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Abstract

This work aims at supporting decision-making related to make or buy strategies for procuring batteries assembled on electric and hybrid vehicles for a car manufacturer that is introducing new models in its portfolio. In particular, several supply chain scenarios have been defined according to the battery architecture. The results show that the purchase of complete batteries implies the highest costs and CO_2 emissions. On the contrary, buying single components helps improving these aspects, but it requires a certain level of vertical integration by the car manufacturer together with specific know how. Finally, purchasing modules results in the lowest costs due to a reduced number of trips due to the product structure. Thus, this paper proposes a framework to guide automotive companies in effectively designing make or buy strategies in their battery supply chain by comparing alternative vertical integration levels.

Keywords: Supply Chain, Low Impact Vehicle, Vehicle Battery, Automotive, Procurement, Make or Buy, Electric Vehicle, Hybrid Vehicle, Scenario Analysis, Logistics

Introduction

Air pollution is one of the main concerns about climate changes and public health (Goswami and Tripathi, 2018; Tian and Sun, 2017) and many companies in the world have been paying special attention to environmental and climatic issues (Jiménez-Parra, 2018). In this context, in recent years a growing interest in the transportation electrification process can be observed (Özel et al., 2014) and vehicles architectures are changing with the aim of reducing the impact on the global emission levels (Cagliano et al., 2017). In particular, today hybrid and electric cars have a low market share, but they are considered one of the most promising solutions to this problem in the next future (Palm and Backman, 2017).

Low impact vehicles, in this paper intended as electric and hybrid ones, have changed the internal vehicle architecture with the introduction of some critical components such as electric engines and battery packs which are analysed by mainstream literature in order to decrease their production cost and improve their environmental performance (Gao et al., 2019; Sabri et al., 2016). In fact, one of the key success factors for vehicles diffusion is the cost reduction of battery packs (Kalaitzi et al., 2019). Thus, the battery pack supply chain (SC) structure and the associated management are among the main determinants of procurement and manufacturing cost reduction (Rafele et al., 2019) and as such they play a significant role in promoting the diffusion of electric and hybrid vehicles (Hache et al., 2019). Different competencies are involved in the product development and a collaborative approach among the actors along the SC is fundamental for effectively and efficiently designing a complex, valuable and strategic product as a battery pack (Masiero et al., 2017). In this context, manufacturing strategies are becoming crucial in addressing the future market evolution and the level of competition in the sector under study. (Huth et al, 2015). Coming to low impact vehicle batteries, few authors have addressed this topic by developing assessments of the SC implications of different procurement as well as manufacturing strategies, without offering a quantitative methodology to guide the decision of whether internally produce or purchase such components (Huth et al., 2013; Huth et al., 2015; Özel et al,2013). In order to contribute to the still narrow state of the art about this topic, the present paper puts forward an approach to analyze the impacts of alternative procurement plans for battery packs. In general, this issue, which is related to make or buy choices, can be addressed from different points of view related to the market, the available technologies, manufacturing approaches, necessary skills, and logistics issues (Kwak and Whang, 2008; Sardim et al., 2015). Such aspects ultimately impact on costs. The present study takes a transportation logistics perspective by proposing a novel approach facilitating procurement decisions whose effectiveness has been proven by applying it to a primary car maker that is currently addressing the introduction of electric and hybrid car models in its product portfolio and the associated battery SC problems. In particular, the authors investigate the SC organizational and economic impacts of battery procurement decisions, from suppliers to vehicle manufacturing plants and how to choose the most efficient and effective solution.

The paper is structured as follows. First, a literature review on the main topics framing the present research is performed. Second, the methodology is outlined. Third, the developed scenarios are presented and their analysis is carried out. Then, results are discussed and finally implications and conclusions are traced.

Literature Review

The present research analyses different procurement options for the SC of batteries to be mounted on low impact vehicles. Thus, a literature review on such a SC with particular emphasis on supply and manufacturing strategies is carried out in the next sections.

Overview of the supply chain for low impact vehicle batteries

Lithium-ion batteries have been gradually developing as the dominant design in the low-impact vehicles architecture (Chen et al., 2018; Nazri, 2002). This product can be divided into three main components: cells, modules, and pack cells, constituted by cathode, anode and electrolytes, are the electric units that provide the energy to the vehicle. They are assembled with different configurations (series or parallel) into modules to obtain the required power.

