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Methodology and Application of Electric Vehicles Battery Packs Redesign for Circular Economy

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Abstract

Li-Ion packs are high added-value products with great amounts of critical materials (e.g. Lithium and Cobalt), therefore an effective circular economy strategy is mandatory for these components. Nevertheless, commercial electric vehicles' batteries are not designed to be easily, safely and cost-effectively disassembled, tested and remanufactured or recycled. To overcome this industrial limitation, this paper presents a circular-economy-oriented redesign study for e-mobility batteries. Through a structured design criteria evaluation methodology (House of Quality), product's features impacting the most on circular economy design requirements have been assessed.

Keywords: redesign; e-mobility; Lithium-ion batteries; circular economy; remanufacturing; house of quality.

1. Introduction

Nowadays, the exponential growth of electric mobility is mainly due to energy and environmental issues, with CO_2 regulation, oil price and cost of ownership as main drivers for Electric Vehicles (EVs) diffusion [1]. It was predicted, indeed, that EVs sales will overcome combustion engine cars in 2040 [2].

The main EV component is the Lithium-ion battery (LIB) pack, where several individual electrochemical cells are connected in series and parallel to reach the desired power [3]. The modularity and the management of EV LIBs, from single cells to modules to the final pack, require the presence of other components (e.g. cooling systems, controlling devices, external protective frameworks and electrical and mechanical connections), leading to complex structures of about 1x2 m, 200-400 kg and at least 300 V [4].

According to the high economic value of constituent materials (first of all Cobalt and Lithium), to safety concerns and to the growing amount of End-of-Life LIBs, a Circular Economy (CE) approach could be advantageous in order to recover the residual functionalities or the raw materials contained in this product. In particular, reuse, remanufacturing and recycling strategies are currently under investigation in terms of economic and technical feasibility, in order to reduce their environmental impact [5,6]. However, such strategies cannot be fully implemented since the current EV LIB packs are not designed to be easily, safely and cost-effectively disassembled, tested and reassembled. In particular, the presence of irreversible joints (e.g. welding and rivets), glues, non-protected high voltage components and the huge variability of car and LIB models make the disassembly process extremely complex, with low opportunities for automation [7].

To overcome these limitations, product re-design should be considered, promoting a strong collaboration between different actors of the value chain, from the producers to the final recyclers. Examples of circular product design include standardization of formats and subcomponents, architecture modularization, easy identification of parts and materials and minimization of hazardous tasks [8,9].

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According to this concept, in the following work the main circular design strategies will be analyzed in order to identify the most important guidelines for an efficient and effective EV LIBs Redesign.

2. House of Quality for Circular Economy redesign

The House of Quality (HoQ) is a well-known design tool used to link product's engineering specifications to customer expectations [10]. For its robustness, HoQ has been chosen as the redesign support methodology for this paper, downstream of a specific customization to CE.

The funding idea of HoQ is that products should be engineered to integrate users' requests into technical design requirements. In its most basic form, the tool is founded on the relationship matrix, where the product development team assesses how much the design specifications affect the customers' needs. Other features of the methodology, as the prioritization of customer needs or the roof matrix which evaluates the interdependence of engineering requirements, complete the design support tool.

Considering that in recent years the design and engineering communities put great effort in the conceptualization and exploitation of design for CE, specific guidelines have been drawn in order to allow the manufacturing of a product which is by purpose easy to be reused, repaired, remanufactured or recycled [11]. Some examples can be the use of recyclable materials, the choice of easily accessible and reversible joints, the use of modular components and so on.

In this paper, the HoQ is declined for design for CE purposes: the generic "customer needs", which populate the rows of the evaluation matrix, are then substituted by these criteria. This enables the systematic evaluation and prioritization of engineering specifications to derive the product CE suitability during design phase.

3. House of quality for automotive battery packs redesign

In this paragraph, the rows and columns which populate the HoQ evaluation matrix of Fig. 1 are described. Particularly, the first sub-paragraph presents engineering specifications which commercial EV batteries must consider in their design, while the second sub-paragraph presents the CE oriented redesign requirements to rise the applicability of recovery strategies to EV batteries.

