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Design of electric vehicles for Industry 4.0: the case of an Autonomous Mobile Robot

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Abstract

In Industry 4.0, electric vehicles for logistics are widely used, such as shuttles for transporting people and Autonomous Guided Vehicles for industrial equipment. Environmental impact analyses and eco-design guidelines are essential tools in the design phase, where choices have a decisive effect on the entire product life cycle. This work proposes a method and tool aiming to make industrial electric vehicle designers aware of their choices. The proposed tool allows the preventive analysis of the different life cycle phases to highlight the consumption of materials and energy required to optimize the use and the End of Life strategy. Furthermore, it is intended to support the designers who are not provided with much product lifecycle information to obtain an overall picture of how environmental impacts are spread throughout the lifecycle; this will help provide feedback on their choices a pave the way for a more sustainable use phase in the manufacturing plant. It is based on developing a simplified and modular structure where the main product parameters are included for each life cycle phase. The tool is validated in a case study regarding the customization of an Autonomous Mobile Robot, equipped also a robotic arm; the two are connected by a customized structure. The results, which focus both on environmental and economic perspectives, contribute to filling the existing gap in the environmental evaluation of the analyzed product segment; moreover, they highlight how the material and manufacturing phase may be outstanding over the use or End of Life. This is mainly due to the short distances covered during the useful lifetime, which only cover industrial plant areas.

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1. Introduction

In recent years, industries are experiencing the fourth industrial revolution, which has therefore led to a gradual modernization of their production facilities through the inclusion of automated and interconnected machinery and many digital technologies, such as big data analysis, information technology, Internet of Things (IoT) and Additive Manufacturing (AM) [1]. Industry 4.0 is also driving toward the computerization and automation of the supply chain: for example, regarding the logistics chain, the handling of materials is increasingly improved using a mobile robot, such

as Automated Guided Vehicles (AGV) or Autonomous Mobile Robots (AMR) [2]. The complex systems of perception, locomotion and navigation composed of many sensors and powerful processors allow the AMRs to continuously monitor the surrounding environment and internal systems. AMRs that can move freely within an industrial facility is increasingly in demand for industrial processes 24/7 [3].

They mainly contribute to the efficiency of warehouses, accelerating the handling of materials [4] and the entire logistics chain. To accomplish at best the plant needs, AMRs may be customized, and made efficient, according to the tasks accomplished in a specific process.

In the meantime, it is necessary to achieve the commitment of companies to adopt strategies aimed at following sustainable paths. Environmental degradation, climate change and the scarcity of natural resources highlight the need for a radical change of direction at the social and industrial levels to protect natural ecosystems.

Design choices made in the first phases of product design can significantly affect the sustainability of the entire life cycle of the product [5], such as the choice of material for the components. Along with other conventional design criteria, the environmental effects of a product's life cycle must be considered when assessing the feasibility of a proposal. This requires early to assess the design process environmental performance of numerous potential components, materials and life cycle phases [6]. Several tools have been created to help designers make informed judgments; the Life Cycle Assessment (LCA) technique is one of the most used. The study proposed by Graba M. et al. [7] is oriented to analyze only the sustainability of the use phase of an AGV and therefore aims at optimizing the traveled path; instead, a complete evaluation based on LCA of a variety of lightweight options for compact passenger vehicles is presented by Raugel et al. [8]. Moro et Helmers suggested a hybrid approach that incorporates LCAs based on the emissions (Global Warming Potential -GWP) that occurs during the construction of the battery pack while maintaining the basic assumptions of the Wheel-to-Wheel (WTW) methodology. Compared to typical LCA analyses of electric cars, the life cycle proposed in the work has narrower boundaries. Furthermore, it refers only to a single impact category. The quantification of other impact categories can highlight criticalities and negative effects, not discoverable with a single indicator [9]. The aim of the review by Nordelof et al. consists of examining various electric vehicle (EV) LCA studies to provide reliable and relevant information to interested parties. A distinction is made between WTW, full LCA and battery LCA studies. They described placing a lot of emphasis on greenhouse gas emissions and light passenger vehicles [10]. Also, no reason was pointed out to help in the design phase. The technical background the designers have, may not include experience in environmental sustainability matters; it is thus obvious that the need to provide them with sustainability information and clues during the design phase. In addition, the literature should examine a wider range of products because electrification affects many sectors and products beyond cars.

