Exploring the relationship between the adoption of lithium-ion battery forklifts and warehouse organisational patterns

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Abstract: The introduction of the lithium-ion technology boosted the market for electric forklifts, by providing high performing batteries that guarantee greater energy efficiency in warehouse operations. On top of the substantial savings obtained in terms of both operational and environmental costs, lithium-ion batteries offer the possibility to perform fast partial charges – known as 'opportunity charging' – that can be carried out during idle times such as operator breaks. Opportunity charging increases forklift availability and enables to leverage on warehouse organisation for reducing the battery lifecycle cost. So far, the interest of the scientific literature towards forklift lithium-ion batteries has mainly focused on technological aspects, neglecting the implications of organisational factors on the system performance. In addition, contributions have mostly tackled the adoption of lithium-ion batteries on Automated Guided Vehicles (AGV) serving manufacturing processes, without deeply examining warehouse applications. The present paper aims at investigating the relationship between the adoption of lithium-ion battery forklifts and warehouse organisational patterns. The research was structured into three main steps. First, a review of the literature on lithium-ion batteries in industrial applications was performed. On one hand, contributions related to the characteristics of lithium-ion batteries were investigated, highlighting how technological, contextual, and organisational variables affect lithium-ion battery lifecycle costs. On the other, the relationship between the use of lithium-ion batteries and organisational patterns was explored. In a second step, semi-structured interviews were conducted with both material handling providers and Third Party Logistics (3PL) providers to test and extend the literature findings. Finally, an analytical model was developed to study the relationship between the lithium-ion battery forklift lifecycle cost and different organisational patterns. Results showed that the opportunity charging is turning operators' downtimes into levers to improve warehouse operational performance, and opened room for further research on the sustainability of warehouse activities.

Keywords: Lithium-ion batteries, Opportunity charging, Warehouse organisation, Logistics, Green Warehousing.

1. Introduction

The lithium-ion (Li-ion) technology for electric batteries has recently gained attention in numerous industrial fields (Liu et al., 2018) thanks to its high energy efficiency, long-lasting lifespan, and ability to operate over a wide range of temperatures. Recognising such significant benefits, the logistics industry has also started to look at this new technology for material handling operations (Alshaebi et al., 2017).

According to Cicconi et al. (2019), despite the significant economic and environmental improvement offered during its operating life, the average cost of a Li-ion battery still prevents its adoption, being estimated more than four times the cost of the equivalent lead acid (LA) one. Since the Li-ion battery cost mainly depends on the battery capacity, the optimal battery sizing represents an important lever that might help in recovering sooner the investment cost.

For conventional batteries, battery sizing requires selecting the battery capacity so that the machinery powered by the battery is available for the duration of the operations needed. The optimal battery sizing is affected by the charging strategies adopted, which are in turn bounded by the battery technology (Kabir and Suzuki, 2018; Zou et al. 2018). In particular, the Li-ion technology is suitable for the so called 'opportunity charging', a charging strategy that consists in performing fast, sometimes partial charges during the operation phase, by the use of fast-chargers (Lajunen, 2018). Since opportunity charging allows the battery to be charged while being in the forklift, no battery swapping is needed. Moreover, thanks to the fast, frequent charges enabled by the opportunity charging, a smaller and consequently cheaper battery is required to complete the operations (Cicconi et al., 2019). Therefore, opportunity charging represents a way to foster the adoption of Li-ion batteries. Opportunity charging is usually performed during the system idle times. Therefore, its effectiveness in reducing the battery size is affected by the system organisational patterns such as working shifts and breaks (Bi et al., 2016).

Recent studies have started exploring the effect of opportunity charging on the economic suitability of Li-ion technology in different field, such as mobility – focusing on electric buses (Lajunen, 2018) – and in production and warehousing − mostly focusing on Automated Guided Vehicles (AGVs) (Zou et al. 2018, Cicconi et al., 2019).

The application of Li-ion batteries in warehouse contexts has recently gained attention in the literature (Liu, et al., 2018). Indeed, beside the applications in AGVs, the opportunity charging strategy might boost the adoption of Li-ion batteries also in manual warehouses equipped with forklift trucks, which still represent the majority of logistics facilities (Ries et al., 2017). Specifically, the focus on manual warehouses, whose idle times are highly flexible being determined by operators' breaks (Bartolini et al., 2019) offer interesting opportunities to investigate the relationship between the adoption of Li-ion battery forklifts and warehouse organisational patterns.

