Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 217 (2023) 248–257

Procedia Computer Science

www.elsevier.com/locate/procedia

4th International Conference on Industry 4.0 and Smart Manufacturing

A predictive eco-design method and tool for electric vehicles of Industry 4.0

Luca Manuguerra[a*], Federica Cappelletti[a], Francesca Manes [a], Michele Germani[a]

[a]Università Politecnica delle Marche, Via Brecce Bianche 12, Ancona 60131, Italy

Abstract

Decisions made at the design stage have a far-reaching effect on the product's entire life cycle. The present paper proposes a method, from which a tool is further developed, to support designers of industrial electric vehicles in making informed decisions. The eco-design method and tool can be applied to the design of different electric vehicles such as autonomous guided vehicles and shuttles, which are widely used for improving logistics in Industry 4.0 contexts. The goal is to make the designer more aware of the consumption of material resources and able to configure a use phase more efficiently in energy resource consumption. Unlike existing literature, this method contemplates all the product lifecycle stages and provides qualitative results. The method is intended for the design of electric vehicles and evaluation of choices from the environmental point of view; nevertheless, it can be further adapted for other products and economic evaluations.

Keywords: Design for X; Life Cycle Analysis and Design; Impact; Sustainable Design

1. Introduction

The issues relating to environmental pollution, climate change, and natural resource scarcity underline the need for a drastic change of direction at both social and industrial levels, to preserve natural ecosystems and human existence. Nevertheless, this must cope with the constant technological development that is pervading private and industrial contexts. With the fourth industrial revolution, multiple tools have popped up in shopfloors, i.e. cobots, (collaboration robots), Automatic Guided Vehicles (AGVs), and highly automated lines.

---

* Corresponding author. Tel.: +39-071-220-4880;
E-mail address: l.manuguerra@staff.univpm.it

10.1016/j.procs.2022.12.220

Their contribution to process optimization is not under discussion, however, these solutions need electricity to run and may require critical materials for their construction. It is, therefore, necessary to review the design and production of these products, focusing on sustainable development. Early design decisions can have a very significant impact on sustainability. These not only relate to material and manufacturing choices but have a far-reaching effect on the product's entire life cycle [1], including End of Life (EoL), logistics, and maintenance. Environmental impacts of a product's life cycle should be considered in the evaluation of the concept feasibility together with other traditional design criteria (e.g., operational performance and costs). This requires the design team to be able to evaluate the environmental performance of many alternative concepts early in the design process [2]. To support designers in making informed decisions several tools have been developed; among the most used, is the Life Cycle Assessment (LCA) methodology. The present paper focuses on a method to support the design of Electric Vehicles (EV), which represent a product category significantly affected by the environmental issue. The EV emissions are not eliminated but are allocated upstream of the fuel cycle and downstream on materials, production, and EoL processes [3]. Several environmental sustainability analyses focus only on the use phase or battery life, excluding materials, maintenance, and EoL phases [4]; [5]. In addition, there are also comparative analyses between traditional and electric cars[6]. Moro et Helmers proposed a hybrid method that keeps the main hypotheses of the Well-to Wheel (WTW) methodology but integrates them with LCA data restricted to the Global Warming Potential (GWP) occurring during the manufacturing of the battery pack. The life cycle suggested in the work possesses narrower boundaries compared to usual LCA studies of electric cars. Also, it is restricted to carbon footprint quantification. The authors are aware that the quantification of other impact categories can lead to adverse results [7]. Nordelof et al. review 79 works with the purpose to investigate the usefulness of different types of LCA studies of EVs to provide robust and relevant stakeholder information. They distinguish WTW studies, complete LCAs, and battery LCAs; they also classified the main research field and what the different groups of studies cover in terms of vehicle technology and impact assessment. They outlined a strong focus on light passenger vehicles and greenhouse gas emissions [8]. In addition to that, any purpose for supporting the design phase has not been highlighted. It is thus clear that there is a lack of methodologies whose purpose is to provide information and sustainability hints in the design phase; moreover, literature should widen the range of analyzed products, because electrification is a topic that is pervading many sectors and products not only with passenger vehicles. Urges also the need for research that includes all stages of the life cycle and is simultaneously suitable for the early stage of design. To be suitable for the first stage of design, a tool must be able to handle very little data and nevertheless return consistent results. Raugei et al. [4] propose a complete and fully consistent LCA-based comparison of a range of light weighting options for compact passenger vehicles. Through their flow diagram of the main steps in the manufacturing of a complete Li-ion battery pack Raugei et al. [5] only focus on the battery lifecycle for electric vehicles. On the other side, Petrauskiene et al. [6] rely on the data of common products already released on the market to collect data for their inventory. Similarly, Marmiroli et al. [8] compare the impact of electric, compressed natural gas and diesel light-duty vehicles knowing the main features of the products. It is clear how studies related to the evaluation of the environmental impact of electric vehicle and their comparison with a traditional combustion engine are available, but the methods proposed are not intended for the early design stages when little data are available. In this way, it is not possible to support designers in decision making and goodness evaluation of their choices when it is still possible to make changes, nor the designers can obtain a complete overview of the environmental impacts throughout the lifecycle, under different circumstances, also comparing them to traditional vehicles. The literature needs a streamlined environmental evaluation tool for the early stages of the design process. In this context, the goal of the paper is to provide a simplified and flexible predictive method for environmental analysis that considers every phase of the whole life cycle and supports the designers in quantitatively evaluating the consequences of their choices. Thus, the method aims to provide support to the designer in the early design phase, estimating the environmental burden of an EV. The proposed approach overcomes the existing literature filling two main gaps: i) the need for tools able to handle few data and thus be suitable for the very early stage of design and ii) the chance is given to designers the possibility to assess and compare alternatives head in time in the product lifecycle. In addition to that, firstly, all lifecycle phases are accounted and secondly, the derived tool is meant to be adapted to a wide range of electric vehicles, that encompasses also vehicles employed in industrial contexts. The tool allows for to implement of a personalized driving cycle of the vehicle in terms of speed, distance and slope required, as well as to define different scenarios related to the workload; in this way, it will be possible to configure the best strategy in detail the Use Phase of the vehicle to make it more efficient in the consumption of energy resources. The paper is structured as follows: Section 2 describes the proposed method, Section 3 introduces the tool developed from the method for the design of EVs and critically discusses it; Section 4 shows the result of the first implementation of the tool, and the conclusion briefly summarizes the work.