A tool must be able to handle very little data while producing reliable results to be appropriate for the first design phase and covers each stage of the life cycle. Liu B. and De Giovanni, P. [11] examine a dynamic supply chain model in which a supplier decides both the wholesale price and the investment in green process innovation while a manufacturer sets the retail price. AGVs are among the innovative technologies discussed, but the environmental impact analysis in this case is often very general and more oriented to economic aspects. As with cars [12], and also for AGVs [13] the information that can be used for an environmental impact analysis may be partial or missing for the first design phase. As a result, it is hard to assist designers in making decisions and assess decisions they make when changes can still be made.

However, it urges to make them to gain an in-depth understanding of environmental impacts throughout the life cycle, under various conditions, and even compare alternatives.

The literature calls for a lean environmental assessment tool for the early stages of the design process. In this regard, the objective of the present work is to present a simple and adaptable solution that supports the designers in preventively visualizing the distribution of the potential environmental impacts of the entire product life cycle and thus helps them to quantitatively assess the effects of their decisions.

The focus of the present study is on the application of an eco-design strategy on an AMR. The proposed tool can be applied to any type of vehicle and considers all the main aspects of the life cycle. The case study allows us to verify the potential of the proposed tool and also the results and possible scenarios that can be extracted.

The present work overcomes some limitations identified in the literature, such as: i) the need for tools suitable for the very first phase of design and capable of managing few data; ii) the opportunity, for designers, to evaluate and compare alternatives at the beginning of the product life cycle. In addition, iii) all lifespan is considered, and the tool is designed to be adaptable to a variety of electric vehicles used in industrial environments. The tool allows for the implementation of a customized driving cycle for the vehicle in terms of required speed, distance and slope, as well as the definition of various workload scenarios. In this way it is possible to configure in detail the best strategy for the vehicle use phase to increase its efficiency in the consumption of energy resources. The main strengths and innovations of the present work lie in:

- From the proposed method a tool is derived; consequently, a greater implementation grade is ensured;
- The tool derived from the proposed method allows for preventively assess the lifecycle environmental impacts, following the product feature suggested in the concept phase;
- The tool considers all product lifecycle phases;
- The tool applies to multiple industrial EVs
- The application of the tool to the case of an AMR fills the gap in the literature concerning the assessment of the environmental impact of autonomous mobile robots.

The paper is structured as follows: the proposed method is described in section 2, the tool developed from it is introduced in section 3, the results of the initial application of the tool are shown in section 4 and the work is briefly summarized in the conclusion.

2. Method

The proposed method has been developed as a flexible and streamlined way to inform designers about the most important EV lifetime phases, considering also the present literature gaps. The suggested approach is based on the creation of a smooth, modular framework that includes the primary product parameters for each step of the life cycle. Since the methodology is universal, it may be applied to a variety of EVs, including minibusses, buses and also industrial vehicles such

as AGVs, and AMRs. The goal is to give the designer much knowledge about how the product environmental impacts are distributed across the lifetime. The lifecycle steps are investigated through the dedicated model, which will be described in the following paragraphs.

2.1. Material Model

The method classifies the materials and components of EVs into two macro-groups, as suggested by Ambrose et al. [14]. The first is Electronic Assembly (EA). It consists of the electric motor, battery pack, robotic arm and all other electronic components that make up the vehicle's electronics.

Its components are usually commercial products and typically companies are not able to retrieve detailed information about them; consequently, they are modeled as pre-established modules. The remaining vehicle is included in the second macro-group, the Frame Assembly (FA). The FA contains a list of all the materials and elements that aren't mentioned in the EA; these parts and materials cover not only the vehicle's structural framework but also its dynamics, aerodynamics, bodywork, and interior.

2.2. Use Model

The characteristics needed for the use phase are retrieved by calculating the energy consumption, the capacity fade model for lithium-ion batteries, and the modeling of the specific electrical grid mix. The literature describes three methods for calculating energy consumption: data provided by manufacturers, in-depth technical models, and empirical values [15].