Based on these premises, and given the importance that Li-ion battery adoption might have in decarbonising warehouse operations (Ries et al., 2017), this paper aims at exploring the relationship between the adoption of Li-ion battery forklifts in manual warehouses and the related organisational patterns. An analytical cost model has been developed to study this relationship. Specific attention has been paid on investigating how opportunity charging can be combined with organisational variables, how this can affect Li-ion battery size and, consequently, its life cycle cost.

The remainder of this paper is organised as follows. Section 2 describes the relevant literature on the topic, and Section 3 illustrated the methodology. The proposed analytical model is illustrated in Section 4, while Section 5 reports the model application and the main findings. Finally, Section 6 includes discussion of the results, conclusions and streams for further developments.

2. Literature Review

2.1. Li-ion batteries in industrial applications

Nowadays, Li-ion is the most used technology for electric batteries on the market, and its success is guaranteed by the innovative material these batteries are made of. Indeed, lithium is the lightest among alkaline metals and this characteristic allows manufacturing batteries with low weight and high performances in terms of energy efficiency and speed of the charging process (Minav et al., 2013). Li-ion batteries are constituted by parallel branches of series-connected battery cells, each having a specific voltage (Ostadi and Kazerani, 2014). The capacity of the battery affects the duration of the battery itself and the battery cost (Renquist et al., 2012).

Despite the great economic and environmental improvement offered during its operating life, the average cost of a Li-ion battery is still an issue for warehouse managers (Alshaebi et al., 2017), and optimal battery capacity sizing represents an important lever which might help in recovering the great investment cost (Ostadi and Kazerani, 2014). The studies that address the cost analysis of Li-ion batteries for industrial and warehouse applications highlight different investment and operating costs associated with these batteries. In particular, investment costs mainly refer to the battery cost, being considered the highest burdens of Li-ion batteries adoption (Kabir and Suzuki, 2018). Battery cost increases with the capacity of the battery, and therefore with the energy that the battery can provide (Lajunen, 2018). It is important to note that battery might be replaced, since its lifecycle – which is bounded by the total number of full charge and discharge cycle that it can experience – might be shorter than the one of the electric machinery powered (Cicconi et al., 2019). The other investment cost usually associated with Li-ion battery is the charger cost, whose price varies according to the speed of charge provided to the battery (Renquist et al., 2012). The operating costs associated with the Li-ion batteries include the annual energy cost and the maintenance cost. The first depends on the energy consumed by the Li-ion battery. The average energy consumption is usually estimated considering both technological factors – such as the type of machinery hosting the battery (Minav et al., 2013) – and contextual factors. These latter include: the operating route performed by the machinery – which depends on the horizontals and vertical path and speeds (Renquist et al., 2012) and it is bounded by the facility layout where the machinery is working (Vivaldini et al., 2013) –, the average workload carried (Kabir and Suzuki, 2018), and the temperature of the working environment (Alshaebi et al., 2017).

2.2. Li-ion batteries adoption and organisational implications

Recently, some authors have started to study the role that organisational factors such as charging strategy selection have in fostering the Li-ion battery adoption in warehousing and other industrial contexts (Zou et al., 2018; Cicconi et al., 2019). Indeed, Li-ion batteries increase forklift productivity by the use of the so-called 'opportunity charging' (Alshaebi et al., 2017). Recently, some studies recognise opportunity charging as a strategy to lower also Li-ion battery investment cost. In fact, fast and more frequent charges allow decreasing the needed capacity of Li-ion battery, and a smaller battery with a lower investment cost might provide an economic incentive for Li-ion adoption (Zou et al., 2018; Cicconi et al., 2019).

Opportunity charging is usually performed during the system idle times, to minimise the charging downtimes (Kabir and Suzuki, 2018). In this sense, some authors recognise that organisational patterns such as the number and the duration of the idle times during the working day combined with the opportunity charging affect the right battery sizing (Sweda et al., 2017; Lajunen, 2018). Indeed, the shorter the time available for opportunity charging, the lower the charging level reached during the charge, and the higher the battery capacity needed to perform the operating activities required (Lajunen, 2018).