2. Materials and Methods

Being conscious of the current literature gaps, a simplified and flexible method intended to make the designers aware of the most impactful lifecycle phases of an EV has been developed. The method is general and therefore can be used for a wide range of EVs, i.e. AGV, cars, minibus, bus, etc. It is intended to support the designer who is not provided with much product lifecycle information to obtain an overall picture of how environmental impacts are spread throughout the lifecycle; this will be helpful to provide feedback on the made choices. For higher usability in the first stages of design, when few data characterize the product, the method expects standard values to be used, although the grade of detail decreases. The method is for different types of EVs, industrial vehicles among them. The proposed method (Fig. 1) is based on the development of a simplified and modular structure where, for each life cycle phase, the main product parameters are included.

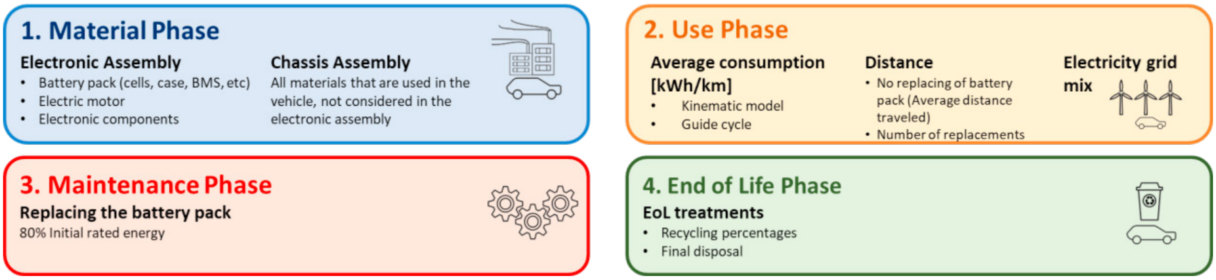

Fig. 1. Life cycle phases and parameters considered by the method

For the Material Phase, the required parameters are the itemization of materials and components employed and their masses. For the Use Phase, the parameters required arise from the formulation at the base of the calculation of energy consumption, the fade model of a lithium-ion cell's capacity, and the modelling of the specific electricity grid mix. For estimating energy consumption, three approaches can be found in the literature: values declared by manufacturers, detailed technical models, and empirical values [7]. The willingness to consider and compare different use scenarios led to the choice of technical models in this study. Empirical values are not available in the first stage of design.

2.1. Material Phase Model

The method focuses on EVs whose structure can be divided into two macro groups [3]:

- Electronic Assembly (EA): all components related to the electronics of the vehicle, namely battery pack, electric motor and electronic components;
- Frame Assembly (FA): all the materials the vehicle is made of, excluding those of the EA.

The approach followed for the modeling of the EA consists in describing its modules and components; also with the support of the most well-known commercial databases [8]. The FA contains the set of all parts and materials that have not been defined in EA [3]; not only the structural part of the vehicle but also all the components that belong to the dynamics, aerodynamics, bodywork, and interior of the vehicle are indicated.

