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Digital Eco-Design and Life Cycle Assessment—Key Elements in a Circular Economy: A Case Study of a Conventional Desk

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Abstract: In recent times, there has been an indisputable need to move towards a more sustainable economy, known as a circular economy, which is basically aimed at reducing the consumption of newly extracted raw materials to manufacture products, and thus, reduces waste generation by recycling products beyond their useful life to ultimately close the economic flow of the product. For the economy generated by products to close the circle, it is essential to tackle the problem at the source, that is, the process to achieve the desired product should be conducted by designing the product with environmental criteria (eco-design) and analysing its life cycle from the extraction process to the point when it ends its useful life (LCA). This article presents an ECO + LCA methodology that provides designers with an easy way of visualising the effect of their design decisions on the final environmental impact of the product. This methodology was tested on a case study of a conventional desk, with four alternative scenarios presented and an assessment of their final impact with a cradle-to-grave perspective. The final design obtained reduces the environmental impact by more than 30% and reduces costs by more than 11%.

Keywords: eco-design; LCA; circular economy; waste recovery

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1. Introduction

The current product development linear model is unsustainable in the long term. The idea of producing a new product, using it, and discarding it in order to manufacture a new one to cover the needs of the discarded product results in a constant increase in the pressure that the globalised economy exerts on the environment. This pressure is twofold. On the one hand, it implies the continuous extraction and reduction of resources, and on the other hand, the constant generation of waste and emissions into the environment.

This economic and industrial model must be redirected towards a circular economy, one where all products contribute to closing the cycle of materials. In this way, the resources initially extracted to create the product are reused at the end of its useful life to create new ones. This limits the continuous increase in the demand for resources to continue manufacturing new products and, in addition, minimises the waste generated at the end of their useful life.

The shift from a linear economy model to a circular economy model is a complex and interesting topic that has been widely discussed in the scientific community in recent years. For instance, Ghisellini et al. [1] conducted an extensive literature review to determine whether the circular economy can be the solution to reduce the environmental impact of our current economic system. They emphasise that, although the circular economy is a good frame of reference for changing the current development model, its actual implementation is still in its early stages and few countries have launched preliminary actions for its implementation. Lobo et al. [2] conducted an extensive literature review to identify the main barriers that companies face in their transition to a circular economy. The authors defined five categories to group the 24 identified barriers. Mazur-Wierzbicka [3] sought to group the 28 European Union countries according to their development, as reflected in the circular economy indicators proposed by the European Union. In this study, it was concluded that there are two clearly differentiated groups of countries according to their progress towards a circular economy. Papageorgiou et al. [4] emphasise the need for a reference framework to assess the transition towards a circular economy. To further explore this aspect, the authors analysed 15 indicator-based reference frameworks. The assessment was based on eight criteria, and they came to the conclusion that none of the reference frameworks studied meet all the requirements.

Other recent studies have focused on specific sectors in which the circular economy can have a significant effect. Poponi et al. [5] defined the agri-food sector as one primarily in need of a system of indicators to monitor their progress in the transition to a circular economy. The authors proposed indicators in three sustainability areas and in three spatial dimensions to guide the agri-food sector on the path towards a circular economy. Freire et al. [6] highlighted the relevance of the construction sector in waste generation and proposed a paradigm shift in consumption patterns to facilitate the transition to a circular economy. The authors analysed different methodologies for pavement rehabilitation using recycled materials. Diaz et al. [7] proposed incorporating the concept of a circular economy in small and medium-sized companies in the plastics sector. In this case, the authors proposed the reuse of products and the reduction of material consumption and waste generation. Hartwell et al. [8] analysed the importance of the reusing and recycling of materials in the building façade sector. They also proposed strategies to minimise environmental impact while optimising economic value. In this way, they sought to align circular economy strategies with the priorities of the investors in the building façade sector.