Although opportunity charging combined with some organisational patterns have started to be acknowledged as a way to foster Li-ion adoption in warehouses (Alshaebi et al., 2017), ad hoc studies in the logistics domain are still underrepresented. To date, no authors analyse how different organisational patterns, and the consequently different opportunity charging strategies, affect the Li-ion battery adoption. The available studies on the impact of opportunity charging on Li-ion battery costs in logistics applications usually consider the number and the duration of idle time as fixed, since they mostly analyse automated systems (Zou et al., 2018; Cicconi et al., 2019). Conversely, in manual warehouses, organisational patterns such as the duration of the forklift idle times can be considered as variable, thanks to the flexibility offered by human operators. These aspects are worth further investigation.

3. Methodology

To address the objective of this research, the methodology was structured into three main phases.

First, a thorough review of the literature on Li-ion batteries was conducted, as reported in section 2. The literature search was performed through a structured approach. First, keywords related to the topic of interest such as "opportunity charging", "electric forklift", "warehouse", "lithium-ion" were combined and searched for using Scopus. Then, the literature was carefully examined and the relevant contributions were selected. Finally, forward and backward reference searching was performed to enlarge the sample retrieved. On one hand, contributions related to the cost analysis of Li-ion batteries for industrial applications were investigated, leading to the identification of the main operating and investment costs related to Li-ion batteries, and highlighting the relevant technological and contextual variables affecting these costs. On the other, the relationship between the adoption of Li-ion batteries and organisational patterns was explored, with a focus on logistics applications. This analysis led to the identification of a number of organisational variables affecting Li-ion battery costs.

In a second phase, semi-structured interviews were conducted with both material handling providers and Third Party Logistics (3PL) providers in order to test and extend the literature findings. The aim was to investigate the relevance of the variables, costs and relationship emerged in the previous phase and to integrate them based on experts' knowledge. Four semi-structured interviews were performed, i.e. two with material handling providers and two with 3PL providers to cover different perspectives and offer a clearer picture of costs and issues related to the adoption of Li-ion battery forklifts. Companies were selected starting from the database of the Contract Logistics Observatory – Politecnico di Milano (Italy). Specifically, the material handling providers interviewed are two European market leaders in the field of Li-ion battery forklifts. The 3PL providers have been selected since both have recently adopted the Li-ion technology for their electric forklift fleets. Confidentiality was guaranteed due to the sensitive nature of the topic, thus neither companies nor individuals can be revealed. The results of the interviews confirmed the variables found in literature, strengthening the idea that organizational patterns affect the cost of Li-ion battery forklift and can be used as a leverage to foster their adoption.

Finally, an analytical model based on an input-process-output approach was developed to study the relationship between the adoption of Li-ion batteries and different organisational patterns. The purpose of the model was to test whether different organisational patterns might have an impact on the adoption of Li-ion batteries. The lower lifecycle cost associated with the Li-ion battery forklift has been chosen as a proxy for the likeability of Li-ion technology adoption (Kabir and Suzuki, 2018). For this reason, the output of the model has been selected according to a Total Cost of Ownership (TCO) approach, whereas the input of the model consists in the relevant technological, organisational, and contextual variables affecting these costs. A sensitivity analysis was then performed to study the impact of different organisational patterns on the costs associated with the adoption of Li-ion battery forklifts.

4. Model Architecture

To explore the relationship between the adoption of Li-ion battery forklifts and warehouse organisational patterns an analytical model was developed as reported in Figure 1.

