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ORIGINAL PAPER

LCA and LCC Analysis of the Recovering and Reusing Scenario of Metal-Plastic Process Scraps

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Abstract

The paper investigates the environmental and economic benefits of the possible scenario of recovering and reusing a process scrap in closed loop, by means of the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) method. As case study a manufacturing process of a large company based in Portugal was utilized. The company demand is to possibly innovate the manufacturing process of one of their products that currently generates non-recyclable scraps when it fails quality control. Before taking decisions, the company wants to assess the environmental and economic benefits of possibly recycling those scraps, as they currently generate waste destined for landfills. The product consisting of a plastic household containing metal inserts was analyzed "from cradle to grave," from raw material extraction to end of life. According to the ISO standards ISO 14040:2006 and ISO 14044:2018, four phases: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and final Interpretation, are reported. SimaPro 9.3 software and Ecoinvent v3 database were used for the assessment. A future scenario where the metal inserts could be easily removed from the plastic household, allowing the complete recycle and reuse of both types of components, was assumed and assessed for a LCA and LCC comparison with the current state. The results highlighted minor benefit from recovering the process scrap but significative benefit when this scenario is extended to the post-consumer end of life. This study will enrich the scientific literature with primary data collected at a company site and will enhance the knowledge needed to develop links between the top-down process that led to the creation of the Sustainable Development Goals (SDGs) and the bottom-up knowledge, data, and methodology in the life-cycle sustainability assessment to help businesses and governments integrating the SDGs into their decision-making processes.

Keywords Plastic-metal recycling · End of life · Environmental impact · Cost analysis

Introduction

This paper reports an LCA and Life Cycle Costing (LCC) study of a component produced by GLN company which is a dynamic group, mainly based in the district of Leiria in Portugal. The group is well known for its high-precision mold production and plastic injection. The product analyzed in this paper is a housing assembly for the automotive industry made through plastic molding process at GLN, where 87% of the product is made of polymers and 13% of inserted metals. Seeking to be more sustainable, GLN is committed to reduce the environmental impact of its products. One of the biggest problems that the company faces with the housing assembly is the final disposal of the rejected products, namely, the finite products that do not pass the final check of the production process. The rejected units go to landfill due the impossibility of recycling the materials because the inserted metals cannot be extracted. This is the biggest challenge that the company is facing on the housing assembly product.

Life Cycle Assessment (LCA) is a structured, comprehensive, and internationally standardized by the ISO 14040 series (ISO 14040; ISO14044) that allows the calculation of the potential impact due to emissions and resource consumption, as well as the potential damages to human and ecosystem health associated with products and services. An LCA considers the product's life cycle, from resource extraction to manufacture, consumption, and recycling, up to the disposal of remaining waste. As a result, LCA is an important and

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useful decision-making tool that complements other methodologies, which are equally necessary to help effectively and efficiently make consumption and production more sustainable. The LCA offers quantitative indicators of environmental weaknesses throughout the product life cycle, guiding decision-makers toward choices that minimize impacts.

Conceptually, similarly to the LCA model is the criteria that guides the LCC model (Ristimaki et al. 2013), with the substantial difference that the latter focuses on the analysis of the life cycle of a product from a purely economic point of view. In fact, the LCC can be used in business management to help companies in how to reduce the costs of a product while LCA can help to reduce the environmental burdens. Conventional LCC consists in the measurement and calculation of all the costs associated with a product during the various phases of its life cycle, following the logical thread of the "cradle to grave" (La Rosa et al. 2021). The various cost items are discounted using the interest rate that corresponds to the rate of inflation present at the time of drawing up the model. Life Cycle Cost (LCC) is the study of all cost involved since the beginning until the end of life of a product. The LCC was modeled in the SimaPro software.

The LCA and LCC conducted will provide information on the environmental and economic benefits of recycling the rejected products. The results will guide the company whether investing on circular economy strategies by promoting a transition from the cradle to grave approach which means from material extraction, manufacture use, and waste production, to the zero-waste approach (including recycling of the rejected products). On this concept is based the modern circular economy attempt that is an economic system aimed at eliminating waste and the continual use of resources.

Circular systems employ reuse, repair, refurbishment, remanufacturing, and recycling to create a closed-loop system, minimizing the use of resource inputs and the creation of waste. ISO/TC: Circularity of Composites 323 is a new ISO technical committee that intends to develop requirements, frameworks, guidance, and supporting tools related to the implementation of circular economy projects. The Circular Economy (CE) concept is of great interest because it is a way for businesses to implement the much-discussed concept of sustainable development (Patil et al. 2020). CE is understood as "realization of closed loop material flow in the whole economic system" (Geng et al. 2013). In association with the so called 3R principles (reduction, reuse, and recycling), "the core of CE is the circular (closed) flow of materials and the use of raw materials and energy through multiple phases" (Yuan et al. 2006).