2.2. Use Phase Model

The use phase model concerns the impact due to the use of the vehicle. Its two main contributions are the emissions related to energy consumption and particulate emissions. The first is proportional to the average consumption of the vehicle [kWh/km], the distance traveled during its lifetime [km], and the reference country electricity grid mix where the vehicle is recharged. The first is calculated through the application of a kinematic model [8] - [13] of the vehicle to a specific driving cycle. A driving cycle prescribes a speed versus time profile [14]. It expresses the speed required for the vehicle during its use on a chosen route, with a time resolution of one second. The driving cycles recommended in this study are part of the Worldwide harmonized Light vehicles Test Procedure (WLTP) [15]. The overall distance traveled may require the battery to be substituted once or more in a lifetime. It is estimated that a battery pack is replaced when it reaches 80% of the initial nominal energy [16]. The battery pack life prediction model is based on empirical formulas deriving from the observation of the results of a lithium-ion cell capacity fade analysis, as suggested by Wang et al. [17]. The calculation of the precautionary life of the battery pack considers the most stressful driving cycle and maximum transport load. The particulate emissions refer to the consumption of wheels, brakes, and the road; their environmental impact is significant; thus, they must not be neglected. The parameters required for this calculation are mass and distance traveled by the vehicle.

2.3. Maintenance Model

The maintenance phase examines the replacement of the battery pack for EVs. Its environmental burden consists of the emissions due to standard control operations during the life and the possible replacement of the battery pack. The prediction of the number of replaced battery packs expects the distance that can be traveled by the battery pack before being replaced to be evaluated. The new battery is only produced for replacing the old one; thus, the material and EoL phases of the new battery are attributed to the maintenance phase. In this way, it will be possible to compare the impact of the maintenance phase when the replacement takes place and does not. In the maintenance phase related to the vehicle, the impacts related to the maintenance workers of the cooling system and wheel change are also considered.

2.4. End of Life Model

EoL phase modeling consists of defining which, how much and how materials and components are managed and/or disposed of. Despite a possible use for a second life, the total environmental impact of the replaced battery pack is allocated to its first life, as suggested by Faria et al. [18]. The considered parameters concern the mass percentages of the components and materials sent to a specific treatment. The percentages of materials/components that remain or that do not undergo any treatment are sent to landfills.

2.5. Environmental impacts calculation

The classification of the life cycle stages is the basis of the data acquisition; thanks to this, it is then possible to calculate the environmental impacts. Multiple methods are available, nevertheless, as suggested by Schau et al. [22], it is advisable to rely on recommended and satisfactory characterization models and associated characterization factors. Consequently, the categorization factors selected in this study belong to the two highest levels of recommendation. Five impact categories were selected to analyze the impact of the EVs on the environment, human health, and consumption of natural resources; in particular, the categories are: Climate change [kg CO2 eq], Human toxicity [kg 1,4-DB eq], Ionizing radiation [kBq U235 eq], Metal depletion [kg Fe eq] and Fossil depletion [kg oil eq]. The focus is on these five categories to carry out an accurate analysis, which considered different aspects of environmental impact but is still simple and immediate to be used in the early design phase. These categories of impact have been considered the most relevant, as suggested by Petrauskienė et al. [6]. Climate change is the most common environmental indicator used for EVs environmental impact due to its simplicity and overall impact comprehension [19]; Human toxicity and Ionizing radiation make it possible to consider the impact on human health; in Ionizing radiation, consistent considerations on the electricity grid mix are involved; Metal and Fossil depletion allow considerations on resources consumption; in recent years, Metal depletion is acquiring an increasingly important role; the second is important in the comparison with Internal Combustion Engine Vehicle (ICEV).

3. Tool

The proposed method has been applied and then a tool has been developed. This is useful to increase the designers' awareness concerning both the environmental impact of EVs and the consequences of their choices. The tool can be employed very early in the design stage, also when few data characterize the product; in fact, standard values are proposed by default and may be used in the calculation when any more specific information is not available. The tool is meant to be used in the design process of electric vehicles, in industrial scenarios of companies smaller in dimensions, than the multinational car manufacturer. For example, the first implementation regarded an enterprise that produces industrial, military, and electric vehicles for public purposes whose design phase is still simple and the market still not as wide as the multinational corporations' market. Further implementation of the tool is expected to be in the case of an AGV, provided with a robotic arm. Here again, the main strength of the tool will be exploited: in the design process, the tool will have the role to introduce the concept of sustainability and provide a provisional quantitative comparison between different use and manufacturing scenarios. Although advisable, the tool is not linked yet to any 3D model software; thus it proposes itself as an additional tool for designers. However, its simplicity in use and clarity in function allows the designer to employ it very in advance of the 3D modeling phase, in the conceptual phase. Not all data are provided with suggestions; in addition to that, some suggestions partially adjust to the case; for example, the type of vehicle selected suggested changes up to the grade of the amplitude of the overall distance traveled by the vehicle in a lifetime; the number of cells of the battery, that is often unknown information because the battery is a commercial product and not produced by the EV manufacturer, is suggested according to the nominal cell voltage, the capacity cell voltage, the nominal battery capacity and nominal battery voltage. The driving cycle is also suggested according to the motor peak power and vehicle mass. The user can choose multiple driving cycles, however, the suggested one should be included among those. The tool, developed in Excel, is composed of multiple sheets, few must be edited by the user. The first is a general guide to the tool; the input sheet follows and information about the vehicle must be inserted; a third sheet shows all the results. The results can be edited depending on the choices related to the load and the driving cycle. Most of the sheets contain support material that the user can view, but not necessarily edit, because they are automated; these are dedicated to the evaluation of energy consumption with customized transport load and guide cycle, estimation of battery duration, and environmental impacts evaluation.

