A BI-OBJECTIVE APPROACH FOR DESIGNING END-OF-LIFE LITHIUM-ION BATTERIES LOGISTICS NETWORK

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Abstract: *This paper presents a bi-objective approach for designing logistics network for end-of-life lithium-ion batteries from electric vehicles. The first objective determines the optimal locations of collection points and treatment facilities, for collecting and processing of end-of-life lithium-ion batteries, with aim of minimizing total costs of the system. The second objective minimizes risk associated with transport of end-of-life lithium-ion batteries for end users located along the routes of transportation vehicles. Proposed model was tested on illustrative example.*

Keywords: *electric vehicles, lithium-ion batteries, logistics network design*

1. INTRODUCTION

Lithium-ion batteries (LIBs), have been used widely in many electronic devices like cell phones, laptops, leisure equipment, etc., due to its rechargeable nature. In recent years, LIBs have been used as a power source for electric vehicles, replacing nickel-metal hydride batteries (Wang et al., 2014). Electric vehicles are becoming popular worldwide, due to economical and environmental benefits (Figure 1). According to EEA (2018) there are several different electric vehicle types which includes: battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), range extended electric vehicles (REEVs), hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs). The emphasis of this paper is on BEVs, defined as vehicles that uses electricity stored in an on-board battery and powered by an electric motor. Due to technologic development and environmental concerns, it is expected that production of LIBs will continue to grow. Only in EU, BEVs comprised around 0.6 % of all new car registrations in 2017 and by 2030, BEVs could be between 3.9 % and 13.0 % of new car registrations (EEA, 2018). This means that significant quantities of LIBs will enter the waste stream in the future, so some changes in logistics infrastructure as well end-of-life LIBs processing will be needed (Figure 2). For example, facilities for remanufacturing or recycling of LIBs must be located. That means that existing logistics infrastructure needs to be reorganized or new

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logistics infrastructure should be designed in order to deal with end-of-life LIBs in environmental and safe manner.

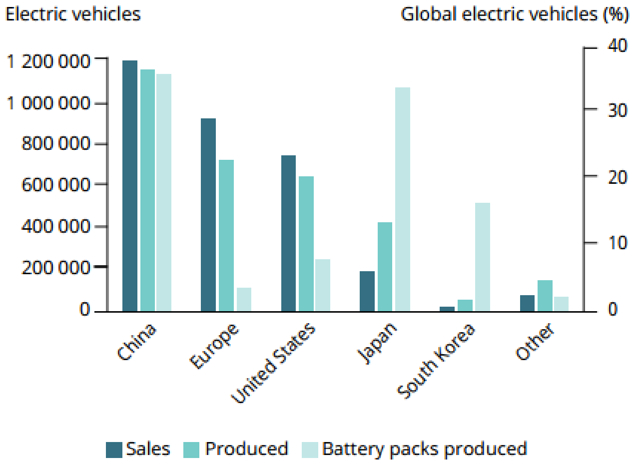

Figure 1. Number of light-duty passenger electric vehicles sold, produced, and battery packs produced between 2010 and 2017 (EEA, 2018)

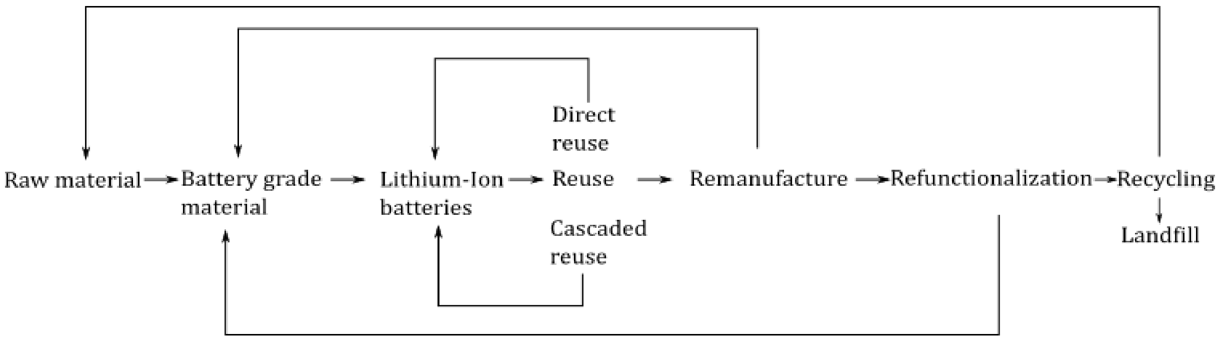

Figure 2. Options for the end-of-life stage of LIBs (EEA, 2018)