The technological models used in this study were selected by considering and comparing various use situations. The use phase model focuses on the influence of vehicle utilization. Its two main sources of contribution are particle emissions and pollutants from energy use. The first is determined by considering the vehicle's lifetime mileage [km], average consumption [kWh/km], and the energy grid mix of the reference nation where the vehicle is recharged. Applying a vehicle's kinematic model [13][16][17][18] to a certain driving cycle results in the calculation of the first. A driving cycle prescribes a speed versus time profile [19]. It expresses the operating speed of the vehicle along a chosen route with a temporal resolution of one second. At the initial design stage, vehicle driving cycle data may not be available; realistic driving cycles found in the literature (WLTP or Worldwide Harmonized Light Vehicle Test Procedure [20]) were used to solve this problem. The driving cycle should be chosen following the vehicle features. Whenever not available, to be consistent with the maximum speed achieved by the vehicle and to obtain credible electricity consumption, the driving cycle could be scaled.

2.3. Maintenance Model

Throughout the entire maintenance process for the vehicle, the impact of replacing the cooling system and the wheel on the maintenance is considered. Another important aspect concerns

the replacement of the battery pack, which for mobility uses is recommended to be replaced when it reaches 80% of its nominal capacity [21].

2.4. End of Life Model

The EoL phase modeling process determines which, how much, and how materials and components are managed and/or disposed of. Despite the prospect of a second life, the entire environmental impact of the modified battery pack is attributed to its initial life, according to Faria et al. [17]. The features that are considered are the mass percentages of the components and materials supplied to a certain treatment. The proportions of the materials/components that are left over or that are not handled are sent to landfills.

2.5. Environmental impacts

To investigate the impacts of EVs five impact categories are suggested, specifically, climate change [kg CO₂ eq], human toxicity [kg 1,4-DB eq], ionizing radiation [kBq U235 eq], metal depletion [kg Fe eq], and fossil fuel depletion [kg oil eq]. The focus is on these five areas to conduct an accurate analysis that considered the main aspects that characterize the environmental impact of EVs, in accordance also with Petruskien et al. [22].

3. Case study and results

A tool has been developed following the proposed method. To overcome the lack of data at the early phase of design, the tool suggests standard values, in case the user is not confident with certain data. Moreover, the goal is to reach a compromise between a high level of detail and approximation. The tool is intended to be easily used also in the conceptual phase. Besides the output, the designer is supported also in the input definition: by the inserted input, 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's peak power and vehicle mass. There are multiple driving cycles to choose from. The tool is developed in Excel. Firstly, a guide is proposed to the user; the input sheet follows; ultimately the results are shown. The results can be edited depending on the choices related to the load and the driving cycle. The tool is meant to be used in the design process of small industrial realities that design electric vehicles, rather than design processes and supply chains of multinational car manufacturers. In the current context, the tool analyzes an AMR on which a robotic arm was installed. The vehicle is expected to work for 7 years and to travel 4000 km during its lifetime. During this period there is no replacement of the battery pack. In the following, data inserted and elaborated in the tool are presented.

3.1. Material Data

The unladen mass of the vehicle is 150 kg. The masses of each component of the electronic assembly are indicated in Table 1. The electronic components include commercial AMR – without battery and motor; this is because the company bought both the AMR and the robotic arm and is responsible for the design and construction of the remaining structure. The battery pack and the electric motor refer to AMR, as the engines of the robotic arm have already been considered within its mass.

Table 1. Electronic Assembly, materials, the total mass is 100 kg.

Components	n. part	Part mass [kg]	Sub-assembly mass [kg]
Battery pack	1	27,5	27,5
Electric motor	2	1	2
Electronic components	Other (electronic material)	1	2,5
	Other (cable)	1	2,5
Robotic arm	1	33,3	33,3
Commercial AMR – without battery and motor	1	32,5	32,5

The materials of frame assembly are shown in Table 2. A lithium-ion battery is considered. It is composed of ten cells and the 5 battery cases are made of reinforced aluminum.

Table 2. Frame Assembly, materials; the total mass is 50 kg

Material	Percentage	Mass [kg]
Steel	60%	30
Plastic	15%	7,5
Glass	5%	2,5
Fiberglass	1%	0,5
Rubber	3%	1,5
Aluminium	16%	8

3.2. Use Data

The AMR can reach a maximum speed of 5 km/h. Since there is no real guide cycle of use available, one has been hypothesized. The standard WLTP driving cycle doesn't include the AMR vehicle class; therefore the Worldwide harmonized Light vehicles Test Cycles (WLTC) Class 1 driving cycle was chosen and scaled in such a way that the maximum speed is 5 km/h (Fig. 1).