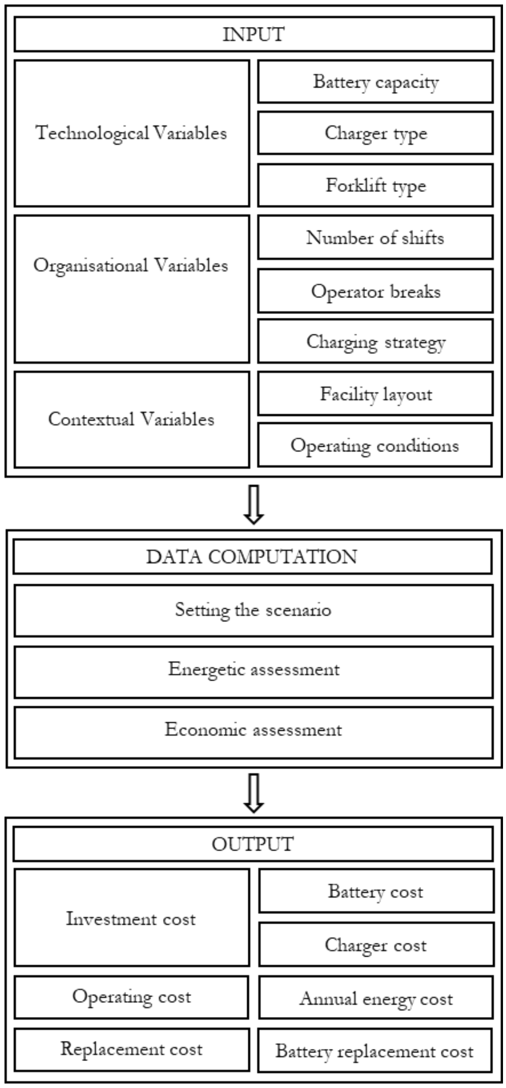

Figure 1: Model overview: phases and input-output data

Three different types of inputs were considered, namely technological, organisational, and contextual variables. They consist in the main relevant variables affecting the life cycle costs of a Li-ion battery forklift. They were selected according to both the literature analysis and the interviews with experts.

Technological variables include:

- ***Battery capacity***: it is the capacity of the battery expressed in kWh; it affects the total available energy provided by the battery;
- ***Charger type***: it is the type of charger used to perform the battery charging (e.g. fast charger);
- ***Forklift type***: it is the type of Li-ion battery forklift used for the warehouse handling operations (e.g. picking truck, counterbalance forklift truck, straddle reach truck).

Organisational variables include:

- ***Number of shifts***: it represents the number of operating shifts related to the manual warehouse scheduling. It affects the forklift total operating time;
- ***Operator breaks***: it includes the time and the duration of the operator downtimes (e.g. breaks, lunch). It affects the total forklift idle time;
- ***Charging strategy***: it consists in the selection of the way to perform the battery charging (e.g. opportunity charging, battery swapping).

Finally, contextual variables include:

- ***Facility layout***: it comprises the size, shape and space arrangement of the manual warehouse where the Li-ion battery forklift operates;
- ***Operating conditions***: they comprise the warehouse temperature according to the requirements of the stocked goods, the average weight of goods to be loaded, and the maximum operating height reached by the Li-ion battery forklift.

The process leading to the output identification, named as data computation, comprises three steps. The first consists in determining the scenario of analysis by elaborating all the input variables according to the system studied. The second involves an energetic assessment, where the Li-ion battery State of Charge (SoC) is evaluated, intended as the percentage of residual energy of the Li-ion battery during its operating conditions with respect to the overall energy provided by the fully-charged battery. The purpose of this evaluation is to check whether the selected battery capacity is able to supply the energy required for the entire duration of warehouse operations. Given the exploratory nature of this study, the charging and discharging profile of the Li-ion battery was approximated to a linear function, according to both the experts' suggestion and the approaches adopted in the literature (Renquis et al., 2012). The average charge and discharge values over time represent the slope of the charge and discharge functions respectively. The final step includes the economic assessment of the costs included in the model output.

The outputs of the model were selected according to a total cost of ownership (TCO) approach, which analyses the cost to be sustained throughout the Li-ion battery forklift life cycle. As suggested by Cicconi et al. (2019), the TCO computation considers the investment cost (C_{CAP}), the operating cost (C_{OPE}), and the replacement cost (C_{REP}) of the electric battery. The investment cost (C_{CAP}) includes:

- ***Battery cost (€)***: the purchasing cost of the battery which includes, among others, the number of cells and the Battery Management System;
- ***Charger cost (€)***: the cost related to the equipment used for the battery charging; it is affected by the power value selected for charging.