In the future, fully recyclable products should be produced. The highest priority of the Circular Economy principle is to reduce waste production and, at the same time, minimize the extraction of raw materials (Composite Materials Report 2022). Recycling plastics is also virtuous for the littering problem for marine environments as at least 267 species of marine organisms worldwide are affected by plastic waste (Hou et al. 2018). The world is producing around 1.1 Gt/a of consumer waste (municipal solid waste or MSW), with production varying from < 1 kg/capita per day for low-income countries to > 2 kg/ capita per day for high-income ones (Hoornweg and Bhada-Tata 2012; Lange 2021). Globally, about 12% of the spent plastic is recycled (Hundertmark et al. 2018). A larger fraction is incinerated (25%), but the bulk (~60%) ends up in the environment, in landfills, in unmanaged dumps, or as litter on land or in rivers and oceans. With its ambitious "Green Deal," the EU aspires by 2050 to become climate neutral, to have developed a circular economy, to have restored biodiversity, and to have cut pollution (A European Green Deal 2019). Finally, this study will contribute to the scientific literature with primary data collected at a company site and with findings that will enhance the knowledge needed to develop links between the Sustainable Development Goals (SDGs) and the methodology of the life-cycle sustainability assessment to help businesses and governments integrating the SDGs into their decision-making processes. More specifically SDG12 for 2030 target to achieve the sustainable management and efficient use of natural resources and substantially reduce waste generation through prevention, reduction, recycling, and reuse.

LCA Methodology

An LCA consists of four main phases according to the ISO standards, and in the following order they are as follows:

1. Goal and scope. The goal shall clearly define the purpose and intended application of the LCA, in addition to other things such as who the commissioner is and the intended audience of the report. The scope relies on the goal and shall further specify the functional unit which is being studied, the reference flow and system boundaries, and evaluate data quality. It is important to clearly define the goal and scope, since these make up the framework for the whole study.
2. Inventory analysis. This phase contains all the inputs and outputs in the product system, which are used in the calculations. What the inventory includes and excludes is determined by the scope of the study, and it is important to be consistent with this throughout all the phases (but it should be noted that the goal and scope can change since the process of conducting an LCA is iterative).
3. Impact assessment. This phase contains three mandatory parts, which are the selection of impact categories and category indicators (I), classification of impact cat-

egories (II), and characterization of the inventory data in regard to the category indicators (III). Optionally, it could be chosen to normalize, weight, or group the results. Normalizing the results means comparing them to a baseline (for example could a new product be normalized to the one it replaces given they fill the same functional unit), which highlights the differences.

4. Interpretation. In this last phase interpretation of the findings in alignment with the goal of the study is conducted, keeping transparent the study's limitations regarding for instance data quality, uncertainties, allocation methods, or sensitivity analysis.

Goal of the LCA

Purpose of this LCA is to seek for the critical processes during the annual production of one housing assembly at GLN company site and evaluate their impact on the environment. The product under investigation is a 385.5-g component made of a thermoplastic reinforced composite (70% polybuthylene terephthalate, PBT, and 30% glass powder) and additional 12 inserted metal pieces consisting of copper, zamac, and brass. The purpose is to evaluate the environmental impacts and costs generated by the rejected households that accumulated during the product quality control, and how these can be reduced or avoided to make the entire production process more sustainable and circular. The LCA/LCC results aim to enhance material's recycling and cost savings by avoiding the current landfilling of the rejected households.

Scope

Functional Unit and System Boundary

The study is an attributional LCA using the cut-off approach. The functional unit is 1-year production of housing assembly at the plant site (the company is based in Portugal). Figure 1 is a flowchart of the main steps of the housing assembly production. A more detailed description is given in Fig. 2 with the system boundaries that include raw material acquisition and transport, production process, quality control, and rejected/scrap products' management:

a) Raw material: the polymer material and the metal inserts are bought in European countries. Transportation from their origin countries to Portugal is accounted.
b) Process: PBT polymer is injection molded. After cooling the metal parts are inserted into the housing by a robot through press fit. Electricity used for the process is accounted.
c) Quality control: in the first verification, the robot collects and scans the housing to see if the product is in perfect shape, dimension, and condition. If approved by the robot the product goes to the distribution for the client; if the robot considered that the product it is not perfect, it is put in a box of "scrap" that will be verified by a human to make sure if the product can go to the client or should be rejected. Electrical energy consumed on the quality control by robot is accounted.
d) Distribution: if the product is conformed to the quality standards it goes to market, alternatively it is rejected, and send to landfill. Recycling is still not an option for the manufacturer due to the metal components. The use phase is not included of the system boundaries.

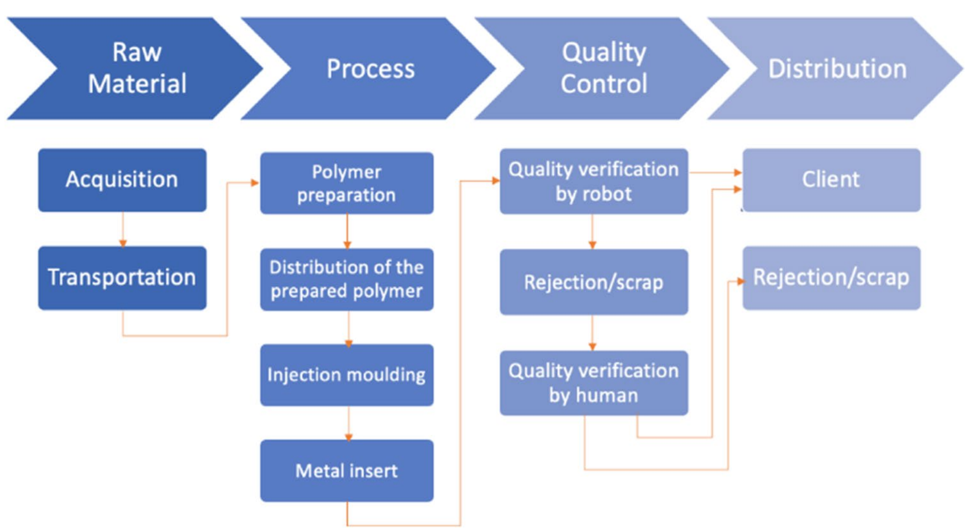


Fig. 1 Flowchart depicting the key stages in the production process of the housing assembly