This production process requires a SC structured as follows. First of all, lithium and other critical metals such as cobalt and manganese are extracted. One of the crucial issues is the limited and concentrated presence of raw materials in few areas of the world such as Australia, Congo, South Africa and China (Ciez and Whitecre, 2017). Afterwards, the raw materials are processed to produce the component of the battery (*e.g.* cathode, anode and electrolyte to obtain the cells) (Yoshio, 2009). Other structural and functional components are manufactured by specialized companies (Saw et al, 2016). Finally, battery packs are assembled starting from the previously mentioned elements and integrated in the vehicles. Cell components are currently produced near the extraction sites, then shipped to lithium-ion batteries producers and finally to car companies.

The structure of the lithium-ion battery SC as well as the geographical concentration of its main actors pose relevant challenges to vehicle manufacturers from a procurement point of view. The availability of raw materials in limited areas of the globe, together with the concentration of battery suppliers in certain countries, mainly located in the Far East (Mayyas et al., 2018), expose vehicle makers to relevant procurement and logistics risks, including supplier lock-in and disruption (Sun et al., 2019).

Such battery SC issues add to those brought by the so called “green automotive revolution”, which has implied a significant shift from the traditional automotive competences, more based on mechanics, to electric and electronic ones. As a consequence, the coordination of different classic and innovative automotive competences, held by multiple SC actors (Feyissa et al., 2019), has emerged as a crucial topic in recent years. The ultimate goal of such an integration is being able to exploit economies of scale and learning economies during the development of new automotive products.

Thus, the need for investigating the SC of batteries for low impact vehicles from both the procurement and the manufacturing points of view emerges from what discussed so far.

Procurement and manufacturing decisions in the low impact vehicle battery supply chain

Generally speaking, procurement in the automotive sector has been mainly addressed by literature from the perspective of make or buy decisions related to the different vehicle components. In fact, one of the main advantages for a car maker of buying components from suppliers is flexibility: the company can easily modify or convert its production process due to the absence of high sunk costs. Moreover, it can focus only on the core competencies in order to gain a significant competitive advantage. On the contrary, outsourced production introduces a growing need for quality control and a potential loss of know-how (Kwak and Whang 2008; Sardim et al., 2015).

When coming to procurement decisions about low impact vehicle batteries, the topic is usually tackled by analyzing the value added by the different operations along the entire chain, namely component cell production, cell production, module production and pack assembly, and the final vehicle integration. These steps increase the battery value along the production chain highlighting the importance of the battery SC and the need for new competence acquisition. Moreover, a battery can even account for almost 40% of the total cost. (Giannetti et al., 2016). Within such a context, there are also some recent contributions focusing on manufacturing batteries for electric and hybrid vehicles. A broad analysis is offered by Sarkar and others (2018), who study the local production of lithium-ion batteries in India as a possible solution to decrease the battery costs. The entire battery SC is investigated by identifying and discussing the roles of its key players.

The performed literature review relevels a still scarce research about the implications on the SC organization, and the associated economic impacts, of different procurement and manufacturing strategies for battery packs. However, such decisions have a significant influence on the success of economic strategies adopted by car makers and their consequent survival in the industry.

In order to bridge this research gap, the present paper aims at putting forward a structured analysis of the logistics and related cost implications of different stages of vertical integration for the procurement and manufacturing of battery packs to be integrated in low impact vehicles. Vertical SC integration together with logistics costs are key parameters in determining the final value of lithium-ion batteries (Mayyas et al., 2018).

Methodology

The research has been conducted through the following steps in order to achieve scenario-based decision making (Cagliano et al., 2011). First, the different make or buy procurement scenarios investigated in this work have been defined. In particular, they have been developed according to three main possible strategies for procuring the batteries that will be integrated into vehicles as recognized by literature (e.g. Giannetti et al., 2016; Huth et al., 2013), as well as taking into account the procurement options available to the cased company. As already mentioned, batteries can be purchased as finished entities or modules can be purchased in order to assembly batteries. Also, cells can be provided so that modules and in turn batteries can be produced. Thus, the first scenario is related to the purchasing of the entire battery pack, the second one is based on the intermediate choice of buying the modules, and the last one is merely related to purchasing of cells. For each scenario the logistics cost of the battery has been computed.