3.1. Tool structure

Three are the key elements of the tool structure, shown in Fig. 2:

- Database (DB), which is composed of Vehicle DB and Environment DB. The first contains the driving cycles and the fade model of a lithium-ion cell's capacity; these, together with the data inserted by the user, are used in the data processing. The second contains the unitary impacts for the product lifecycle phases and enables the environmental analysis;
- Admin interface, responsible for the data processing and the environmental analysis;
- User interface, that concerns both the input data entering and the output configuration; the user can choose which driving cycle and load to show.

Fig. 2 depicts examples of the abovementioned interfaces, about driving cycles and analysis output; moreover, it contains input and analysis data tables in a summarized version, only for demonstration purposes. Fig. 3 summarizes the three main steps (Input, Analysis, and Output) of the tool, described in detail in the next paragraphs.

3.2. Input

In the first step, the user is required to insert all the information needed for the analysis, of each lifecycle phase, as suggested in Section 2. Each of these categories provides data for the analysis phase.

Not all data coming from the designer can be used directly for the calculation of impacts, but some of these must first be processed. For this reason, the authors distinguished the data provided by the designer (Data Collection) from those computed by the tool (Data Processing). If some data are not available to the designer, the tool will recommend input values based on the information that is added progressively. The product function collects general information about the function of the vehicle, i.e. type of vehicle and its use, i.e. days of service per week, years of service provided, the total distance traveled required during the years of service, the maximum speed required and the number of seats. In the product structure, the materials and components of the vehicle are defined. As suggested by the method, the material phase is divided into EA and FA.

For the EA the main components are identified by specifying some of their characteristics:

- Battery pack (mass, number of batteries inside, battery efficiency, capacity, and nominal voltage):
    - Cells (number, capacity and nominal voltage of the cell, number of cycles per replacement);
    - Houses (type of material and its masses);

  - Battery Management System (BMS) (mass);
  - Other internal components (mass).
- Electric motor (number of motors, mass, efficiency, peak power);
- Electronic components (list of the other most important components, indicating the mass and relative efficiency, e.g., converter, weight, and efficiency).

For the FA, the main materials are identified and their percentage by mass of the total is reported.

The use phase collects data necessary to estimate the energy consumption and the reference electricity grid mix. The first requires the average consumption of the vehicle; this parameter is calculated by the tool through the definition of the driving cycle (customized or standard), Cx (coefficient of aerodynamic drag), the front area of the vehicle; transmission efficiency; percentage of recoverable energy during braking/deceleration, function attributed to the use of KERS (Kinetic Energy Recovery System), Charging power.

