type of batteries used in electric and hybrid vehicles (Dinger et al., 2010). However, the growing market for low impact vehicle traction batteries brings a number of economic and environmental concerns related to their production and disposing. First of all, LIB costs are too high and should be reduced by at least one third to effectively support electric vehicle adoption. Second, their in-vehicle useful life is about 8 years implying a significant value loss and waste from spent batteries. Finally, LIB production accounts for approximately 13% of energy consumption and 20% of greenhouse gas emissions of an electric vehicle (Li, Dababneh and Zhao, 2018).

All what discussed so far asks for an efficient battery SC, whose management becomes even more difficult given the relevant growth rates (Jaffe, 2017). One crucial factor for the battery SC is that raw materials come from a limited number of areas in the world, mainly located in China, Australia, Congo, South Africa, and Philippines (Ciez and Whitacre, 2017). Consequently, the SC can be long and complex, especially for European manufacturers. In fact, due to the proved SC complexity, car makers prefer to buy complete batteries from suppliers rather than producing them in-house. This is also driven by the fact that most of the car manufacturing companies are mainly skilled at vehicles with a conventional powertrain system (Christensen et al., 2012) and have a low level of expertise associated with batteries, mainly related to their assembly (Golembiewski et al., 2015). Battery SCs need to be carefully designed and managed also because a number of product characteristics that require specific transportation and storage conditions. In particular, extreme temperatures (both high and low) can jeopardize the battery performance. (Pelletier et al., 2017; Dinger et al., 2010). As well as, humidity needs to be controlled because it can cause condensation inside the battery pack and in turn it can negatively impact the overall quality (Richter et al., 2017). As a consequence, battery warehouses should be appropriately equipped with controlled temperature and humidity systems, which however imply high electricity consumption with a consequent increase in energy costs (Li, et al., 2017). Finally, the increasing development of low impact vehicles has triggered a number of contributions on managing the end of life of propulsion batteries and on the economic and environmental analysis of their recycling (Gu et al., 2018; Hao et al., 2017; Hendrickson et al., 2015; Tagliaferri et al., 2016).

The performed literature review reveals that the research on electric/hybrid vehicle production SCs is mainly focused on manufacturing strategies while additional fundamental issues should be addressed in order to make them effective and feasible (Egbue and Long, 2012). In particular, there is a lack of studies about the procurement of the crucial components differentiating low impact from conventional vehicles. Among them, as previously discussed, traction batteries play a significant role because they represent the most influent cost factor in the production of electric and hybrid vehicles. Nevertheless, the available literature addresses battery production and recycling and tackles storage and transportation just for what concerns the associated requirements. To be more precise, the design of that portion of the vehicle propulsion battery SC related to the transportation and storage processes between manufacturers and car makers is largely ignored. However, it is heavily influenced by the aforementioned constraints about supplier concentration and keeping conditions, which play a significant role in ensuring battery availability and determining the associated SC costs.

In order to contribute to fill the identified research gap, this work develops a case study about the selection of the most efficient logistics network configuration in order to deliver complete LIBs ready to be integrated into vehicles. The route from a supplier to the manufacturing lines of a European vehicle manufacturer producing hybrid cars is considered.

3. Methodology and scenarios definition

The research has followed the following steps. First, the main available logistics network solutions for traditional vehicle components have been analysed in order to obtain the scenarios about the configuration of the SC for traction batteries bought by the case company based on its requirements. Group meetings have helped for the localization of the battery warehouse (hereinafter called Advanced Warehouse because it is addressed to stock with appropriate equipment the traction batteries for vehicles), the potential adoption of an additional storage area as a buffer inside the production area, and the scenario development. According to literature review and company experience, the main costs have been identified to compute the unit battery SC cost calculated as the sum of the following cost items (Izdebski et al., 2016; Golda, 2013) over the volume of batteries to be purchased:

- Material handling cost has been computed as: *Material handling cost = number of towing tractors * unit rental cost of towing tractors + number of forklifts * unit rental cost of forklifts*
- Labour cost has been calculated as: *Labour cost = number of worked hours * hourly HR* cost
- Transportation cost has been computed, according to the maximum capacity of a truck that is equal to 56 batteries, as: *Transportation cost = cost per km for one truck * distance* (from the battery supplier to the Advanced Warehouse/manufacturing plant or from the Advanced Warehouse to the plant).
- Warehouse operations and renting costs for the facility are defined by an external service provider and they are the same for all the scenarios.