Since in the third scenario the location of module assembly facilities needs to be addressed, the Network Design Theory approach is then applied. This approach based on optimization is widely used in designing SC and distribution networks (Botton et al., 2013; Rodríguez -Martin et al., 2016). Starting from a set of input parameters it can be possible to obtain the minimum cost for a network (Ljubić et al., 2017). The optimization has been carried out via a company-owned linear programming software whose name and detailed methodology cannot be disclosed for confidentiality reasons. The software according to an objective function minimizes the total transportation costs, considering the most suitable transportation options. Many constraints enable the correct representation of the network and the possible alternatives for good transportation through it; the constraints concern transport link capacities and modalities to effectively represent the logistics network and its features. The main input data feeding the software are the following ones:

- Sites: the geographical location of the suppliers' and the vehicle manufacturer's plants are defined. This allows to determine the transportation distances that have to be covered.
- Battery demand: this information is related to the volumes that need to be transported.
- Battery Bill of Materials (BOM): this information is crucial in the definition of the inbound logistics flows because the number of BOM components determines the complexity of such flows.
- Products that are moved: in each scenario different products with different volumes, weights and requirements that impact the transportation costs, are moved.
- Network organization: this aspect includes the presence of intermediates nodes (such as hubs) between the supplier and the car manufacturer plants.
- Transportation modes: this information refers to the different possible ways of moving batteries and their components.

The total transportation cost has been coherently computed, and it has been obtained as the sum of every cost item to carry every battery component from the origin to the destination site, taking into account the material handling and transport logistics cost.

The company has already undertaken the decision of outsourcing the service to a third-party logistics operator; many players in the automotive industry have adopted this strategy in order to focus on their core competences (Karbassi Yazdi et al, 2018). The service can be carried out as Less Truck Load (LTL) or Full Truck Load (FTL). FTL consists of a direct shipment from source to destination corresponding a fee related to the entire volume of the truck (Tang et al, 2017). The resulting cost is based on the distance travelled and it can change based on the region of supply. LTL is made up of a double shipment: from the source to an associated hub and from the hub to the final destination plant (Tang et al, 2016). According to the agreed contract, both fees include the external material handling and transport logistics costs (Lin and

Lee, 2018). The proposed model is aimed at evaluating the properest transport shipping strategy for every material transportation carried out. Therefore, the model could embed the different transport fees that could be corresponded to the third-party logistics operator and, consequently, it is able to highlight the cheapest available solution among the ones identified.

In addition, the transportation of cells, modules and battery packs need special conditions in terms of temperature and humidity. As a matter of fact, thermal and humidity shocks might heavily jeopardize the battery performance (Dinger et al., 2010). The ADR (**A**ccord européen relatif au transport international des marchandises **D**angereuses par **R**oute - European agreement concerning the international carriage of dangerous good by road) provision provides for these special items particular transportation conditions that require an additional expenditure. It is an European regulation for the transport by road of dangerous goods and provides instructions for a safe and controlled transport. Also, cells and modules need refrigeration (paid by the car manufacturer for the entire forward and backward shipment) in the vehicle loading compartment to mantain the electrochemical properties (Kouchachvili et al, 2018).

Moreover, another important aspect associated with low impact vehicles is the CO_2 emission; in the proposed research an assessment for every scenario has been developed, given the increasing relevance of the environmental issue (Pierre et al, 2019). For each trip, the CO_2 emissions have been computed according to the g/km of CO_2 emission of the truck and the total amount of kilometers that are travelled.

For the comparison among scenarios return transport costs are also computed. As a matter of fact, reusable containers are employed for transporting all the components. Since boxes that are made up of plastic are foldable, the return number of trips and the transportation costs are lower (Rogers et al., 2002).

For the third scenario different plant locations for the production of modules have been compared in terms of costs in order to identify a possible area wherein the facility can be developed. As a matter of fact, in this case a new plant is required for the assembly of the batteries that in turn will be delivered to the car manufacturing plant for the final integration into vehicles. Three approaches have been applied to get the alternatives: in particular, the Center of Gravity (COG) method, the Greenfield analysis, and company expert judgement.

The COG method is a sub-optimal approach that allows to define a first possible location (Ma.Teodora et al., 2018). The associated exact position in terms of latitude and longitude can be obtained as the weighted mean according to the volumes shipped from one of the network points (each point represents a supplier) and received by another point (representing a plant that receives materials). The Greenfield analysis is an iterative optimal method that considers geometric distances between points. In particular, it analyzes the area inside the coordinates of a number of points. The analysis starts from the point with minimum latitude and longitude. After that, for each point it calculates the product between the cubic meters moved and the distance covered between the origin – the supplier – and the destination – the plant. The minimum product is consequently selected (Munasinghe, 2017). Finally, the expert judgement has been based on a several meetings between a panel of company experts together with academic consultants. The objective was to take into account potential constraints, such as the presence of logistics service providers that can support the business, that the already mentioned method are not able to consider.

The three investigated scenarios have been defined for a given demand level in order to take an appropriate decision considering the demand forecasting for the low-impact vehicles.