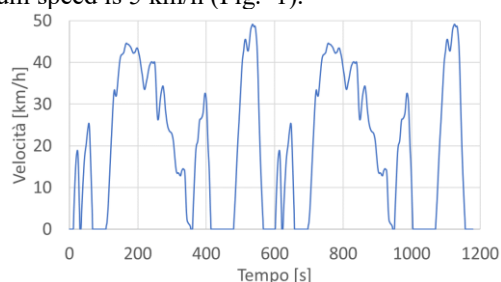


Fig. 1. Driving cycle.

The data required as input to the vehicle consumption calculation model are indicated in Table 3,

Table 3. Use data

Parameter	Quantity	UM
Average load	12	kg
Cx aerodynamic drag coefficient	0,8	
Front area	0,2	m ²
Battery pack efficiency	0,97	
DC/AC Converter efficiency	0,95	
Motor efficiency	0,85	
Trasmission efficiency	0,9	
Auxiliaries power	50	W
Peak Power Motor	10000	W

The consumption is calculated as a function of a partial load (0% - 0,029 [kWh/km]; 25% - 0,030 [kWh/km]; 50% - 0,031 [kWh/km]; 75% - 0,031 [kWh/km]; 100% - 0,032 [kWh/km]).

Due to the low workload compared to the total mass of the vehicle, the load discretization does not produce a significant difference in terms of consumption. The Italian electricity grid mix is used by the company.

3.3. End of Life Data

A specific percentage of mass is chosen for the treatment of materials and components (85% of recycling for steel, aluminum, battery case; 50% of recycling for fiberglass, glass, plastic, rubber; 50% specific disposal treatment for an electric motor, electronic components, battery BMS, 85% specific disposal treatment for the robotic arm and commercial AMR – without battery and robot; 50% of hydrometallurgical and 50% of pyrometallurgical treatment for battery cells).

3.4. Result

Fig. 2 shows the environmental impact of AMR which has been reported in percentage. The material phase is the most important for all impact categories.

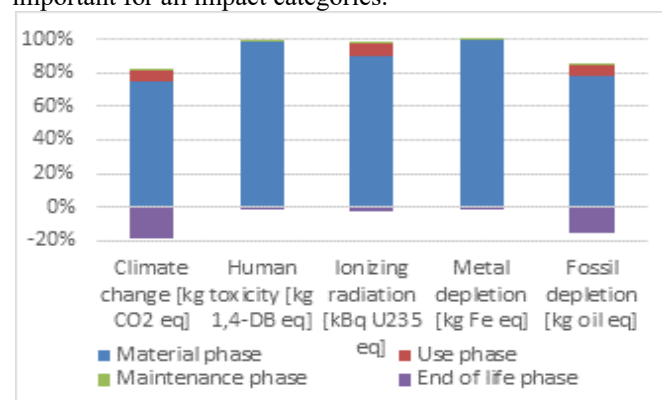


Fig. 2. AMR impact assessment.

In the specific of the material phase, Fig. 3 shows that the Electronic Assembly is the most impactful assembly of the material phase, also because it represents almost 2/3 of the total

mass. The graph compares the contributions of impacts for five impact categories and their mass. Blue scaled bars refer to the environmental impacts of the main blocks of the FA; red and green scaled bars refer to the EA; the last depicts the impacts of the battery's components.

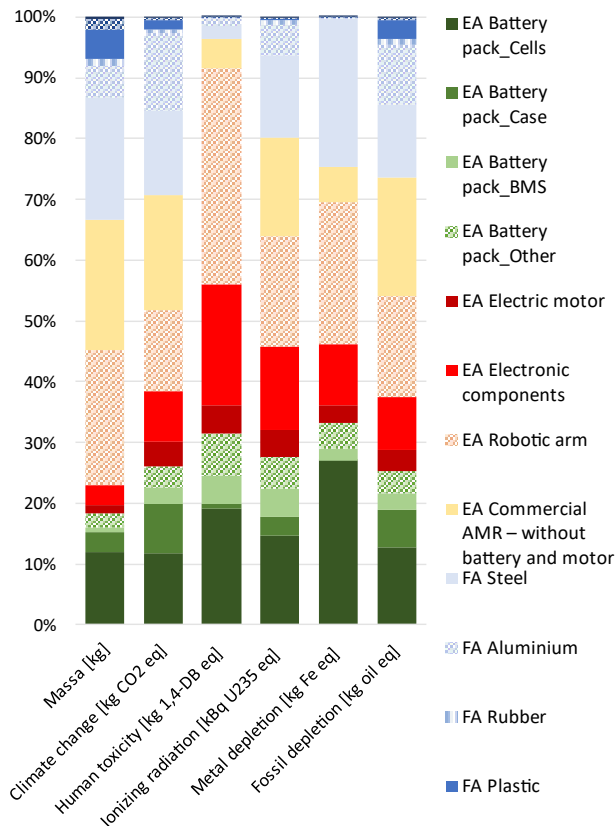


Fig. 3. Material phase impact assessment.