Therefore, the objective of logistics network structure design is the minimization of the SC cost arising for a certain volume of demanded products (Jacyna-Golda and Izdebski, 2017). In particular, the material handling cost results as the sum of the forklifts and the towing tractors used inside the stock and manufacturing areas. The company has decided to rent this material handling equipment, due to its relevant market price (Renquist, Dickman and Bradley, 2012; Bouh and Riopel, 2015; Arnaiz et al., 2016). In addition, the leasing strategy enables companies to carry lower costs since there is an external actor in charge of maintaining and replacing the equipment (Stryja et al., 2015). Furthermore, the human resource cost associated with battery handling and storage has to be taken into account. Another important cost is related to transportation that significantly influences the logistics network structure (Santosa and Kresna, 2015). Warehouse operations and renting costs complete the cost analysis; they depend on the size of the rented warehouse area (Fan and Wang, 2018). Once the all cost elements have been considered, the unit battery SC costs have been computed for every scenario considering a broad range of production volumes. The following step involves the scenario definition aimed at describing a suitable configuration for the storage and transportation of traction batteries. Four scenarios have been designed and examined as reported in Figure 1. These scenarios have been defined through group meetings with employees from the focus company, according to the current organization of its SC. The supplier has already been identified about 2,000 km far from the production plant, due to its high level of know-how in battery manufacturing. Additionally, in the car maker area there are no traction battery production plants. As well as, the presence of the Advanced Warehouse between the supplier and the production facility has been discussed.

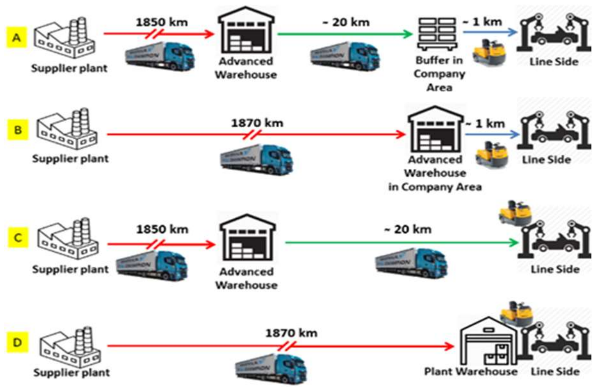

Figure 1: Scenario definition

The identified scenarios are described as a way of understanding the main features of each of them. It is worth highlighting that, according to the logistics organization characterising the case study, all the following four scenarios are based on full truck-load shipments. Additionally, the same kind of truck, with a maximum carrying capacity of 56 batteries, is used for both the route from the supplier to the Advanced Warehouse and the route from the warehouse to the facility hosting production lines.

Scenario A is designed to locate the Advanced Warehouse 20 km far from the production plant. A full truck-load brings batteries for a distance of 1,850 km from the battery supplier to the Warehouse. The traction batteries are stocked inside the Advanced Warehouse. The buffer for feeding the car manufacturing facility is replenished by trucks from the Advanced Warehouse. The batteries are then picked up by the towing tractors to the line side. When a container becomes empty, it is moved back to the buffer area and finally the empty ones are loaded on a truck headed to the Advanced Warehouse. The stock-out or shortage risk is mitigated by the presence of the buffer close to the assembly line and of the warehouse that can guarantee a certain amount of stock near to the production site.

The Advanced Warehouse in scenario B is inside the company area. Therefore, the distance between the Advanced Warehouse and the assembly line decreases from 20 km to 500 meters. A full truck-load is unloaded when it arrives at the warehouse, then batteries are loaded on towing tractors and delivered to the assembly plant. The empty containers follow the same path from the assembly line to the Warehouse as in scenario A.