Scenarios definition

The aim of the study is the development of a methodology to define alternative make or buy and related SC configurations and choose the most appropriate one from a logistics point of view. Thus, three different scenarios have been defined based on the main components of a battery pack: cells, modules and other items, (*e.g* monitoring, electrical and thermal control system) (Saw et al, 2016). The scenarios have been developed according to the current structure of the logistics process in the focused company.

In particular, four final plants producing electric vehicles and a network of suppliers for the procurement of the components required to assemble batteries have been addressed. Furthermore, the location of the supplier's hub was considered to calculate the total transportation cost in the case of LTL transport. The main relevant aspects are the configuration of SC nodes and their links, the facility location for the third scenario and the analysis to define the best alternative.

The overall demand for battery packs has been considered to be the same for the all the scenarios in order to make them comparable.

Scenario 1 or Buy Packs scenario

This option represents the pure buy strategy for the supply of the lithium-ion batteries. In this case, there are two battery pack suppliers, which are the main European providers, and four production facilities. Batteries are picked up from the suppliers and directly shipped to the final plants. In this scenario there are only 2 suppliers for the assembled pack and 4 car production facilities. The average distance weighted by volume is equal to 1400 km.

Scenario 2 Buy Modules scenario

This configuration represents an intermediate stage for the make or buy strategy. It considers assembled modules as bought products, which are then assembled together to obtain a complete battery pack. In this case, a certain number of components (such as cables) need to be purchased and shipped from external suppliers. Therefore, the number of suppliers might increase.

The logistics flow begins with modules' suppliers that send assembled modules to the battery pack assembly plants. At the same time, battery pack component suppliers send these components to such a facility. The logistics network of this scenario is similar to the one of Scenario 3 except for suppliers that are only 17 due to the absence of module assembly.

Scenario 3 Buy Cells scenario

This scenario represents the make solution. As a matter of fact, the company purchases all the components starting from cells, then it assembles them into modules and in turn the entire battery pack is produced. Module components are delivered from the different suppliers to the module plant. This is a facility wherein module components are assembled to obtain the final battery modules. Its location is not identified *ex ante*, but it can be found through the COG and Greenfield Analysis described in the Methodology section. In this configuration, some components are directly delivered from the suppliers to the final battery assembly plant. On the contrary, the components of the modules are first shipped to the module plants and, once the production of modules is completed, they are delivered to the final manufacturing plants.

The location of the module assembly plant becomes a strategic decision. Two possible sites for the modules plant are obtained through Greenfield and Center of Gravity Analysis respectively: Location 3 and Location 2. Furthermore, Location 1, one of the most important logistics sites in Italy, has been evaluated with the aim of considering a strategic location and the cost associated to this decision. In fact, a lot of companies (e.g. Amazon, Ikea, Leroy Merlin) have their logistics hubs in that area.

The logistics network associated with Scenario 3 is the most complex one of the three networks addressed in this work. It is constituted by different suppliers, regional hubs, and car production facilities that have to be combined together. The minimum distance between two points is equal to 100 kilometers and the maximum distance is equal to 1920 kilometers. The average distance weighted by volume is equal to 1200 km.

For confidentiality reasons, costs are not shown as they are but as a percentage of the values related to Location 3 scenario that is the cheapest one, as presented in figure 1, Location 1 has the highest cost because it is far from the optimal area, represented by the other two sites resulted from analytical methodologies, and thus the travelled distances and associated costs increase. The Greenfield analysis, as previously stated, is a methodology that enables to find an optimal solution for facility location and this is confirmed by the cheapest solution referred to Location 3. Therefore, Location 3 is selected as the module assembly plant site for the make or buy decision analysis.