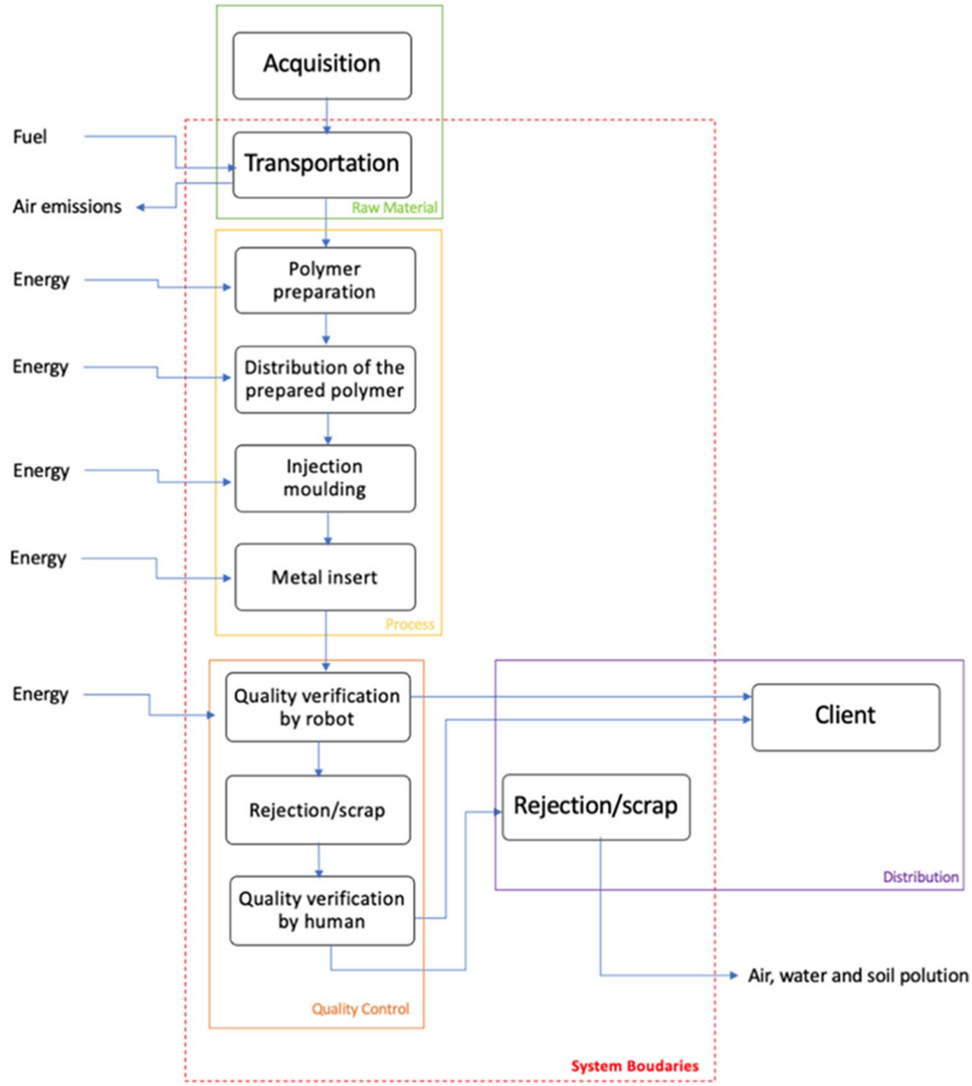


Fig. 2 System boundary from cradle to gate including scrap management

Data Quality

The foreground data regard the internal executions of the plant and have been provided directly from the plant manager by means of a questionnaire and a visit at the industrial unit.

All the background data, such as raw material extraction, transportations, and electricity origin, are taken from the SimaPro database "Ecoinvent 3–allocation cut-off–system." Data from literature and online research are used, too.

The used impact assessment method for the damage evaluation is IMPACT 2002 + updated. The midpoint evaluation was conducted by using the CML-baseline method.

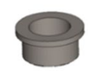
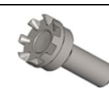
LCI — Life Cycle Inventory Analysis

Foreground data were collected at the company site and integrated with data from the Ecoinvent3 database. SimaPro 9.3 was used for the LCA and LCC evaluations. The final Housing Assembly consists of the household and 4 metal inserts (MX1, MX2, MX3, and MX4) listed in Table 1. The complete inventory data list is reported in Table 1. For the insertion of the metal parts in the household a deep drawing steel 38,000-kN press was selected from the Ecoinvent database as this is the closest to the process used by the company that was not available in the library. Similarly, PBT was not available in the database and nylon 6 was selected following the company's suggestion.