3.1 Engineering specifications

Determined as the fundamental design parameters to be considered for the production of a functional EV LIB pack, the engineering specifications represent the columns of this HoQ tool. Their precise identification, then related to customer's needs, will lead to a prioritization of design parameters for the simplification of CE tasks, distinguishing between the necessary ones and those less impacting to be independently chosen according to designer own preferences.

The identified engineering specifications have been grouped in categories and their importance is highlighted in the following:

- *Cell parameters*: the geometry and size of cells have a strong impact on space arrangement and connections in a LIB pack. Pouch cells, for example, need protective frameworks and are generally held together with lot of glue, making disassembly extremely difficult. Moreover, LIBs chemistry is a significant factor both for final functional properties and recycling strategies.
- *Junction types*: there are two different types of joining systems, whose management is different in terms of safety issues, required tools or stored potential energy. Electrical connections are used at each hierarchical level (cell, module, pack) to allow the flow of current and the monitoring of temperature and voltage through sensors. Conversely, structural connections allow to maintain LIB pack components in position, to isolate the pack from the external environment and to ensure the proper pressure inside modules. Currently, junctions represent the main challenge for disassembly.
- *Cooling/heating system*: the control of temperature is essential to ensure the optimal operating performances and to avoid thermal runaway. Nowadays different options are available (passive/active, air/liquid) and the T range is monitored through external systems and embedded materials (e.g. dissipative metal plates).
- *Pack case:* the external case ensures LIB protection and isolation from mechanical stresses, pollution, vibrations, etc. It strongly influences the final pack weight and stability.
- *Pack specifications*: according to the specific application (Hybrid/Full electric vehicles and different car models), the number of modules, the type of connections, the stacking efficiency and the BMS typology change, influencing pack materials and weights.
- *Assembly architecture*: the final arrangement of each component in terms of space orientation and direction could drastically modify the disassembly procedure, limiting the introduction of automated solutions. For example, the use of a layered structure where components are overlapped or the positioning of cells to have all terminals on the same side have a significant impact on operating times in case of non-destructive disassembly.

All these engineering specifications must satisfy LIB safety requirements, ensured through standardized tests on the final product, and manufacturing and material costs, related to the readiness of technologies and the provision of primary raw materials. Being these parameters unavoidable, they are not considered as modifiable variables and are excluded from the relationship matrix.