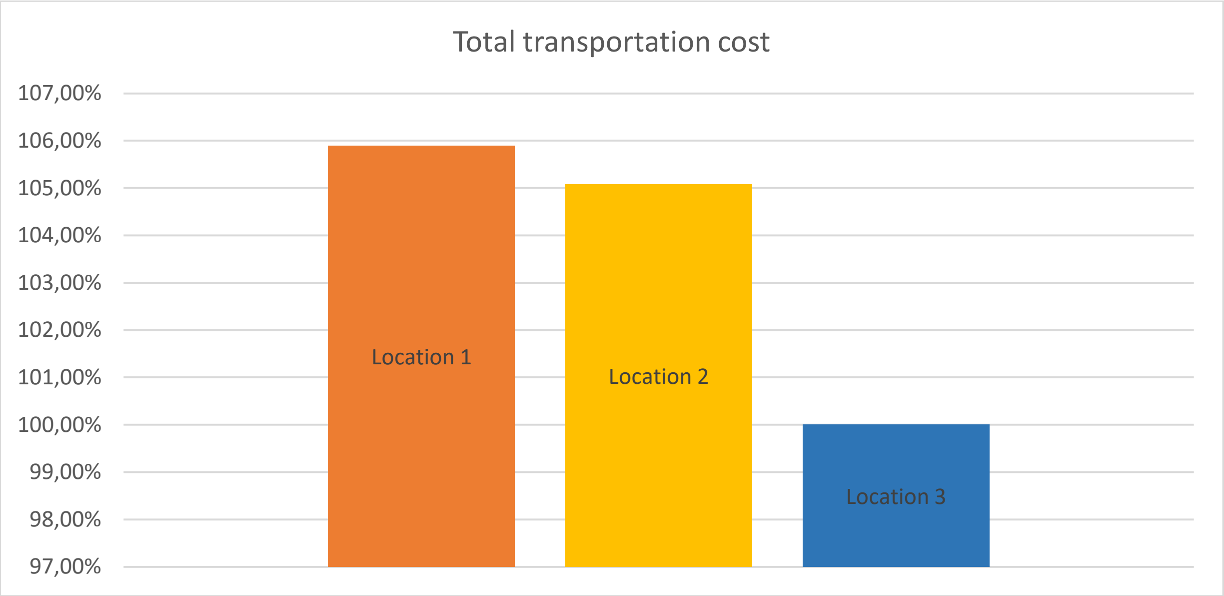

Figure 1. Module plant location: total transportation cost

Scenario Analysis

In this paragraph, the input unit parameters for each variable introduced in the Methodology Section are presented. For confidentiality reasons, their values cannot be declared. Number of trips is a key aspect for describing a logistics network and the features of the related trips (Černá, 2017). The associated costs are a fundamental driver for every decision in the logistics area and they have to be precisely determined in order to have a complete picture (Guijarro-Rodríguez, 2017). Number of trips and costs are considered for both the delivery of batteries, or of their components, and the return of empty containers to account for the complete logistics flow. Finally, the increasing focus on environmental problems implies a special attention to CO_2 emissions in order to highlight the importance of the problem and take correct decisions to face it (Jiménez-Parra, 2018). Thus, the values have been shown taking as 100% reference the fee associated with the material handling and the truck shipment costs. Transportation is performed by third party logistics operators (, for this reason the company has to pay an overall fee that includes all the costs following listed:

- Transport Cost: $\delta = \mu*\alpha*\varphi$ (including material handling cost and truck shipment costs)
- Transport cost for ADR: $\gamma = \delta *\beta$
- Transport cost with refrigeration and ADR: $\omega = \gamma*\lambda$
- Total Co_2 emissions: $\psi = \mu*\iota$

The material handling cost includes the costs to perform all the operations required to load and unload trucks and to move the goods inside the different kg operator facilities. The truck shipment cost is referred to the execution of the transport journey and the additional cost for ADR and refrigeration have already been explained in the methodology section.

Different input parameters enable the computation of the variables considered by the model. First, transport cost δ [€/km] has been computed as the product between μ, that is the transport costs coefficient (it includes material handling and truck shipment and it change with FTL or LTL transport; for LTL it considers also the shipped volume to determine the exact cost that is proportional to the volume on the truck), and α [km], that is the distance between the origin and destination. φ is considered with LTL transport and it is the shipped volume in cubic meters. Transport cost could be increased by ADR restriction (defined as γ), in fact β is the coefficient that third-party logistics operators apply to carry out a shipment with ADR restrictions. Refrigeration may be necessary in ADR shipment, for this reason λ is the incremental coefficient that considers the presence of specific asset for refrigeration on the truck. For the CO_2 emission (defined as ψ) computation, μ and ι are considered, respectively the unit emission coefficient per kilometer for the trucks considered [kg of CO_2/km] and the distance from origin to destination[km]. In the cases of modules and battery assembly the cost of the investment for the associated plants are not computed, because the company is able to convert an existing facility for the production of batteries. Moreover the purchasing costs of complete batteries, modules and cells are not included in the analysis because in Scenario 3 the lower cell costs are compensated by the investment costs for the configuration of the plant that would be devoted to the production of the batteries. The same applies to the strategy of buying intermediate modules, that will form packs. On the contrary, Scenario 1 requires a greater expenditure on complete LIBs but does not require additional investments in any manufacturing facilities.