Scenario C is comparable to the scenario A with the exception for the presence of an intermediate buffer. The Advanced Warehouse is 20 km far from the production area where batteries are sent to the production line by trucks. When the shipment arrives at the manufacturing plant, towing tractors are immediately loaded to feed the assembly area. The return flows are similar to those discussed in the previous scenarios. This configuration requires more trips as a way of avoiding stock-outs due to the limited number of batteries that can be stocked next to the line.

In scenario D the Advanced Warehouse is located inside the assembly line facility and it directly receives the batteries from the supplier, after their unloading from the trucks. The towing tractors deliver the batteries to the production site and return the empty containers. In this scenario there is no available space next to the manufacturing plant for locating the Advanced Warehouse, thus the facility is integrated in the assembly line only 50 meters far.

As already mentioned, the transportation cost is an important component of the SC cost and it is computed as function of the distance (Laitila, Asikainen and Ranta, 2016; Masoud and Mason, 2016). In the case study the distance from the supplier to the Advanced Warehouse is approximately constant for all the scenarios and for this reason the associated cost is not taken into account. Such an assumption does not influence the reliability of the results of scenario analysis mainly due to two reasons. First, the distances between the battery supplier and the Advanced Warehouse are equal to 1,850 km in scenarios A and C and to 1,870 km in scenarios B and D (Figure 1), with a difference of just 1% between the two values. Second, the distance travelled from the supplier to the warehouse is not associated with an urban route where even a couple of more kilometres might significantly affect transportation conditions as a consequence of the peculiar and heterogeneous characteristics of last mile urban deliveries (e.g.: limited traffic zones, congested areas, etc.) (Cagliano et al., 2017b). On the contrary, the transportation cost from the Advanced Warehouse to the production plant is taken into account in the related scenarios.

4. Discussion of results

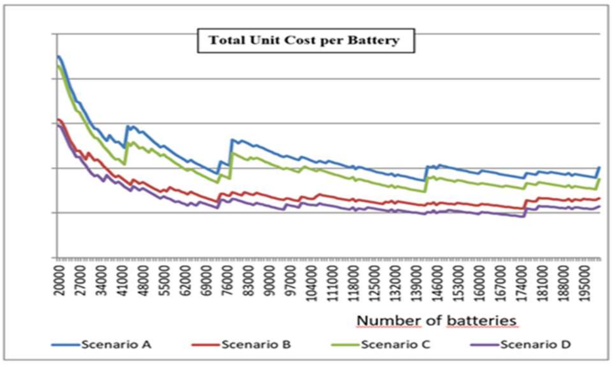

Figure 2: Unit battery SC cost

Figure 2 reports the trend of the unit battery SC cost for every scenario over different battery volumes, which are function of the number of hybrid vehicles that are planned to be yearly produced. In particular, the total cost has been computed as the sum of all the costs described in Section 3 over the total production volume of low impact vehicles. The values are not shown for confidentiality reasons. According to Figure 2, the economies of scale are confirmed by the trend of the cost curves: the higher the volumes, the lower the cost. The peaks are due to the fact that over a certain number of batteries additional equipment and workers are required for carrying out the associated operations. In addition, for all the scenarios a warehouse rent cost is considered; this facility is rented from an external logistics service provider.

In particular, scenario A shows the highest unit costs. In fact, the Advanced Warehouse is 20 km away from the plant with an increasing number of trips. Consequently, this first scenario is affected by the cost of truck shipment (each shipment requires approximately 40 minutes to be carried out). Concerning towing tractors, they are loaded in the buffer area, thus the operation is easier and quicker than in the other configurations. Moreover, in scenario A the buffer storage and Advanced Warehouse have to be taken into account with an increasing cost for operations due to the required number of forklifts and human resources. Overall, the human resource cost is higher than the other costs because most of the operations that has to be performed require labour force.