Foreground Data Collection

After the visit to the plant, rough foreground data were furnished, and others were successively collected by an exhaustive questionnaire via Excel. This table includes a complete set of numerical values and is divided into sections: location information, supplying, production, and shipping to

Table 1 Inventory list

Input	Quantity
Household	
PBT GF30 *(Nylon 6)* *(Glass Fibre)*	335,3 g *(234,71 g)* *(100,59 g)*
Transportation from Germany	2171 km
Injection Moulding	335,3 g
MX1	
Brass	4 g
Transportation	3450Km
MX2	
Steel, low-alloyed	2 g
Transportation	2730Km
MX3	
Steel, low-alloyed	2 g
Transportation	2060Km
MX4	
Steel, low-alloyed	42 g
Transportation	2100Km
Process for the insertion of the metals	
Deep drawing steel 38000kN press	50g

customer. A detailed scheme of the indoor lines was furnished, too. By visiting the factory, it was possible to understand and take contact with the process line and interrelate data with the correspondent machines. Data are referred to different periods of time, but the main interest is for annual data because the FU of the first part of the assessment is the yearly granulate production. Data are referred to the year 2021. It should be more representative to have a long-term trend of data throughout many years, to obtain a realistic tendency of values. Anyway, this LCA does not assess this evaluation and does not make statistical calculations.

Data were collected for year 2021. The yearly production of GLN was of 133,277 units of housing assembly of which 128,956 went to market and the rest (4321 units, 3.2%) were landfilled. The challenge of the company is to find a solution to assembly the product in a way that each single component could be separated and reuse.

Life Cycle Impact Assessment

This section is focused on the evaluation of environmental impacts related to the inventory data provided by the company. A midpoint analysis was conducted using the impact assessment method IPCC2013 GWP100. The method replaces the IPCC 2007 that was developed by the Intergovernmental Panel on Climate Change and was used for the assessment of the Global Warming Potential (*GWP*) impact category, reported in Fig. 3. This indicator stands for the contribution to the greenhouse effect, expressed as CO_2 equivalent, by summing the quantities of the individual greenhouse pollutants (m_i) multiplied by their respective greenhouse characterization factors (GWP_i), according to the following formula (Klöpffer and Grahl 2014):

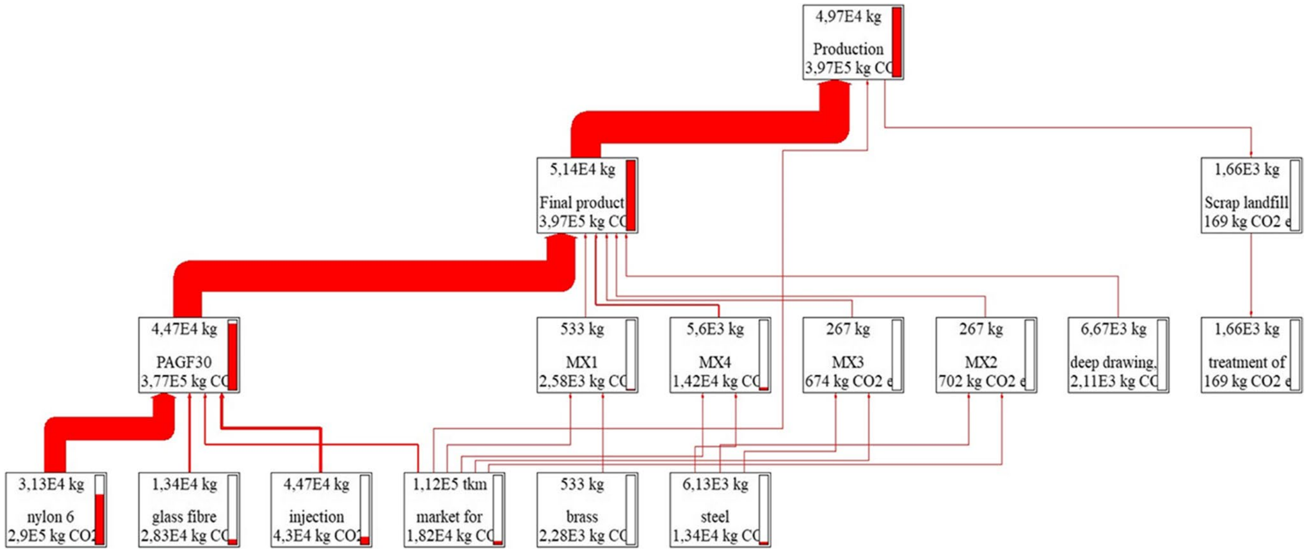


Fig. 3 Network of the yearly (2021) production including landfill of rejected households. *GWP* reported in kg CO_2 eq

Table 2 Main greenhouse gas and relative characterization factors (from Klöpffer and Gral, 2014)

Greenhouse gas	$(GWP_i)_{100}$ (CO_2 equivalents)
Carbon dioxide (CO_2)	1
Methane (CH_4)	25.75
Methane (CH_4), regenerative	23
Dinitrogen monoxide (N_2O)	296
Tetrachloromethane	1800
Tetrafluoromethane	5700
Hexafluoroethane	11,900

$$GWP = \sum_i (m_i \times GWP_i)$$

The main greenhouse contributors are reported in Table 2 with their respective characterization factor.

An endpoint analysis was conducted by means of the Impact 2002 + assessment method to evaluate the damage on Human Health, Ecosystem quality, Climate Change, and Resources.