Analysis of the number of trips

One of the most important variables to consider in transport logistics is the transported volume measured as the number of trips. In particular, it has a significant impact on the cost, in fact the higher the number of trips the higher the cost, due to the increasing number of required trips. Figure 2 reports the total number of trips performed from suppliers to manufacturing plants in different scenarios. The impact of make or buy choices results clear from the graph below: the Buy Packs scenario is characterized by the highest number of trips due to the lowest saturation of containers for safety and stability reasons. Decomposing batteries into their components enables a better saturation of containers and lower volumes, but the presence of additional components (modules components in Location 3 scenario) increases the overall volume, compared with the transportation of modules already assembled. In particular, a single module component has a volume equal to the entire volume of the assembled module. Therefore, the decision about the level of vertical integration has an important impact from a technical point of view, especially on the structure and on the assembly activities of the final component.

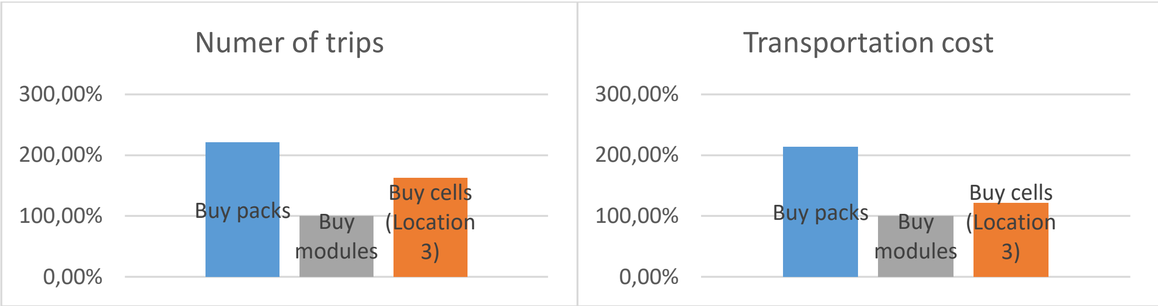

Figure 2. Number of trips and related costs

Cost analysis

In this section, the cost to carry different components for batteries and battery packs is analysed. As already mentioned, the costs are expressed as a percentage of the values related to the scenario Buy Modules because of confidentiality reasons.

Transportation costs have been computed as the sum of every trip for battery packs. In particular, they have been calculated as the product between distances and the related transportation fee for both FTL and LTL. Figure 2 reports the cost in the three make or buy scenarios for a given level of production that has been considered equal to 300,000 packs per year. This value has been selected in order to consider logistics flows that are already at the level of maximum production speed for the car maker. The Buy Packs scenario has the highest cost since the decision of purchasing assembled battery packs requires higher number of trips and the payment of an additional ADR fee for the entire shipment. Location 3 scenario as Buy Modules presents the highest level of vertical integration with a consequent better saturation of containers and total volume reduction. These two scenarios need to consider the additional fee for cells and modules refrigeration, as well as the associated ADR fee. In addition, another aspect that has to be taken into account is the geographical proximity of supplier and customer plants, which has an obvious impact on transportation and its associated costs .This is due to the fact that in the Buy Packs scenario the assembled battery pack is carried from suppliers to the final manufacturing plants; in the other two options, the battery pack is assembled near the vehicle production plant and only the components for the assembly are moved from suppliers to the company's facilities.

CO_2 analysis

CO_2 emission has become a crucial issue due to recent climate changes, especially concerning transportation sector. For this reason, analyzing CO_2 in logistics transportation for low impact vehicles is fundamental (Cariou et al., 2019). Figure 3 shows the levels of CO_2 emission in the different scenarios. It has been calculated by multiplying the distance travelled in every trip by the CO_2 emission per kilometer of the truck. This value has been obtained as the mean of the emissions in the technical sheets of the considered truck models. In this way, a plausible level of emission is used. Buy Packs option has the highest emissions due to the largest number of required trips. Location 3 and Buy Modules scenarios present lower emissions because the overall number of trips is considerably smaller compared with the first scenario. CO_2 emissions are also influenced by the total travelled distances for the considered volumes. In fact, as already described in the cost analysis section, in the Buy Packs scenario the battery packs, with their high volumes, are moved from suppliers to manufacturing plants; on the contrary, in the other scenarios, lower volumes are moved from suppliers to plants, while battery packs travel a shorter distance being assembled close to the vehicle production site.