Since, end-of-life LIBs is relatively new waste stream there has been little incentive for the development of infrastructure and processes for recycling and reuse (EEA, 2018). Also, there aren't a lot of papers that can be found in the literature dealing with design of logistics infrastructure for end-of-life LIBs. Li et al. (2018) proposed a mathematical model for designing closed loop supply chain network model for LIBs remanufacturing considering different quality levels of spent battery. Authors developed an optimization model to maximize the network profit. Gu et al. (2018) optimized total profits in the EV battery supply chain in different batteries period of use, by developing the optimal pricing strategy between manufacturer and remanufacturer, discussed the relationships between return yield, sorting rate and recycling rate. Wang et al. (2014) developed an optimization model to analyze the profitability of recycling facilities, commodity market prices of materials expected to be recovered, and material composition for three common battery types. The majority of the paper dealing with end-of-life LIBs is concentrating on predicting quantities of end-of-life LIBs, remanufacturing and recycling process technologies, and investigating future demands of raw materials for LIBs manufacturing (Richa et al., (2014), Winslow et al. (2018)). On the other hand, LIBs falls in the category of dangerous goods according to the International Air Transport Association (IATA), requiring special handling (EPA, 2018). According to EPA (2018) LIBs technology is not intrinsically safe because short circuit, overcharge, over-discharge, crush, and high temperature can lead to thermal runaway, fire, and explosion. Hence, dangerous characteristics must be considered when designing logistics network for end-of-life LIBs. From here, the main attention of the paper is to present a possible approach for designing logistics networks for end-of-life LIBs. Two objectives are defined, where first one minimizes costs of establishing facilities as well transportation costs. The second objective minimizes the risk associated with transport of end-of-life LIBS for end users located along the routes of transportation vehicles. The rest of the paper is structured as follows. Description of the problem as well as mathematical formulation is presented in Section 2. In Section 3 an illustrative example is presented, while Section 4 summarizes findings and provides some thoughts regarding future research.

2. DESCRIPTION OF THE PROBLEM

Problem considered in this paper has following characteristics. End users as LIBs generators, are represented by population centers located at known sites *i*. It is assumed that v_i residents are located at site *i*, each one generating q_i units of LIBs. Also, it is assumed that generation of LIBs, has uniform distribution with parameters (500, 2500) like in Subula et al., (2015). All generated units of LIBs should be collected from end users and transported to treatment facility via collection points. Also, during the treatment process, some of the LIBs, due to number of reasons, could end up in the landfill site (Figure 3). In proposed model, we assumed that location of landfill is known, so no modeling parameters and variables for landfill is used.

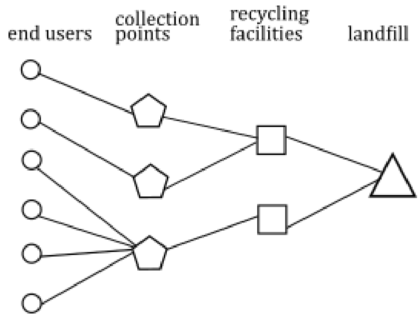

Figure 3. Modeled reverse logistics network for end-of-life LIBs

Following notation is used for mathematical formulation of the problem.
Sets:

$I = \{1,\dots N_i\}$ end users zones (LIBs generators)

$K = \{1,\dots N_k\}$ potential locations for collection points (CPs)

$J = \{1,\dots N_{j+1}\}$ potential locations for treatment facilities plus disposal option

Parameters

α minimal disposal fraction of LIBs

G_k capacity of collection point *k*

G_j capacity of treatment facility *j*

C_{ik} transportation costs of transporting LIBs from to end users zones *i* to collection point *k*

C_{kj} transportation costs of transporting LIBs from collection point *k* to treatment facility *j*

C_{j+1} transportation costs of transporting LIBs from treatment facility *j* to landfill site j+1

Variables

X_{ik} fraction of LIBs quantities transported from end user zone *i* to collection site *k*

X_{kj} fraction of LIBs transported from collection point *k* to treatment facility *j*

X_{j+1} fraction of LIBs transported from treatment facility *j* to landfill site *j+1*

Y_k binary variable, Y_k=1 if collection point k is opened, otherwise Y_k =0

Y_j binary variable, Y_j =1 if treatment facility j is opened, otherwise Y_j =0

p_j - LIBs quantities transported to treatment site *j*

p_k- LIBs quantities transported to collection site *k*

Then, the formulation of the problem as a mixed integer linear programming problem is given by

min $$OF1 = \sum_k f_i y_k + \sum_j f_j y_j + \sum_i \sum_k C_{ik} X_{ik} + \sum_k \sum_j C_{kj} X_{kj} + \sum_j C_{j+1} X_{j+1} \quad (1)$$

min $$OF2 = \sum_i \sum_k v_{ik} X_{ik} + \sum_k \sum_j v_{kj} X_{kj} + \sum_{j+1} v_{j+1} X_{j+1} \quad (2)$$

s.t.