The operating cost (C_{OPE}) includes the ***Annual energy cost (€/year)*** intended as the cost related to the energy consumed for charging the battery. Although other contributions consider also the battery maintenance cost (Lajunen, 2018), this model does not include them, as they can be considered as negligible given the small size of the batteries analysed, in line with Cicconi et al. (2019).

The replacement cost (C_{REP}) includes the ***Battery replacement cost (€)***, which is related to the substitution of the battery at the end of its lifespan.

Given the different nature of the costs considered (investment versus annual costs), a Net Present Value (NPV) evaluation was then performed. The following calculation represents the discounted TCO (TCO_{NPV}):

$$TCO_{NPV} = C_{CAP} + \sum_{t=1}^{n} \frac{C_{OPE}(t) + C_{REP}(t)}{(1+k)^t}$$

Where t is the year of ownership of the Li-ion battery forklift, n is the total years of ownership of the Li-ion battery forklift, k is the discount rate.

5. Model application and results

This section describes the application of the model starting from the description of the base case (Scenario A) and those considered within the sensitivity analysis (Scenario B and C). The results of the application are then presented and discussed.

The model was applied to a manual warehouse located in the North of Italy, with a total floor space equal to 33,000 m^2 and a storage capacity of 34,000 pallets. The warehouse is fully equipped with single-deep selective pallet racks and served by straddle reach forklift trucks. The main input variables related to the base case are reported in Table 1.

Table 1: Input variables for the base case (Scenario A)

Input variable	Value
Battery capacity	28.8 kWh
Charger type	Fast charger (300 A)
Forklift type	Straddle reach forklift truck
Number of shifts	2 shifts/day
Operator breaks	1.625 h/day 1 break/shift
Charging strategy	Opportunity charging

Operating conditions	Temperature: 20°C Average loaded weight: 1,800-2,000 kg Maximum operating height: 12 m

Moreover, the following assumptions have been considered to compute the TCO_{NPV} for the Li-ion battery forklift:

- Electric forklift ownership is 10 years;
- Based on material handling providers' references, the expected lifespan of the Li-ion battery is assumed equal to 3,200 complete charging and discharging cycles;
- The warehouse operates 250 days a year with 2 shifts of 8 hours each;
- Each operator break lasts 15 minutes (Renquist et al., 2012) and breaks are equally distributed over the working day, according to the organisational pattern selected;
- Discount rate equal to 5%/year.

Besides the analysis of the base case, a sensitivity analysis was further performed aiming at understanding the relationship between the adoption of Li-ion battery and the warehouse organisational patterns. First, the organisational variable *Operator breaks* has been varied in order to understand the effect of different break patterns on the TCO_{NPV}. After changing the variable *Operator breaks*, the variable *Battery capacity* was adjusted accordingly, in order to have the minimum capacity required to cover the overall duration of the operating activities. To guarantee the working continuity, the minimum acceptable battery SoC has been set to 2% (Renquist et al., 2012). Table 2 reports the variables that were modified in the three scenarios analysed.

Table 2: Sensitivity analysis

	Scenario		
Variable	**A (base case)**	**B**	**C**
Battery capacity	28.8 kWh	21.6 kWh	19.2 kWh
Operator breaks	1.625 h/day	1.625 h/day	1.625 h/day
	1 break/shift	2 breaks/shift	6 breaks/shift

The average energy consumption is related to the forklift type, the facility layout, and the operating conditions considered, while the average energy recharging is affected by the charger type used. Therefore, both have been assumed the same regardless the scenario (Table 3).

Table 3: Average energy values

Energy values	Value	Unit of measure
Average discharging value	5.50	kWh/h
Average charging value	17.05	kWh/h

The results obtained by applying the model to the previously defined scenarios are discussed here in terms of both energetic assessment – by studying the battery SoC – and economic assessment, by analysing the TCO_{NPV}. According to the model output, Table 4 shows the unitary investment and operating cost considered to compute the TCO_{NPV} analysis. Each cost is related to the Italian market.