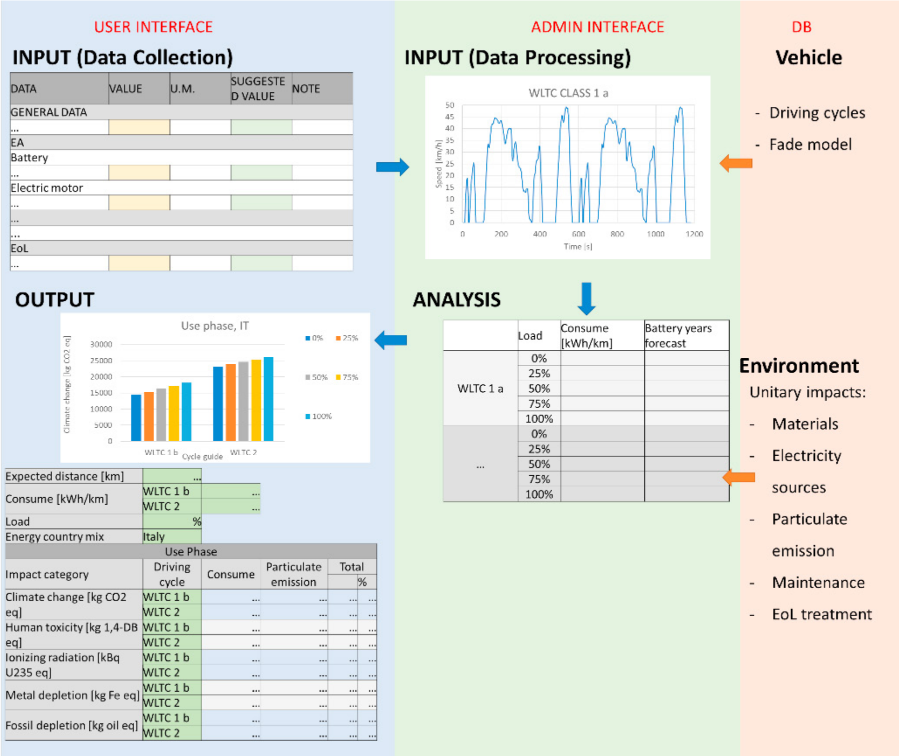

Fig. 2. Tool structure

In this way it was possible to assess:

- Average vehicle consumption [kWh/km]: it is calculated through the kinematic model to which the driving cycle is applied;
- Consumption of a traditional vehicle: a vehicle with the same characteristics but with the propulsion of a diesel engine.

The Maintenance phase core aspect concerns the replacement of the battery pack. The battery pack information previously defined is used to identify:

- Total distance traveled without replacing the battery pack, but respecting lifetime required;
- Prediction of battery pack lifetime: the prediction is based on the fade model of a lithium-ion cell's capacity and average vehicle consumption;
- Number of battery packs to be replaced for a total distance required.

EoL requires the definition of both the desired EoL treatment and the percentage of material sent to each treatment.

3.3. Analysis

This phase consists in calculating the environmental impacts based on the data inserted and previously processed. The impacts for the EV and the comparison scenarios are calculated according to the unitary impacts derived by the EcoInvent 3 database and calculated in SimaPro 8.0 with the Recipe midpoint (H) method. Concerning the Material phase, the EA components data were derived by the available information in the DB, following the method, while the FA components are differently modeled: materials are classified, no matter what function they fulfill, similarly it happens for potential manufacturing processes considered. The chosen impact categories are in accordance with those suggested by the method: Climate change [kg CO2 eq], Human toxicity [kg 1,4-DB eq], Ionizing radiation [kBq U235 eq], Metal depletion [kg Fe eq] and Fossil depletion [kg oil eq].

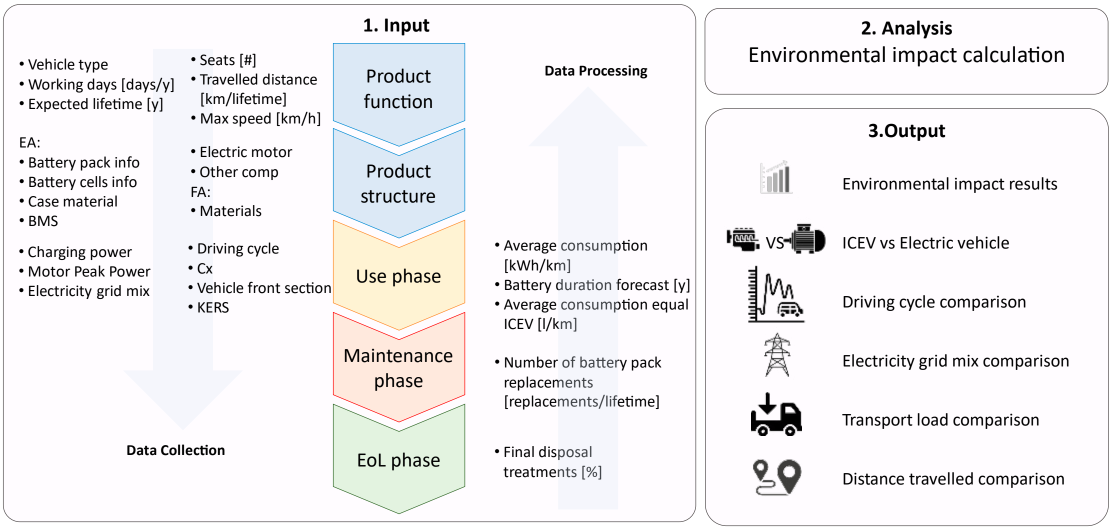

Fig. 3. Predictive eco-design tool workflow

3.4. Output

The main output of the tool is the total environmental impact of the EV expressed for the abovementioned indicators and the impact for each phase of the product life cycle. In addition, environmental impact comparison about: i) EV and ICEV, specifically a Diesel engine; ii) EV recharged with electricity from different grid mixes, i.e. Italian, European, customized (presence of private energy production systems, such as photovoltaic panels, wind turbines, etc); iii) Transport loads of the same EV (0%, 25%, 50%, 75%, 100%); iv) Driving cycles for the same EV; v) Distances traveled by the same EV.