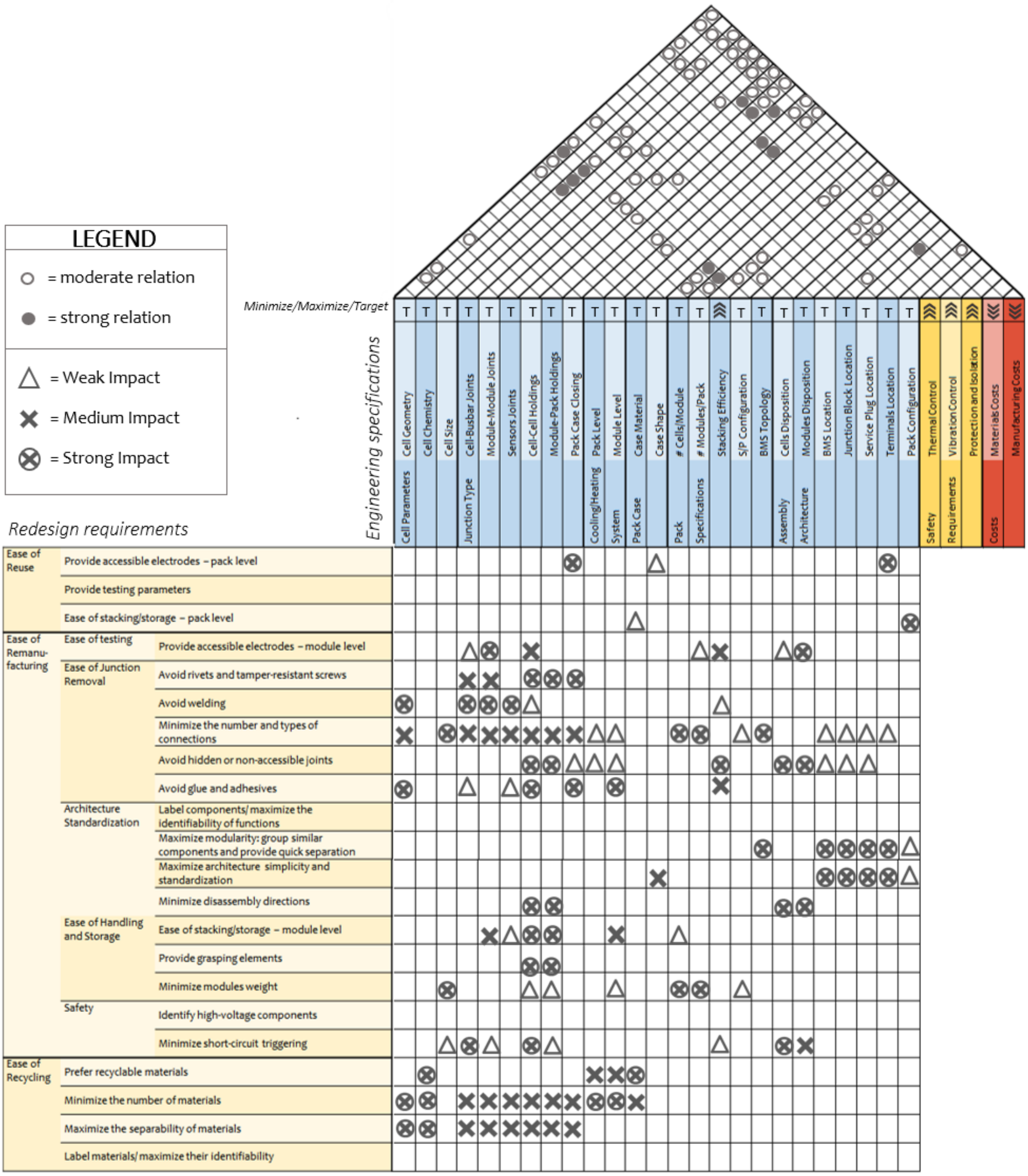

Fig. 1. House of Quality framework for the Redesign of EV LIB packs.

3.2 *Redesign for Circular Economy requirements*

The HoQ rows correspond to the list of design guidelines enabling a CE approach: starting from state-of-the-art design for CE criteria, a set of specific requirements aimed at EV LIBs circularity has been set. Particularly, each of the three main industrial strategies to recover e-mobility batteries (i.e. reuse, remanufacturing and recycling) has been spread into specific subcategories, able to remove the existing challenges of the post-use stakeholders.

- *Reuse*: to reuse an EV LIB pack means to detach it from the vehicle, to test its residual state-of-health and to use it as an electric energy storage system in a less demanding environment, for example for stationary applications to support renewable energy sources [12]. An easy and efficient EV LIB reuse is enabled by accessible electrodes of the battery pack for a quick and safe connection to the testing equipment, by the availability of testing standards for the assessment of the residual state-of-health of the battery and by a stacking-oriented geometry and design.

- *Remanufacturing*: to remanufacture an EV LIB pack means to disassemble it to modules or single cells level, to test the residual state-of-health of these single subcomponents, and to reassemble only the less degraded ones [13] in a new battery pack with a renewed added value [14]. An easy and efficient EV LIB remanufacturing is enabled by accessible electrodes of the battery modules for a quick and safe connection to the testing equipment, by reachable and non-destructive joints for a lean disassembly, by standardization and modularity of the pack architecture promoting the automation of the disassembly and testing phases, by an easy handling of the modules thanks to their shape, weight and grasping elements availability and by safety measures, as the visualization of high-voltage components and the minimization of short circuit hazard.
- *Recycling*: to recycle an EV LIB pack means to treat it with a combination of mechanical, chemical and thermal processes to recover a set of valuable target materials available in the battery [15]. Being EV battery packs complex products, single subcomponents undergo dedicated recycling streams after the disassembly. Among others, the most important components of the pack in terms of materials' value are the LIB cells. An easy and efficient EV LIB recycling is enabled by the availability in the product of a low number of different materials, all recyclable, easily separable, and identifiable by labels.