$$\sum_k X_{ik} = q_i, \forall i \quad (3)$$

$$\sum_i X_{ik} - \sum_j X_{kj} = 0, \forall k \quad (4)$$

$$(1-\alpha)\sum_k X_{kj} - X_{j+1} = 0, \forall j \quad (5)$$

$$X_{ik} \le Y_k G_k, \forall i, k \quad (6)$$

$$X_{kj} \le Y_j G_j, \forall j, k \quad (7)$$

$$\sum_k X_{kj} \le Y_j G_j, \forall j \quad (8)$$

$$\sum_i X_{ik} \le Y_k G_k, \forall k \quad (9)$$

$$\sum_i X_{ik} = p_k, \forall k \quad (10)$$

$$\sum_k X_{kj} = p_j, \forall j \quad (11)$$

$$p_j \ge y_j, \forall j \quad (12)$$

$$p_k \ge y_k, \forall k \quad (13)$$

$$Y_k, Y_j \in \{0,1\} \tag{14}$$

$$X_{ik,} X_{kj}, X_{j+1} \geq 0 \tag{15}$$

Objective function (1) minimizes transportation costs of transporting LIBs from end user zones to collection points, treatment facilities and landfill sites. Objective function (2) minimizes the risk for residents located along the transportation routes of vehicles transporting LIBs. Equitation (3) ensures that all LIBs quantities located at end user zones are transferred to collection points. Constraints (4) and (5) are flow conservation constraints, for collection point and treatment facility level respectively. Equitation (5) models the minimum disposal fraction from treatment point level. Constraints (6) to (9) are capacity and opening constraints, but since we are not determining locations of landfill sites, no opening constraints are used for this type of facility. Constraints (10) i (11) determines the quantities of LIBs transported to collection points and treatment facilities, respectively. While the constraints (12) and (13) enables that locations for collection points and treatment facilities aren't opened if some quantities of LIBs isn't allocated to them. Constraint set (14) enforce the binary restriction on the Y decision variables, while constraint set (15) requires the decision variable X to be continuous between zero and one.

3. NUMERICAL EXAMPLE

In this section, the proposed bi-objective model for collection points and treatment facilities locating for end-of-life lithium-ion batteries was tested on small scale illustrative example. The observed example consists of 335 end users (LIBs generators), 9 nodes which are simultaneously potential collection points and treatment facility locations, and one known location for landfill site. Input parameters for numerical example are presented in Table 1 (adopted and slightly modified from Subula et al. (2015)).

Table 1. Input parameters for numerical example

Parameters	**Values**
LIBs generation (units)	Uniform distribution (500,2500)
Unit transportation cost for LIBs (€/km unit)	0.8
Fixed cost of opening collection centers	100000
Fixed cost of opening treatment facilities ($)	300000
Capacity of collection points (units)	120000
Capacity of treatment facilities (units)	550000
α minimal disposal fraction of LIBs	0;0.3;0.5;1

Due to large number of end users zones, distances used for calculating transportation costs are not presented in this paper. In order to solve proposed bi-objective model a number of methods can be used. In this, paper relaxed lexicographical method was used that allows the decision maker to express importance of the objective functions (i.e. ranks them by relevance). In this paper, the objective function indices define their ranking so the most important is expressed as OF1, and OF2 is second in rank by the relevance. Problem was developed using Python 2.7 programming language and solved by CPLEX 12.6 software. Numerical results for α =(0, 0.3,0.5,1) are presented in Table 2.

Table 2. Numerical result for α =(0, 0.3,0.5,1)