4. Results

The developed tool has been applied during the design phase of an electric shuttle. The vehicle can carry a maximum load of 1920 kg and it has an unladen mass of 5000 kg including both the electronic assembly and the chassis assembly, so first the mass relative to the components of the electronic assembly was calculated; the rest of the unladen mass of the vehicle was used for the calculation of the material masses of the chassis assembly through the relevant percentages. There is no personalized driving cycle available. To conduct a broad analysis, three World-wide harmonized Light-duty Test Cycle (WLTC) guide cycles were chosen: WLTC class 1, WLTC class 2 v1.4 and WLTC class 2 [17]. The vehicle will be used for shifts of 8 hours a day for 5 days a week for 8 years of life, during which there is no provision for the replacement of the battery that will end its life together with the vehicle. It is estimated that the vehicle will be used 250 days a year. The battery pack is lithium-ion and it has been assumed that the replacement will take place when it reaches 80% of its capacity, or at 1500 cycles. The fade model from Wang [19] is chosen. The tool can optimize the curves of the fade model to comply with the design data of the battery pack, which expresses the capacity of the battery pack as a function of the number of cycles. This function, hidden from the user, allows calculating the maximum distance that the vehicle can travel before replacing the battery pack and therefore the battery packs necessary during its useful life.

A precautionary approach that considers the highest average consumption (WLTC Class 2) and the highest load percentage (100%) allows identifying the average distance traveled per day, which is 35 km per day or 70000 km traveled in 8 years. For the end-of-life phase, 85% of metals and 50% of plastics are sent to recycling; specific end-of-life treatments have been chosen for the components of the electronic assembly; everything that is not treated is sent to landfill. Fig. 4 compares the results obtained for the five impact categories for the three chosen driving cycles, with a 100% load, with an Italian electricity grid mix and 70000 km traveled distance.

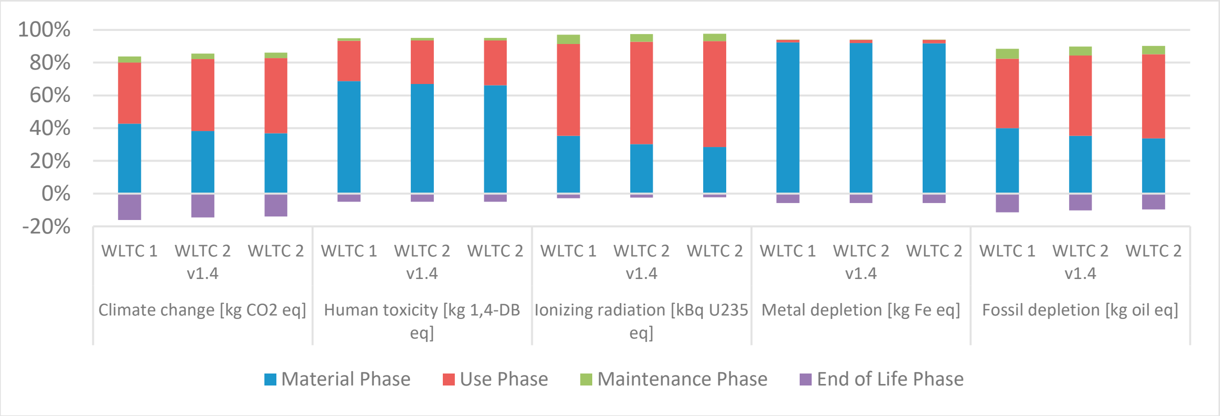

Fig. 4. Electric vehicle impact assessment

Fig. 5. (a) shows in detail for each impact category, which assembly (frame or electronic) has the greatest impact. Fig. 5. (b) compares the use phase impact for three different electricity grid mix scenarios. In addition to the results in percentage, it is possible to obtain punctual results.