4. Results and discussion

Once identified the technical specifications for the production of an EV LIB pack and the redesign requirements derived to enable CE strategies of reuse, remanufacturing and recycling, the HoQ tool has been used with the aim of assess the most important design interventions. All the input data has been processed through HoQ in order to obtain a single, intuitive and highly visual framework, outlining all implications. According to internal correlations and experts' evaluations, the final result is a list of features of a hypothetic product, determined in advance with respect to the effective production and weighted accordingly to their impact on CE management of End-of-Life LIBs.

4.1. Roof matrix

Located in the upper side of HoQ structure, the roof matrix allows the identification of correlations among engineering specifications, clearly highlighting the existing links. Through the identification and the quantification (i.e. moderate or strong) of relations, the cascade effect due to the cause-effect chain among technical requirements is shown to warn engineers and designers on product complexity. For example, the geometry of cells could slightly affect the number of cells per module and has a significant influence on the final stacking efficiency. The use of cylindrical cells, with reduced dimensions, in fact, provides a low capacity and requires lots of parallel connections increasing the number of needed cells and the overall space of LIB pack. Conversely, prismatic sub-components could be modulated according to the required power and could be placed side by side without interspaces between one and the other.

As result, it emerged that the most impactful engineering specifications are cells geometry, size, disposition and stacking efficiency. Other influential requirements are modules disposition and cells and modules holdings.

4.2. Evaluation matrix

Representing the body of the whole HoQ model, the evaluation matrix allows to assess the impact and the relationship strength (weak, medium or strong) of re-design requirements towards each single engineering specification. In particular, for EV LIBs design enabling a CE approach, the following interventions has been prioritized: module-pack holding, cell-cell holding, module-module joining, cell geometry, cell-busbar joining and pack case closure.

The choice of cells and modules framework, indeed, influences the assembly of different components in terms of connections and space arrangement and maintains the product at the optimal operational conditions (e.g. ensuring the proper pressure between cells). A re-design of these holdings could increase the safety and the easiness of disassembly, avoiding glues and non-modular components, and promotes maintenance and remanufacturing operations, reconverting the framework for new applications.

Likewise, the electrical joints among cells and modules have a strong impact on the final EV pack design and could dramatically support CE strategies for end-of-life LIBs. Easily accessible and identifiable joining systems, to be removed with non-destructive technologies, promote the testing and the reconfiguration of sub-components in order to reuse them. Moreover, a proper design is able to minimize operator exposure to high-voltage connections and the possibility of short circuit triggering.

Finally, the conceptualization of a proper pack case, where electrodes remain accessible for testing and the opening procedure is reversible through standard tools, is recommended.

5. Conclusion

Currently available EV LIB packs lack of CE oriented design features. This dramatically reduces the effective applicability of high added-value recovery strategies to these products.

To overcome these barriers, in this paper, a design for circular economy support tool has been presented. The HoQ methodology, adapted for product circularity enhancement through design, has been exploited to match CE requirements and engineering specifications of EV LIBs.

The evaluation matrix highlighted significant outputs. The main one is that the assembly specifications, as the junction types, are the design choices which mostly affect the product disassembly easiness and therefore recovery efficiency.

Although this study already presents valuable structured results to guide designer and engineers in the development of more CE oriented EV batteries, this research can be improved and expanded. For example, a systematic prioritization of the redesign requirements made by CE stakeholders (e.g. through the Analytical Hierarchy Process) is being investigated and would provide a quantitative assessment of the engineering specifications which most impact the LIB EVs circularity.

However, this study represents a valuable tool for e-mobility stakeholders which can be exploited both for the design or redesign of new LIB EV batteries and for the evaluation of CE readiness of already existing products.

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