Scrap Recycling Scenario

The technology for recycling the plastic-metal household is currently not available. However, LCA and LCC were developed for the scenario of material separating and reusing. The metal components were reused in a new household assembly while the plastic component was injection molded before re-manufacturing a new household. Avoided impact of scrap recycling were calculated in closed loop as reported in Fig. 4 (green lines). Fully recycling and reusing the yearly production of household scraps (1.66 ton) reduces of 2.93% the *GWP* of the total yearly production of household assembly (Fig. 4(b)) while the current practice of landfilling the scraps generates 0.042% additional impacts in the yearly production of household assembly.

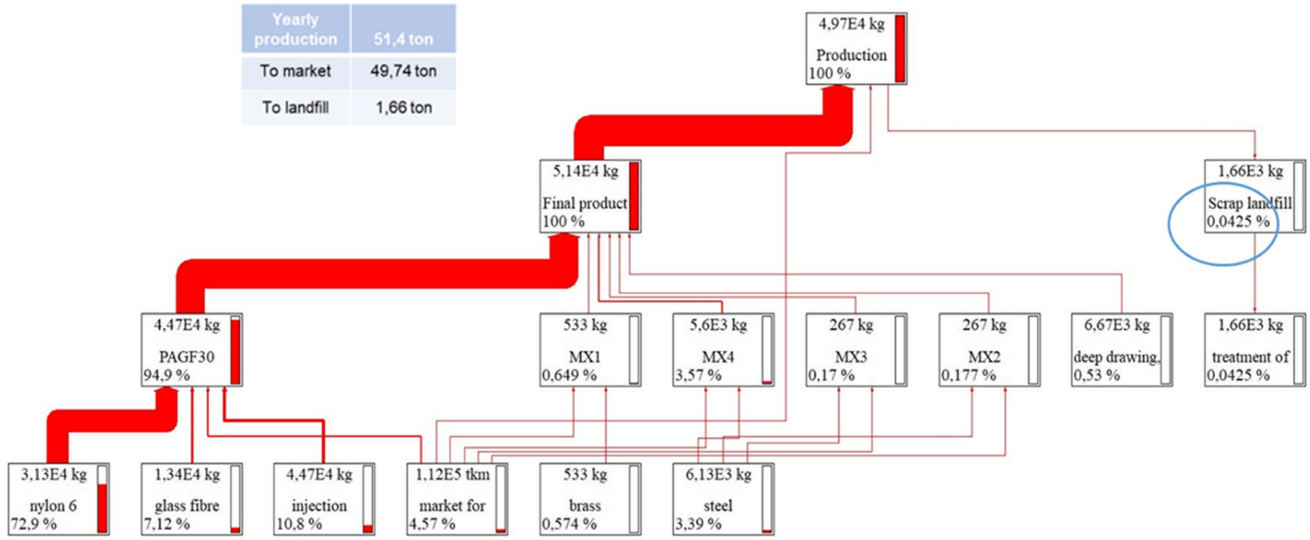
Life Cycle Costing

Life cycle costs are summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced during their life. LCA and LCC are complementary, and they have the same structure, the same functional unit, and the same development criteria.

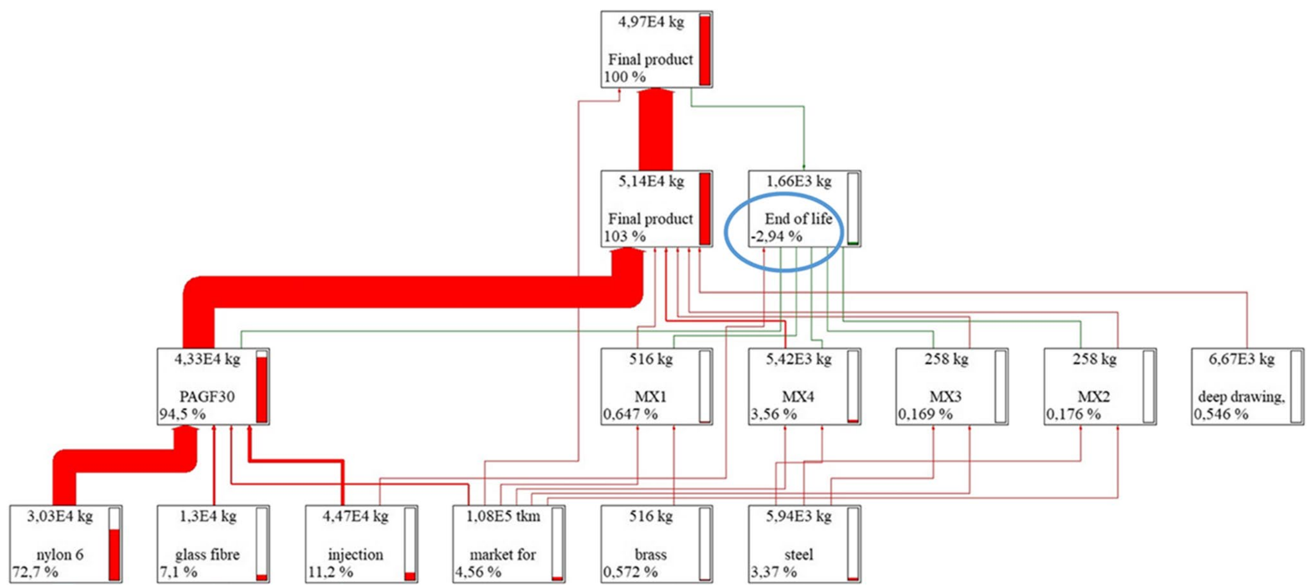
In terms of cost analysis recovering and reusing the yearly produced household assembly scraps allows savings of up to16.000 € in the yearly production of the component, as reported in Fig. 5. Findings from the LCA and LCC analysis seem to suggest that the environmental and economic benefits deriving from the recovery of waste scrap do not reach the thresholds necessary to stimulate the company to invest in the development of new technologies for the recycling of these types of plastic/metal composites. For this reason, the LCA analysis was extended to the end of life of the post-consumer households.