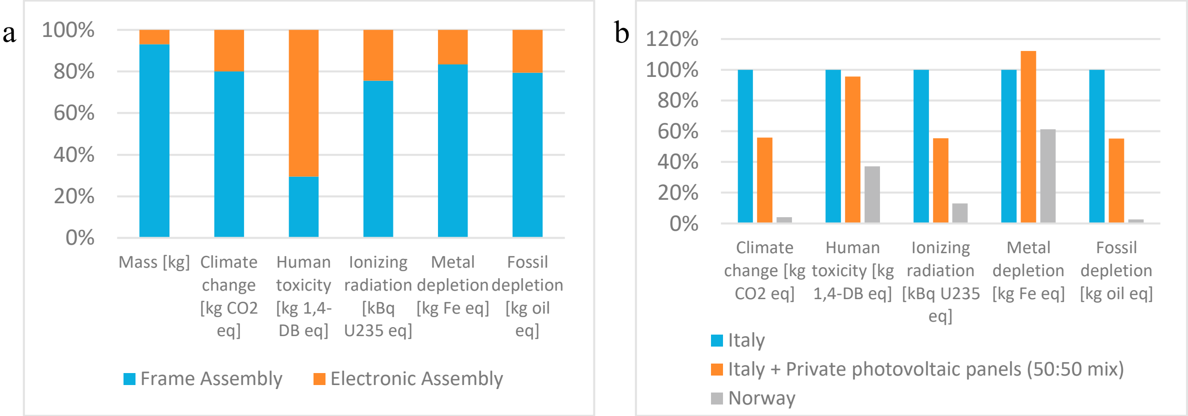

Fig. 5. (a) Material Phase impact assessment; (b) Electricity grid mix impact assessment

5. Discussion

The contribution made by the systematic integration of environmental considerations throughout the design life cycle can be very relevant in the initial design phase and have consequences for the subsequent lifecycle phases. For this reason, the present paper proposes a method and applies it in developing a tool to support designers in highlighting the consequences of their choices (from the environmental point of view), already when little data are available. It has initially conceived for the design of industrial electric vehicles; however, the approach can be applied to the good of different natures. Five are the main strong point of the proposed tool:

- It allows the user to insert customized data (i.e. energy grid mix or driving cycle that carefully described the traveled paths). Compared to traditional tools, it is easier to use because it is customized to require only the data necessary for the analysis of industrial electric vehicles, to quickly obtain feedback on environmental impact performance;
- It successfully addresses and overcomes the problem of scarcity of information; in fact, to carry out a simplified environmental assessment it is provided also with standard data that can be used when any specific information is not available yet for the current case; the user should give priority to the specific data of the use case when available. This turns out to be very advantageous for SMEs, especially for components purchased externally and of which often the information about processes and materials is inaccurate or absent;
- The tool provides a simplified, preventive environmental assessment that nevertheless considers all the product lifecycle stages;
- The outputs of the tool are navigable results; this enables the comparison with different scenarios;
- The tool allows the designers to make changes and optimize critical aspects of the life cycle when it is still possible and not much expensive.

The proposed tool only considers lithium-ion batteries. This aspect can certainly be improved by expanding the types (such as LiFePO4 [19] or LiCoO2 [23]) of batteries treated, also adding the respective capacity fade models.

The results obtained from the tool are an approximated evaluation, not comparable in level of detail and data quality with a full LCA, carried out when the product is produced; nevertheless, the tool is the first step towards the achievement of low environmental impacts for the analyzed product and can be used when LCA is unfeasible, due to the lack of product/process data and information. However, it has a high potential in moving up to the design phase of the environmental performance evaluation. Moreover, it is feasible for all those circumstances where products are customized, following specific requirements, like those that arise when electric vehicles for industrial contexts are designed. With the advent of Industry 4.0 enterprises are providing their shopfloors with a multitude of electric vehicles intended for the transportation of goods within the company boundaries.

The proposed method and tool can be extended to the economic sphere to obtain a comprehensive picture of the lifecycle, maintaining the same structure. Much of the information required for an economic analysis of the vehicle has already been calculated. Future works may also compare the environmental impacts forecast by the tool with results coming from a full LCA of a certain product. This allows for validating the tool and suggesting further changes for improving it.

6. Conclusion

The fast technological development that multiple countries are facing, must cope with the effects of this bloom on the ecosystems. Thus, the need for enabling product environmental sustainability from the very early stage of design led to the development of a methodology for a simplified environmental assessment. The authors overcome the current state of the art because they provided a tool that: i) provides quantitative feedback, ii) extends the WTW analysis to an LCA, iii) is meant to be used in the design stage and thus introduce matters related to sustainability in the first stages of the product lifecycle., iv) results are given for multiple indicators to provide a wide and complete overview. The method has been implemented in a tool that aims to influence the designer in the various decision-making aspects by calculating environmental impacts and comparing different scenarios of an EV lifecycle. Results show how future developments consist of making a complete LCA of the vehicle at the end of the design. The impacts of the complete LCA will then be compared with that of the tool, estimating the errors committed also based on the difference between the starting data with the actual ones at the end of the design. This will allow to make considerations related to the uncertainty of the result obtained by the tool with the real one and identify those parameters that need more attention at an early stage to obtain more accurate results.

Acknowledgments

The activities are related to the project EMoBotS "Electric MObility roBOT & Shuttle", which is part DM 5 MARZO 2018 – CAPO III – Procedura a sportello Progetti di ricerca e sviluppo nell'ambito dei settori applicativi coerenti con la Strategia Nazionale di Specializzazione Intelligente (SNSI) «Fabbrica intelligente» e «Agrifood».