Figure 2 illustrates the charging and discharging profile for the Li-ion battery in the three scenarios analysed. The horizontal axis expresses the daily operating time of the electric forklift, which must cover two shifts of 8 hours each. The vertical axis refers to the current value of the SoC. It is possible to notice the combined effect that opportunity charging and organisational variables have on the energetic profile of the Li-ion battery. Indeed, opportunity charging allows recharging the battery during operator breaks (15 min each), thus increasing the SoC during the warehouse operating time (from 6:00 to 22:00). In the base case (Scenario A), the two long operator breaks (90 min and 105 min respectively) allow to completely charge the Li-ion battery, while in Scenario B the four shorter operator breaks (45 min for the first three and 60 min for the fourth one) allow to restore the battery SoC between the 70% and 100%. Finally, the numerous shorter operator breaks (15 min each) considered in Scenario C determine a substantial reduction of the SoC during the operating time, being assessed between 9% and 34% from 18:00 until the end of the operating time. The slope of the three curves is different, since, as the capacity of the battery decreases, less time is needed for charging and discharging procedures. Consequently, the number of complete charge and discharge cycles increases together with the increase in the number of breaks, thus lowering the useful life of the battery for Scenario C with respect to the base case (Scenario A). In all the scenarios the warehouse non-operating time, between 22:00 and 6:00, allows to completely charge all the selected batteries.

Table 4: Unitary costs considered in the analysis

Variable	Cost	Unit of measure
Li-ion battery cost (28.8 kWh)	19,250	€
Li-ion battery cost (21.6 kWh)	15,125	€
Li-ion battery cost (19.2 kWh)	13,750	€
Fast charger cost	2,313	€
Energy cost	0.15	€/kWh

Figure 3 shows the TCO_{NPV} for the analysed scenarios. The main difference among the scenarios is given by the investment cost of the battery and the battery replacement cost. In fact, Scenario B and C have a lower investment cost at year 1 with respect to Scenario A thanks to a lower battery investment cost. Indeed, the opportunity charging strategy combined with shorter and more frequent operator breaks allow to decrease the size of the battery, thus lowering the initial investment cost. On the contrary,

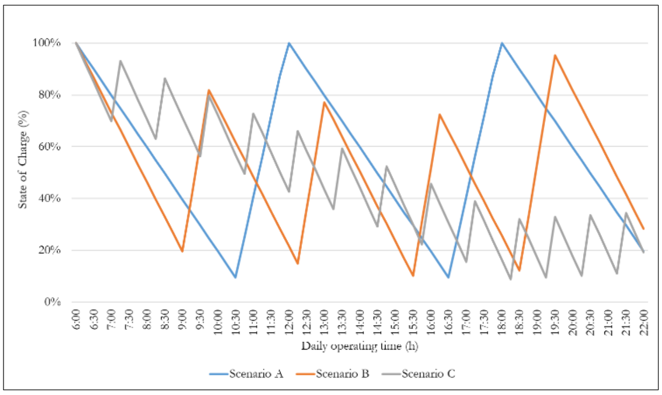

Figure 2 – SoC profile for the scenarios analysed

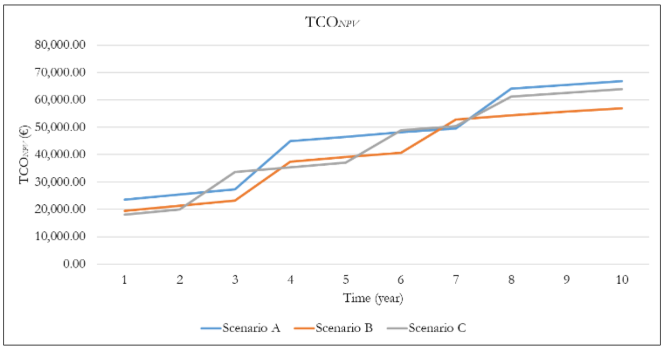

Figure 3 – TCO$_{NPV}$ for the scenarios analysed

Scenario B and Scenario C have a higher battery replacement cost with respect to Scenario A. This is explained by the decrease in battery lifespan caused by the. more frequent charges performed during the day. Indeed, the smallest the battery capacity, the higher the number of complete charge and discharge cycles experienced by the battery. As shown in Figure 3, the increase in the replacement costs might overcome the savings brought by the reduction of the battery capacity. In fact, at the end of the ten years, the TOC$_{NPV}$ of the Scenario C, which has a lower battery investment cost, is not the lowest. This result is explained by the effect of the battery replacement cost. Indeed, being charged more frequently, the smallest battery of Scenario C has to be replaced more frequently with respect to the other scenarios. Finally, it is important to note that the annual energy cost does not vary among the different scenarios, since the variables affecting energy consumption (forklift type, number of shifts, operating conditions), and the variables affecting energy recharge (overall duration of the operator breaks, charger type) remain the same for the three scenarios.