LCC Comparison of Current Practice Versus Future Scenario

It is possible to see on the modeling results (Fig. 6) below.



a) Landfilling of scraps contributes for 0,0425% to GWP in the yearly production of the component.



b) recycling of scraps avoids 2,94% of GWP impact in the yearly production of the component.

Fig. 4 **a** Landfilling scenario and **b** future scenario: closed loop recycling

LCA and LCC Results Including Post-consumer Waste

Plastic waste is classified as pre- or post-consumer. Pre-consumer is generated during manufacturing and directly used in the same production line by entering it upstream. The scrap is rather considered as co-product and used for realizing a new material. Post-consumer, generated after the usage of the good, is a post-consumer waste. Waste collection is the first problem to be addressed for post-consumer waste and it is an obstacle for recycling.

One scenario of 100% recycling the post-consumer waste was applied after use, in addition to the scrap recycling. The assumption is that the components could be recycled in closed loop after use. The LCA network reported in Fig. 7 was created by assuming a 100% recycling scenario of both types of components, plastic, and metals. An intermediate scenario was also considered, 50% recycling and 50% landfilling. The green lines mean avoided impact. These two recycling EOL scenarios were compared with a third scenario where the post-consumer was landfilled. Comparative results of the three selected EOL scenarios are reported

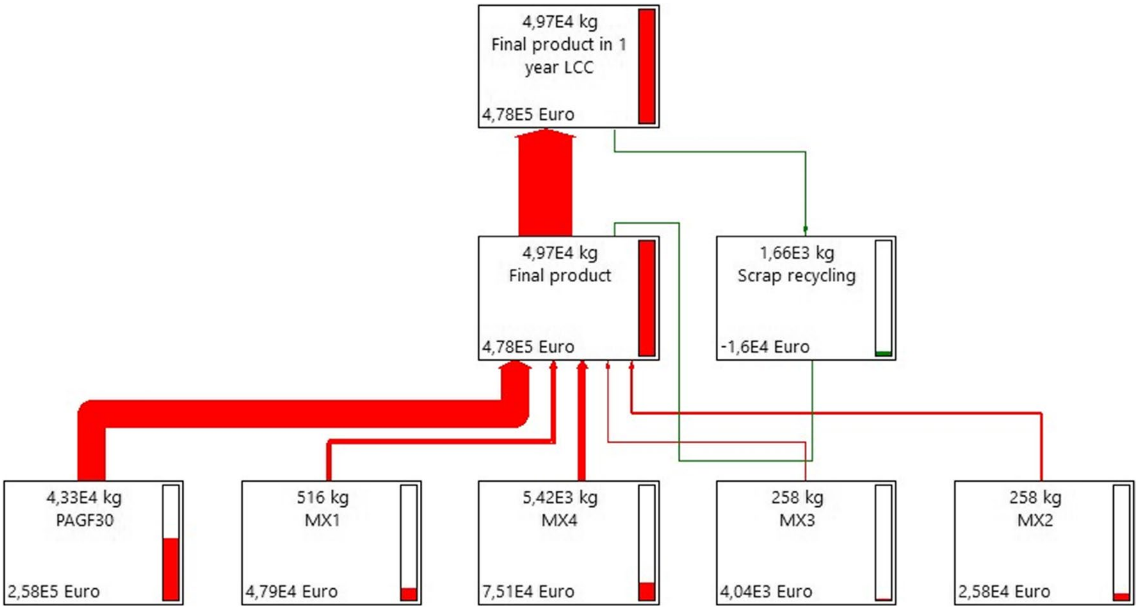


Fig. 5 Recycling of scraps allows savings up to 16.000 € in the yearly production of the component

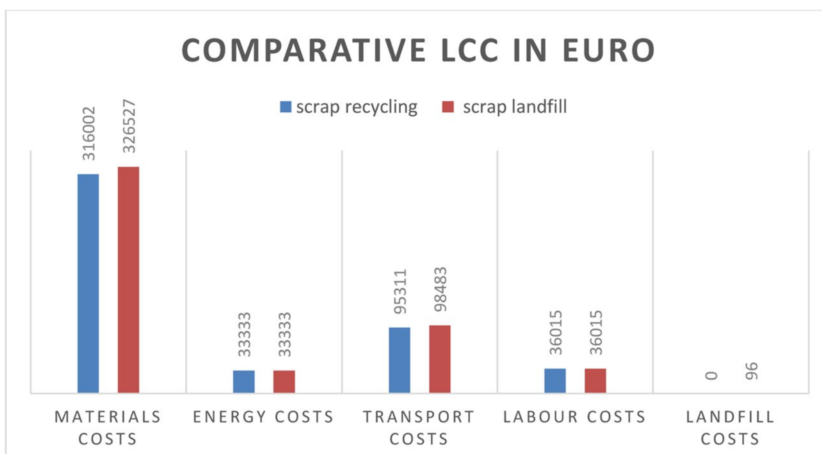


Fig. 6 Comparative Life Cycle Cost (LCC) analysis of the current practice (scrap landfilling) and future scenario (scrap recycling)

in Fig. 8 where it is clear the proportional dependence of the impact reduction to the increase of the post-consumer recycling percentage. The comparison was completed with the LCC results reported in Fig. 9 that are in line with the LCA results meaning that the cost saving is proportional to the increase of the recycling percentage.