References

[1] Ramani K., Ramanujan D., Bernstein W. Z., Zhao F., Sutherland J., Handwerker C., Choi J., Kim H. and Thurston D. (2010) "Integrated Sustainable Life Cycle Design: A Review", *Journal of Mechanical Design.*

[2] Sousa I. and Wallace D. (2006) "Product classification to support approximate life-cycle assessment of design concepts" *Technological Forecasting and Social Change*: 228-249.

[3] Ambrose H., Kendall A., Lozano M., Wachche S. and Fulton L. (2020) "Trends in life cycle greenhouse gas emissions of future light duty electric vehicles" *Transportation Research Part D: Transport and Environment.*

[4] Raugei M., Morrey D., Hutchinson A. and Winfield P. H. (2015) "A coherent life cycle assessment of a range of lightweighting strategies for compact vehicles" *Journal of Cleaner Production.*

[5] Raugei M. and Winfield P. (2018) "Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles" *Journal of Cleaner Production.*

[6] Petrauskienė K., Skvarnavičiūtė M. and Dvarioniene J. (2020) "Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania" *Journal of Cleaner Production.*

[7] Moro A. and Helmers E. (2017) "A new hybrid method for reducing the gap between WTW and LCA in the carbon footprint assessment of electric vehicles" *International Journal of Life Cycle Assessment* **22**: 4–14.

[8] Nordelöf A., Messagie M., Tillman AM. et al. (2014) "Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment?." *International Journal of Life Cycle Assessment* **19**: 1866–1890.

[9] J. Fernandes, F. J. G. Silva, R. D. S. G. Campilho, G. F. L. Pinto and A. Baptista (2019) "Intralogistincs and industry 4.0:designing a novel shuttle with picking system" *29th International Conference on Flexible Automation and Intelligent Manufacturing*

[10] Jacobus Theunissen, Hang Xu, Ray Y Zhong and Xun Xu (2018) "Smart AGV System for Manufacturing Shopfloor in the Context of Industry 4.0" *25th International Conference on Mechatronics and Machine Vision in Practice*

[11] Held M. and Schücking M. (2019) "Utilization effects on battery electric vehicle life-cycle assessment: A case-driven analysis of two commercial mobility applications" *Transportation Research Part D: Transport and Environment.*

[12] Marmiroli B., Venditti M., Dotelli G. and Spessa E. (2020) "The transport of goods in the urban environment: A comparative life cycle assessment of electric, compressed natural gas and diesel light-duty vehicles" *Applied Energy.*

[13] Hernandez M., Messagie M., De Gennaro M. and Van Mierlo J., (2017) "Resource depletion in an electric vehicle powertrain using different LCA impact methods" *Resources, Conservation and Recycling.*

[14] Faria R., Marques P., Moura P., Freire F., Delgado J. and De Almeida A. T. (2013) "Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles" *Renewable and Sustainable Energy Reviews* **24:** 271-287.

[15] Faria R., Moura P., Delgado J. and De Almeida A. T. (2012) "A sustainability assessment of electric vehicles as a personal mobility system" *Energy Conversion and Management* **61.**

[16] Bauer C., Hofer J., Althaus H.J., Del Duce A. and Simons A. (2015) "The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework" *Appl. Energy* **157**: 871–883.

[17] Tutuianu M., Marotta A., Steven H., Ericsson E., Haniu T., Ichikawa N. and Ishii H. (2013) "Development of a World-wide Worldwide harmonized Light duty driving Test Cycle (WLTC)", *UN/ECE/WP.29/GRPE/WLTP-IG.*

[18] Marques P., Garcia R., Kulay L. and Freire F. (2019) "Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade" *Journal of Cleaner Production*.

[19] Wang J., Liu P., Hicks-Garner J., Sherman E., Soukiazian S., Verbrugge M., Tataria H., Musser J. and Finamore P. (2011) "Cycle-life model for graphite-LiFePO4 cells" *Journal of Power Sources.*

[20] Faria R., Marques P., Garcia R., Moura P., Freire F., Delgado J. and de Almeida A.T. (2014) "Primary and secondary use of electric mobility batteries from a life cycle perspective" *Renewable and Sustainable Energy Reviews* **24**: 271-287.

[21] Casals L.C., García B.A., Aguesse F. and Iturrondobeitia A. (2015) "Second life of electric vehicle batteries: relation between materials degradation and environmental impact" *The International Journal of Life Cycle Assessment* **22**: 1.

[22] Schau E., Castellani V., Fazio S. et al. (2018) "Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods : new methods and differences with ILCD" *Publications Office, European Commission, Joint Research Centre.*

[23] Yingzhi Cui, Chunyu Du, Geping Yin, Yunzhi Gao, Lingling Zhang, Ting Guan, Lijie Yang and Fuping Wang (2015) "Multi-stress factor model for cycle lifetime prediction of lithium ion batteries with shallow-depth discharge" *Journal of Power Sources*.