To conclude, the main results obtained by the application of the model can be summarised as follows:

- The use of the opportunity charging strategy, enabled by the adoption of Li-ion batteries, increases the importance that other organisational variables such as the number and the duration of operator breaks have in determining the right battery sizing;
- Organisational variables such as the number and the duration of operator breaks can be designed in order to decrease the lifecycle costs of the Li-ion battery forklifts, consequently fostering their adoption;
- By increasing the number and lowering the duration of operator breaks, a Li-ion battery with a smaller capacity is needed. Therefore, a lower battery investment cost is expected;
- By lowering the number and increasing the duration of operator breaks, the Li-ion battery is exposed to less complete charge and discharge cycles. Therefore, the battery needs to be replaced less frequently, and battery replacement cost decreases.

6. Conclusions

The introduction of Li-ion battery in manual warehouses, combined with the opportunity charging strategy, allows exploiting human operator breaks, turning them from downtimes to an important system design leverage. The analytical model developed showed that opportunity charging is an appropriate strategy to reduce the battery capacity and investment cost (Cicconi et al., 2019) and that different warehouse organisational patterns might affect the adoption of Li-ion battery forklift by lowering the TCO through all the forklift lifecycle. In particular, the sensitivity analysis showed that by increasing the number of operator breaks and decreasing their duration, a smaller battery is needed to cover the entire working day, thus the battery investment cost can be reduced. Besides, the battery experiences a higher number of complete charge and discharge cycles, therefore reducing its lifecycle and increasing its replacement cost. The case analysed showed that when organisational patterns involve short and highly fragmented operator breaks, the higher battery replacement cost might offset the savings brought by the reduction in the battery investment costs.

This study offers both academic and practical implications. From an academic perspective, this research fills the gap found in literature, by providing an exploratory study about the relationship between the adoption of Li-ion batteries and warehouse organisational patterns, thus extending the findings of previous studies (Zou et al., 2018; Cicconi et al., 2019) to the domain of manual warehouses. The result of the study proved the relevance of organisational variables in fostering the adoption of Li-ion battery, contributing therefore to raise interest in this research area.

From a practical viewpoint, the study offers a valuable analytical tool that can be used by warehouse managers to clarify which are the relevant technological, organisational, and contextual variables affecting the TCO for a Li-ion battery forklift in manual warehouses. Moreover, the model supports the decision making process on Li-ion battery forklift adoption. Finally, the sensitivity analysis can be useful to managers to understand how their organisational patterns might affect Li-ion battery TCO, and take actions on their organisational patterns to optimize the TCO.

Despite the relevance of the topic, some limitations may be detected, and streams for future research can be highlighted. First, given the purpose of the study, average charge and discharge values have been selected. Future research could analyse the battery state of charge through simulation, thus increasing the accuracy of the battery capacity estimation. Moreover, further studies could focus on the role of the human operator, to include the effect of driver behavior on energy consumption (Alshaebi et al., 2017). Second, due to the small capacity of the battery, the study did not consider any maintenance cost. In the future, maintenance and battery disposal costs might be included in the model, to refine the TCO analysis with further relevant elements. Third, to allow the generalizability of results an extended study should be performed by examining more scenarios and real industrial cases. Finally, the feasibility of the organizational patterns proposed should be tested in terms of warehouse and operators' productivity, and a comparison with lead-acid battery forklift could be performed, to better understand the organizational impact of the proposed patterns on the adoption of Li-ion batteries forklift. Further sustainability implications might be also investigated synergies among Li-ion batteries and other warehouse solutions for energy efficiency improvement might be explored. Indeed, leveraging on organisational variables such as opportunity charging can increase the percentage of battery charging cycles performed during the day; as an example, green energy from photovoltaic panels can be used to perform these charges. Finally, social sustainability issues might be also investigated by testing the feasibility of the warehouse organisational patterns highlighted according to the operators' needs.

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