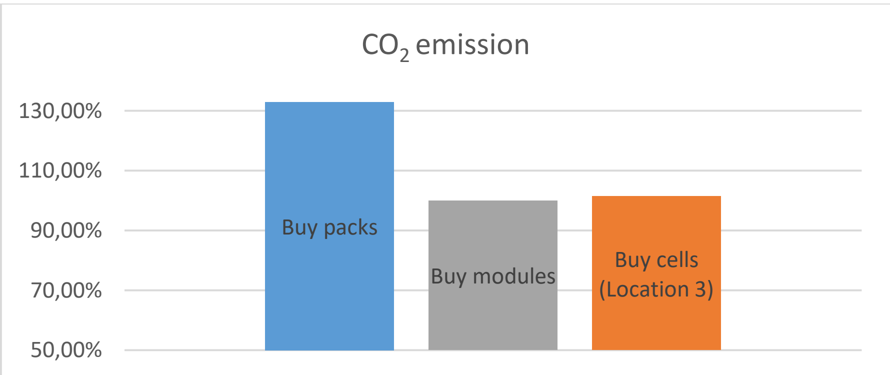

Figure 3. CO2 emissions

Return number of trips and cost

Aiming at having a complete view of the SC for low impact vehicles, return trips are also considered. The focus company uses foldable containers for all the components of the battery packs. On the contrary, for Buy Packs scenario, traditional containers are adopted, since they are able to support the heavier assembled battery packs. For this reason, the return transportation costs with empty containers for the Buy Packs are significantly higher than the other two scenarios where the empty folded containers allow to reduce the volume and the number of trips, as shown in figure 4.

In particular, figure 4 reports the return number of trips and the reduction in transportation costs from the Buy Packs to the Buy Modules scenario. The Buy Packs scenario does not reduce the transportation volumes respect to the other ones wherein they significantly decrease. Another aspect that needs to be considered is the ADR and refrigeration in the return trip. In Buy Packs scenario, ADR additional fee is not charged because it is connected to the presence of dangerous goods on the truck. For the other two options, refrigeration fee is charged for the return because the insulation system is integrated in the truck and cannot be deactivated.

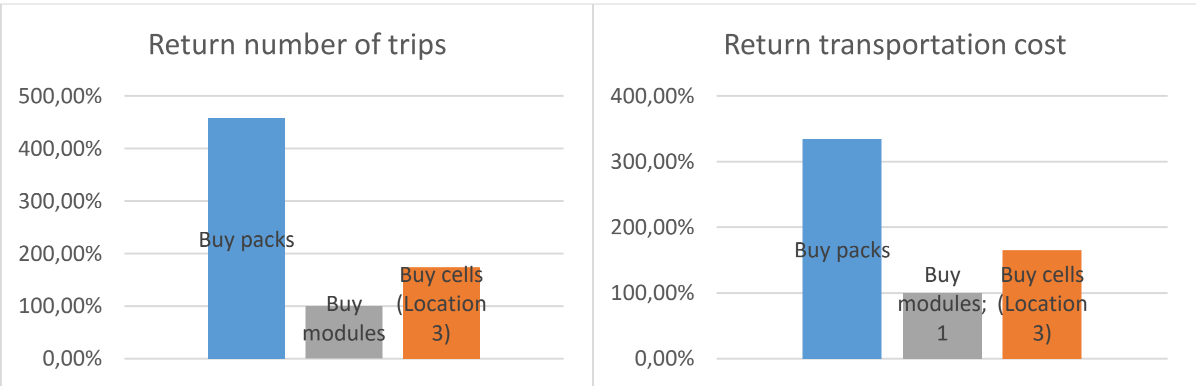

Figure 4. Return number of trips and related costs

Discussion of results

The performed make or buy analysis and the assessment of its impacts on the SC have shown some differences among the scenarios. Table 1 summarizes the findings discussed in the previous sections by ordering the three scenarios from the most preferred to the least one for each considered perspective.

Perspective	Transportation volume (# trips)	Transportation cost	CO_2 emissions	Return transportation volume (# trips)	Return transportation cost
BEST	Buy Modules	Buy Modules	Buy Modules	Buy Modules	Buy Modules
Scenario	Buy Cells	Buy Cells	Buy Cells	Buy Cells	Buy Cells
WORST	Buy Packs	Buy Packs	Buy Packs	Buy Packs	Buy Packs