Scenario C has the same cost of the previous one for forklifts and truck shipment due to the similar logistics configuration. However, this scenario is the cheapest one for the unit cost of towing tractors. In fact, the waiting time of towing tractors at the gate depends on the forklift that enters the container located on the truck and exits with the unit load. Being this operation very quick the associated costs are lower than those of the other scenarios. Thus, scenario C is cheaper than A because trucks are headed from the Advanced Warehouse directly to the car manufacturer without the intermediate buffer in the production area. The presence of a separated Advanced Warehouse 20 km from the plant makes the considered scenario less suitable than B.

In scenario B, the Advanced Warehouse is next to the car line. Consequently, the number of forklifts is lower. On the contrary, towing tractors are loaded by forklifts with significant waiting times and an increasing cost compared to scenario A. The required human resources are less than in scenario A since batteries from the supplier are unloaded closer to the line. For this option there are some problems related to space availability: in fact, to implement this solution, the company has to redesign the current plant in order to build the new facility, since the space for the warehouse has not been established yet.

Finally, scenario D is the cheapest one because it is designed with a direct flow between the supplier and the vehicle production site. This is due to the fact that there is no Advanced Warehouse and consequently a smaller number of handling activities has to be performed. Specifically, forklift and towing tractor costs are significantly reduced by such a logistics configuration, as the human resource cost. However, the battery manufacturer is located 2,000 km far away from the car maker plant and this makes scenario D the riskiest in terms of supply. As a matter of fact, in case of unforeseeable events the provision to plant could be interrupted.

Therefore, based on the obtained results, the SC can be simplified in its last part. In fact, additional battery handling activities can be avoided with a consequent decrease in term of costs and complexity. Scenario B and C streamline the SC due to a reduced number of activities required and associated lower costs than in scenario A. However, by taking into account complexity reduction, the best scenario is D because only a small warehouse is planned near the production line. The company will further analyse scenario D in order to reduce the associated procurement risk, so that it will be actually possible to adopt such a SC structure. Anyway, this risk can be accepted by the company in the production start-up phase because the expected low production volumes will lead to significantly lower SC costs than in the other investigated scenarios.

5. Implications and conclusions

This research addresses the low impact vehicle SC and, in particular, the portion intersecting with the traction battery SC, being such a component key for electric and hybrid vehicles. The study focuses on different ways to purchase and delivery finished batteries that will be integrated in low impact vehicles. Based on the achieved results, an organization without any intermediate nodes appears to be the cheapest one. However, the solution based on Advanced Warehouse covers the risk of supply because a certain amount of stock is always available. The proposed research can be considered as a novel point of view via the analysis of several approaches for battery procurement.

This study has some implications. From a practical point of view, the present contribution might help car makers to define and evaluate different SC configurations for introducing low impact vehicles in their product portfolios or for improving their current traction battery SC. In addition, a method to calculate the battery unit cost is provided to companies that wish to develop economic and financial analyses in order to perform studies on the subject.

From a theorical point of view, this work can encourage research about the SCs for low impact vehicles and their components, that over the next years are going to become crucial in the future forms of mobility (Al-Alawi and Bradley, 2013). The research defines a preliminary methodology in order to provide the most efficient solution among different viable logistics configurations connecting battery manufacturer and car maker plants. Another important support for studies is the coordination among different stakeholders in the heterogeneous and numerous phases of the production process in the electric and hybrid car industry (Chung, Elgqvist and Santhanagopalan, 2015). Finally, the present research adds new elements to existing literature (Gu, Liu and Qing, 2017; Hagman et al., 2016), by affirming how an organized logistics network is likely to positively influence the manufacturing cost and drive the company strategy.

However, this study has some limitations. First, only one vehicle type is included in the analysis. Actually, the SC complexity might significantly increase with the introduction of additional car models. Furthermore, manual operations have been considered in order to calculate the human resource time and cost without taking into account the automation that is likely to reduce the human labour in logistics operations.

Thus, further research will be aimed at defining scenarios with more than one low impact vehicle model and more automated operations inside the warehouse in order to consider the associated impacts on battery logistics activities, also when they are assisted by new technologies.

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