	OF1 value	OF2 value	opened CPs	opened TS
α =0.5	5689740	25559139888	2,3,4,7,9	2,3,4,7
	6000000	22819969120	1,2,3,4,7	1,2,3,4,7
	7000000	14678084881	1,2,4,7,9	1,2,4,7,9
	8000000	13312505871	1,4,7,8,9	1,4,7,8,9
	9000000	13053803405	1,4,7,8,9	1,4,7,9
	10000000	12906755386	1,4,7,8,9	1,4,7,9
	11000000	12759707366	1,4,7,8,9	1,4,7,9
	12000000	12600683304	1,4,7,8,9	1,4,7
	13000000	12507079952	1,4,7,8,9	1,4,7
	14000000	12413476600	1,4,7,8,9	1,4,7
	15000000	12319873248	1,4,7,8,9	1,4,7
	16000000	12238040603	1,4,7,8,9	4,7
	17000000	12210270961	1,4,7,8,9	4,7
	18000000	12182501318	1,4,7,8,9	4,7
	19000000	12154731675	1,4,7,8,9	4,7
	20000000	12126962032	1,4,7,8,9	4,7
	21000000	12095550651	1,4,7,8,9	7
α =0.3	4276880	21911015758	1,2,3,4,7	1,2,3,4,7
	5000000	12854492870	1,2,4,7,9	1,2,4,7
	6000000	11496616210	1,4,7,8,9	1,4,7,9
	7000000	11413014975	1,4,7,8,9	1,4,7,9
	8000000	11329413739	1,4,7,8,9	1,4,7,9
	9000000	11245812504	1,4,7,8,9	1,4,7,9
	10000000	11153181644	1,4,7,8,9	1,4,7
	11000000	11099605647	1,4,7,8,9	1,4,7
	12000000	11046029650	1,4,7,8,9	1,4,7
	13000000	10992453654	1,4,7,8,9	1,4,7
	14000000	10935098729	1,4,7,8,9	4,7
	15000000	10918640213	1,4,7,8,9	4,7
	16000000	10902181697	1,4,7,8,9	4,7
	17000000	10885723182	1,4,7,8,9	4,7
	18000000	10869264666	1,4,7,8,9	4,7
	19000000	10852806150	1,4,7,8,9	4,7
	20000000	10844970038	1,4,7,8,9	7
α =0	9054514	34181131611	2,3,4,7,9	2,3,4,7
	10000000	29208474504	2,3,4,7,9	2,3,4,7
	11000000	24115588859	1,2,3,4,7	1,2,3,4,7
	12000000	19344159134	1,2,4,7,9	1,2,4,7,9
	13000000	18001485362	1,2,4,7,9	1,2,4,7,9
	14000000	17209005166	1,4,7,8,9	1,4,7,9
	15000000	16867675037	1,4,7,8,9	1,4,7,9
	16000000	16479504901	1,4,7,8,9	1,4,7
	17000000	16181284270	1,4,7,8,9	1,4,7
	18000000	15968387193	1,4,7,8,9	1,4,7
	19000000	15755490115	1,4,7,8,9	1,4,7
	20000000	15523945466	1,4,7,8,9	4,7
	21000000	15466636711	1,4,7,8,9	4,7
	22000000	15409327956	1,4,7,8,9	4,7
	23000000	15352019201	1,4,7,8,9	4,7
	24000000	15294710446	1,4,7,8,9	4,7
	25000000	15222002184	1,4,7,8,9	7
α =1	2128240	9190082238	1,3,4,6,7	1,3,4,6,7
	2200000	8969099119	1,4,7,8,9	1,8,9

In case when α=0.5, marginal solution for OF1 is y_k=(0,1,1,1,0,0,1,0,1) and y_j=(0,1,1,1,0,0,1,0,0) and objectives' values are OF1=5689740, OF2=25559139888. Marginal solution for OF2 is y_k=(1,0,0,1,0,0,1,1,1) and y_j=(0,0,0,0,0,0,1,0,0) and objectives' values are OF1=21000000€, OF2=12095550651 residents*kg. In case when α=0.3, marginal solution for OF1 is y_k=(1,1,1,1,0,0,1,0,0) and y_j=(1,1,1,1,0,0,1,0,0) and objectives' values are OF1 4276879.568€, OF2= 21911015758. In case when α=1, which represents the case when all collected LIBs units are sent to landfill site, marginal solution for OF1 is y_k=(0,1,1,1,0,0,1,0,1) and y_j=(0,1,1,1,0,0,1,0,0) and objectives' values are OF1= 9054514.351€, OF2= 34181131611. In case when α=0, which represents the case when all collected LIBs units are sent to transfer stations, marginal solution for OF1 is y_k=(1,0,1,1,0,1,1,0,0) and y_j=(1,0,1,1,0,1,1,0,0) and objectives' values are OF1= 2128240.322€, OF2= 9190082238. It is usual that the decision maker has preferences for certain objectives (e.g. costs), so one solving approach could be relaxed lexicographic method to support such preference expressed by their order. If the decision maker chooses in this model OF1 as preferable objective, then if for example he/she allows the total cost to increase for 5.45 % from the optimal OF1 (from 5689740 to 6000000€), OF2 could decrease for 10.72 % (from 25559139888to 22819969120) for α=0.5.

3. CONCLUSION

This paper presents a possible approach to define the optimal logistics network for end-of-life LIBs. The proposed model aims finding effective strategies for the return of discarded LIBs from end users to treatment facilities and landfill site, via collection points, with minimal costs. The second objective in the proposed model minimizes the risk associated with transport of end-of-life lithium-ion batteries for end users located along the routes of transportation vehicles. Although the results obtained give some answers related to the possibility of defining optimal locations of these facilities, in sense of indicating complexity and importance of the problem, numerous aspects of the problem are still without answer, and need future research. Future research could include aggregation concept to be applied for grouping end users to be analyzed as a LIBs generation sources, different approaches for problem solving, consideration of uncertainty in generated LIBs quantities, etc.

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