Table 1. Summary of scenario outcomes

Buy Packs has the highest transportation cost because the decision of buying packs calls for high transportation volumes and a larger number of trips. Coherently, the CO_2 emissions are significant due to the number of trips and the longer distances between battery pack suppliers and final car manufacturing plants. Similar reasons motivate the outcomes for the Buy Packs scenario in terms of return number of trips and cost. The Buy Cells scenario presents lower transportation costs than the Buy Packs one due to the choice of purchasing the components for the battery pack assembly. This reduces the total number of trips and the cost and in turn it improves the CO_2 emissions. The intermediate make or buy solution, the Buy Modules scenario, has the lowest transportation costs. In fact, the required transportation volumes and number of trips is lower due to the architectural composition of the components of the battery pack, as explained in the previous sections. In addition, this solution does not require the location of a new facility for module assembly but only the location of the battery pack assembly site near the final car manufacturing plants. From this analysis, the impact of make or buy choice on operations and, more in detail, on logistics clearly comes up. Table 1 shows that from both a cost and an ecological perspective the best scenario is the intermediate one, Buy Modules, that, compared with the Buy Cells one, presents a moderate level of vertical integration. The focus company will probably start the electrification process from the Buy Packs option because it is the most flexible one, a characteristic that appears to be a crucial feature during the current mobility paradigm transition. In particular, even if the buy option is not the cheapest one it appears to be the most feasible one, at least in the first phases of the production of low impact vehicles. As a matter of fact, for the intermediate scenario that has proven to be as the cheapest one, specific skills related to the assembly of the battery packs are required. So far, these competencies are not fully established in the company and more in general in the automotive industry wherein big players often still outsource battery production and focus on their mature competencies (Masiero et al., 2017). However, in the next future, thanks to the expected increase of the demand of low impact vehicles, it is possible to assume a gradual shift to the scenario based on the purchasing of the modules and on the assembly of the packs. Finally, the scenario related to the purchase of cells is still not suitable in terms of costs but also from an operations perspective since the company has first to implement the intermediate scenario.

Implications and conclusions

This study develops an approach supporting decision making about make or buy strategies for the SC of batteries assembled on electric and hybrid vehicles. The purpose of the research is guiding the identification of the SC implications of alternative procurement strategies from different perspectives, such as transport costs and CO_2 emissions, in order to transport and even assemble batteries, by considering a structured network of suppliers. In particular, it is focused on defining a quantitative approach to a make or buy procurement problem for batteries SC, in contrast with the existing literature that is mainly focused on make or buy decision models based on theorical and strategic aspects (Özel et al., 2013) without considering the impacts of such decisions on the cost structure of the company. In particular, the proposed research is based on well consolidated methodological approach focused on a quantitative comparison among scenario. This is required by the high level of novelty of the topic under analysis. In fact, the research stream about SC of batteries for electric and hybrid vehicles is still in its infancy and not deeply investigate. Thus, in order to overcome this lack of comprehensive knowledge robust and reliable methods are necessary.

The outcomes show that the buy modules solution, that represents an intermediate strategy between the make and buy strategies, is the most convenient one. As a matter of fact, the make all solution is very resources and facilities consuming, due to the largest number of operations and facilities required to assemble battery packs. The buy packs solution is very expensive because of the relevant number of trips and it is risky due to the dependence from two main suppliers for all the battery packs required. Also, most of long-distance shipping line is controlled by few shippers only (Watada and Wu, 2017).

This contribution originates some theoretical and practical implications. From an academic perspective, this paper contributes to enlarge the body of knowledge related to managing the SC of batteries for electric and hybrid vehicles, by considering the complexity of the system under study. Furthermore, this paper can stimulate research about make or buy decision models for batteries SC by deepening quantitative and operational aspects. This paper also adds a contribution to the existing literature (Huth et al.,2013; Huth et al., 2015) by underlining how different stages of vertical integration have important consequences on the technological and logistics firm structure.

From a practical perspective, this paper can support the automotive companies, that have already developed hybrid and electric vehicles, or that are designing new ones, in the adoption of make or buy strategies by taking into account the related consequences on their SCs. Furthermore, this paper might support companies in a most effective design of their battery SCs. Such a topic is acquiring growing importance, especially considering that a very high demand for low impact vehicles is expected in the near future. Also, effective SCs could support the economic company growth (D’Aleo and Sergi, 2017) In this context, the proposed work can be considered as a preliminary framework assisting companies in their SC strategic decisions. This contribution may suggest to companies the main different steps of vertical integration for the production of battery packs, defining the main logistics and productive impacts.

However, this work suffers from some limitations. The analysis is mostly focused on costs: as a matter of fact, operations aspects related to the warehouse activities for each scenario are not considered. Furthermore, in this first study only one battery model is taken into account, consequently the impacts on the logistics processes related to the production and the purchasing of more than one model are not addressed. Finally, the cost of the auxiliary components that need to be purchased is not considered.

Thus, future research will consider different kinds of batteries. Also, the analysis of the internal logistics activities according to different procurement and assembly strategies will be deepened, and the cost of equipment such as cables and connectors will be taken into consideration. Finally, the application of the proposed decision making approach supporting make or buy strategies will be extended to other automotive companies in order to fully validate the methodology.

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