Conclusions

In conclusion, this paper underscores the advantages of recovering and reusing process scraps in a closed loop system to minimize the environmental impact and promote a circular economy. The in-depth analysis conducted employing the LCA and LCC methods on a manufacturing process for a plastic household item containing metal inserts revealed that recycling the rejected products has minor environmental and economic benefits for the company. Nevertheless, extending the recycling scenario to the post-consumer end of life leads to significant benefits. Undeniably, the closed loop recycling scenario can significantly minimize the product life cycle carbon footprint, save costs, and contribute to a greener circular economy. This paper proves how important is the life cycle approach in product development where manufacturers must not only focus on the sustainability of their production process but also include the end of life of their products, waste management supply chains, and recycling solutions. This will lead to the need, in addition to waste recycling, to have products redesigned to maximize material recycling and achieve the sustainable development goals (with major

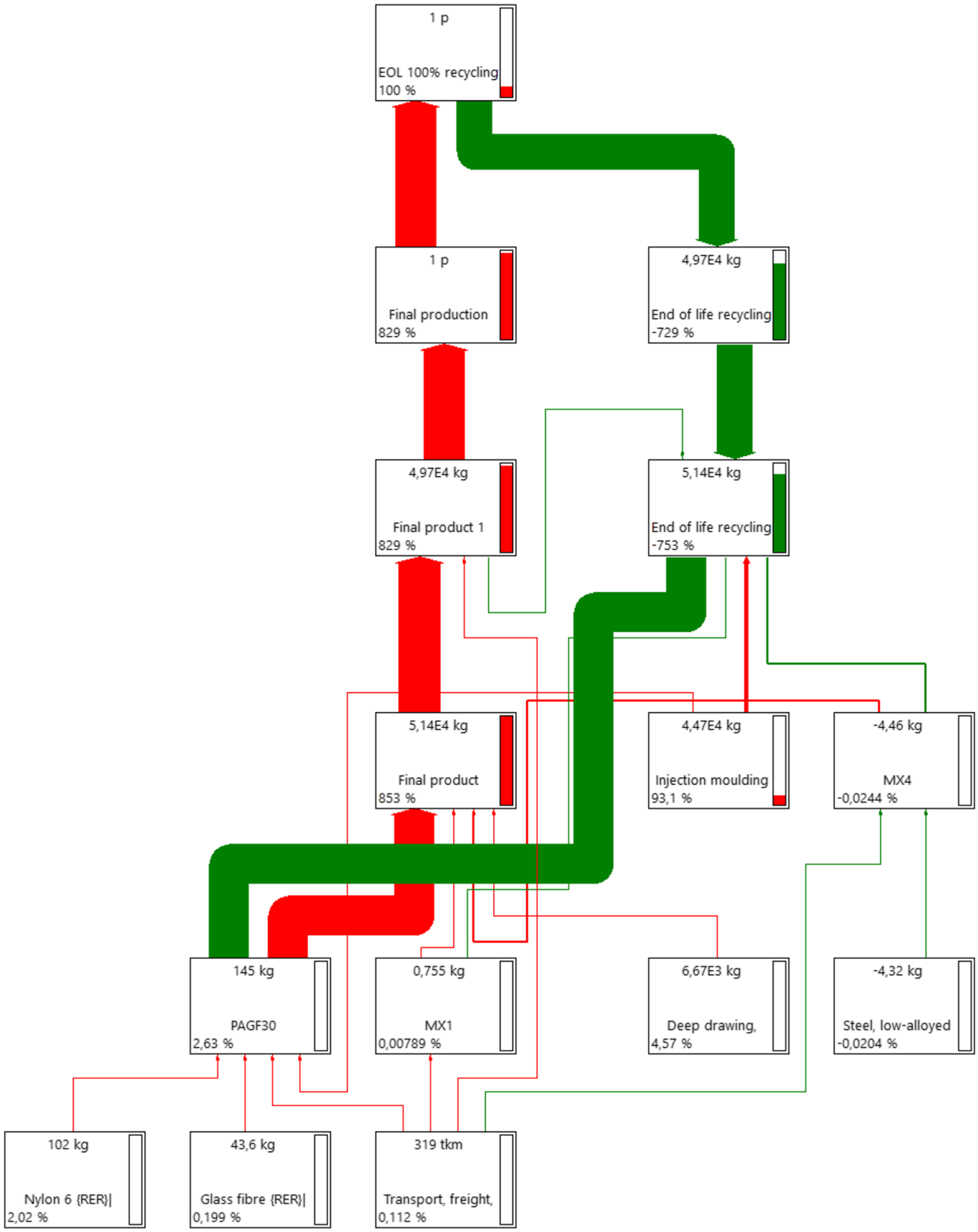


Fig. 7 Network of the 100% recycling end-of-life scenario

contribution to SDG 12) and circular economy principles to reduce waste production and, at the same time, minimize the extraction of raw materials. In the future, fully recyclable products should be produced and moving to efficient recycling of materials is ultimately essential to create a better future. To achieve this, it is needed to develop disruptive technologies able to quickly provide the material solutions to accelerate their uptake and prevent landfilling and adopting design for circularity as an industry standard.