From the graph is clear that the designer's area of intervention, in this case, is very small because the Electronic Assembly is made up of commercial components, also chosen for technical reasons. Design is a multi-objective process and the environmental impact is only one of these objectives, which must coexist and be aligned with the others. The aim is in fact to create new opportunities and to reach the optimal solution. The area in which the designer can intervene in the AMR falls on the choice of materials, reducing the masses of steel and aluminum, as far as possible, or increasing the amount of use of aluminum that with recycling returns an environmental benefit. Another aspect that the designer can consider is the optimization of the use phase, in addition to the aspects of efficiency and logistics, it is possible to intervene through the supplier on the electricity grid mix. In Fig. 4 a comparison between three electricity grid mixes is reported:

- Italy (IT): the reference state of the company
- Italy + Private photovoltaic panels (50:50 mix) (IPh): It has been hypothesized that 50% of the energy required by the vehicle is supplied by the company's photovoltaic system
- Norway (NO): low carbon energy mix, when 96% of sources are renewable, hydroelectric [23].

As expected, the alternative scenarios reveal how investing in

electricity grid mixes that have high percentages of renewable resources leads to a significant reduction in impacts.

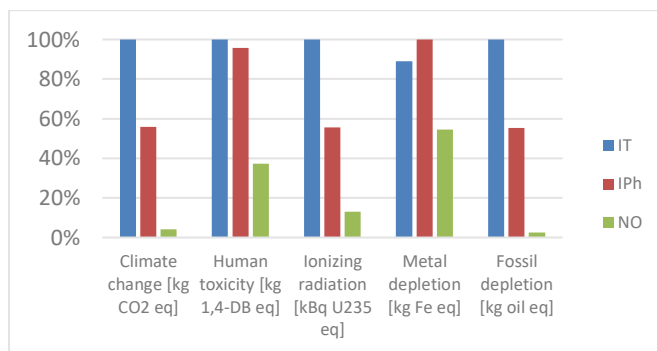


Fig. 4. Electricity grid mix impact assessment.

4. Discussion and conclusion

The need to allow the environmental sustainability of the product from the early design stages led to the development of a methodology for a simplified environmental assessment. The term simplified is used because a preliminary result is obtained in the initial design phase, compared to a complete LCA analysis conducted at the end of the design. The tool can be used to quickly obtain quantitative and preliminary results. Those are useful to make comparisons between the different solutions that in many cases the designer must choose. In this way, an overview and greater awareness of the phases that most influence the impact are achieved. The authors go beyond the current state of the art and have provided a tool that: is designed to be used in the initial design phase with little data available to quickly receive information relating to the sustainability of the product life cycle. The application of the method to an AMR has made it possible to highlight the practicality and potentiality of this tool for the environmental impact analysis of industrial vehicles, overcoming the actual limit of the literature on this theme.

The manufacturing phase was excluded from the outset because in the electric vehicle literature, the focus falls mainly on the use phase which, even in the case of cars, is the most impacting phase of the life cycle [15]. The processes and technological choices are very difficult to define and therefore to evaluate in the very early stages of design, where the production choices are not always considered, leading to possible problems in the production phase. Furthermore, there was a lack of variability between the different vehicle models in the manufacturing phase [15], this appears to be a constant in which the designer is unable to intervene therefore a simplified environmental analysis for the early design stages can be neglected. However, the results obtained in this study contrast with those obtained for electric cars, given that in this case, the material phase is the most relevant. For this reason, in the next steps, the manufacturing phase is expected to be introduced within the method by parameterizing what are the most important operations. In detail, it will deal with the operations of welding, painting, trimming and assembly, which are the main recurrent in the automotive sector. Furthermore, the study between raw and semi-finished products will be

deepened with a differentiation that will also involve the material phase [12].

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