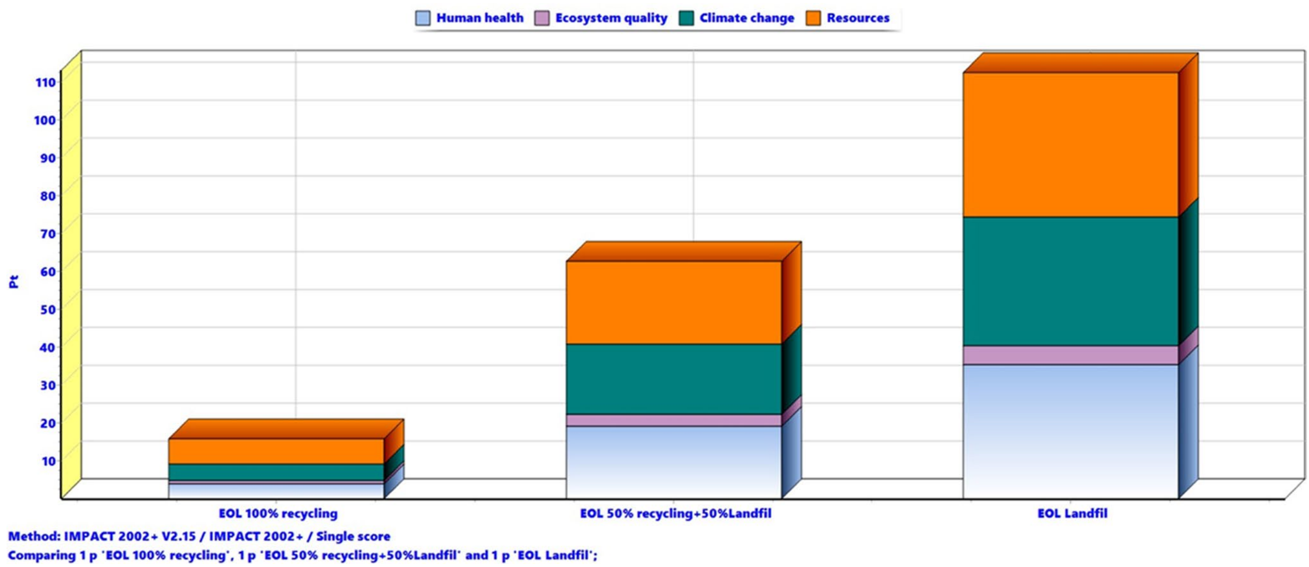


Fig. 8 LCA including the household end of life. Comparison of 3 end-of-life scenarios: 100% recycling, 50% recycling + 50% landfilling, and 100% landfilling

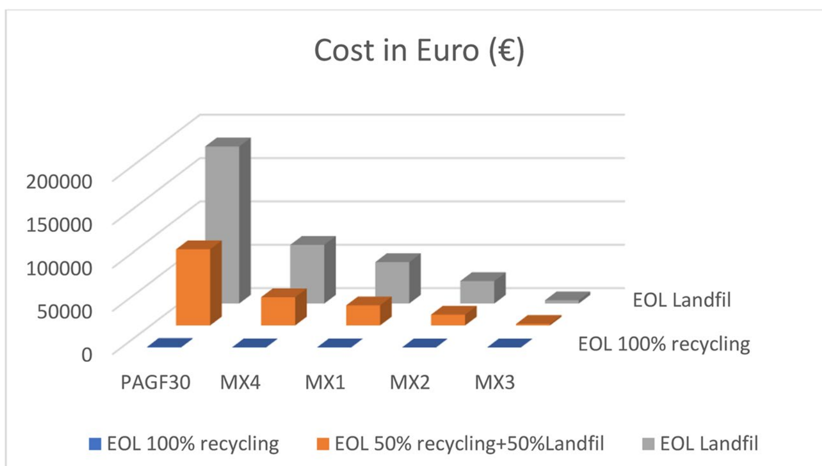


Fig. 9 LCC including the household end of life. Comparison of 3 end-of-life scenarios: 100% recycling, 50% recycling + 50% landfilling, and 100% landfilling

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Author Contribution Angela Daniela La Rosa: conceptualization, writing the original draft, formal analysis, software, original draft preparation, LCA and LCC analysis, use of SimaPro software. Ramon Carvalho: data curation, software, inventory data collection and SimaPro software use, writing as master student at NTNU under the tutoring of Prof. A.D. La Rosa. Marco Dias: data curation, primary inventory data collection as representative of GNL company. Vitor Paulo: data curation, primary inventory data collection, as representative of GNL company.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare no competing interests. They disclose that one author, Angela Daniela La Rosa, has role as an Editor of the journal Materials Circular Economy.

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