Another area in which the circular economy is widely studied is that of waste treatment. Zhang and Liu [9] argue that the circular economy will result in a fundamental change in municipal water treatment technologies. This change will transform these technologies from simple waste treatment to resource recovery and reuse in an economically and environmentally sustainable manner. Candido et al. [10] applied the principles of a circular economy to the development of a wastewater treatment system for a pig farm. This low-cost wastewater treatment system can be used to generate energy, produce fertiliser, and recover water that can be reused for cleaning processes on the farm itself. Colangelo et al. [11] highlighted the problem of construction and demolition waste in the construction sector and proposed a comparative LCA of eight different types of concrete mixtures with geopolymeric and recycled aggregates.

The concept of a circular economy has also been studied within the scenario of the COVID-19 pandemic. Felix et al. [12] highlighted the increase in different types of industrial waste resulting from the COVID-19 pandemic. They conducted a thorough review of the thermochemical treatment options for these types of waste, as well as their contribution to the circular economy. Sharma et al. [13] analysed the impact of the COVID-19 pandemic on the United Nations Sustainable Development Goals. They highlighted the need for solid waste treatment systems in the post-COVID era to prioritise an approach to a circular economy. Kumar et al. [14] analysed the environmental impact of personal protective equipment under two disposal scenarios, identifying an environmentally sound management option for this kind of waste.

The notion of a circular economy has increasingly gained more traction in the current policies set by the authorities. For example, the European Union adopted, in March 2020, a new action plan for the transition to a circular economy [15]. This plan is aimed at promoting a circular economy by means of the implementation of 35 defined actions. It also establishes the legal obligation of the member states to implement the initiatives developed at the European level in the different areas included in the plan.

This paper presents the authors' research about three measures that will be introduced under the new action plan:

- make sustainable products the norm in the EU;
- make circularity work for people, regions, and cities;

- a sustainable products policy initiative, which includes a revision of the Ecodesign Directive.

For the methodology proposed in this study, we took the context defined by the European Union in the new action plan for the transition to a circular economy as a starting point. This does not imply that its application is restricted to Europe or any of its member states. The methodology is generic and can be applied to any type of product or process, regardless of where it was designed.

The main objective of this study was to provide an eco-design methodology that uses life cycle assessment [16,17] (ECO + LCA) as a basis and allows designers to propose and study different product alternatives from an environmental perspective. The implementation of this methodology in the initial phases of product design would facilitate a reduction in the environmental impact of the products and would provide designers with the tools to weigh, from the beginning, the environmental impact of their decisions, from the raw material extraction phase to the end-of-life phase.

2. Materials and Methods

2.1. Conceptual Background

One of the key elements to making a circular economy a reality is to tackle the problem from its origin when the product is still an idea—a concept to be designed from scratch. This is the moment to incorporate the environmental criteria, to serve as the basis for designing the product. Such a product must also comply with the reference framework guidelines offered by the circular economy.

Implementing these ideas from an industrial point of view, based on the increase in product consumption, is an economic, social, and environmental challenge. Managing to align these three parameters in the same direction is a contradictory manifold challenge. As a matter of fact, Knight and Jenkins [18] concluded that different eco-design techniques may not be widely implemented in companies because they are not generic tools that can be applied directly but require specific customisation processes before they can be used. This is clearly a barrier that hinders the adoption of eco-design or leads to its simplification and, therefore, deviates from the objective of a circular economy. In an attempt to overcome these barriers, Chebaeva et al. [19] analysed 33 available environmental assessment methods and presented their systematic classification to facilitate their integration with other studies and projects. Dahmani et al. [20] explored the relationship between Lean Design and Eco-design, and their interconnection with the Industry 4.0 technologies. Finally, they proposed a reference framework that, through the synergies of those three fields, provides designers with the necessary tools to implement sustainable product development strategies. Manzardo et al. [21] proposed a methodology that combines eco-design (ISO 14006) with the product environmental footprint methodology. This methodology was applied to the eco-design of new red wines, reducing their environmental impact. Micheaux and Aggeri [22] stressed the need to encourage producers to implement eco-design. To this end, they proposed an incentive scheme (eco-modulation) that applies modular rates to products according to their level of eco-design. Soh and Wong [23] conducted a study on the importance of involving customers in the transition process towards a circular economy. The authors concluded that to avoid a slowdown of this transition, it is necessary for both people and companies to internalise the competitive advantages and business benefits that a circular economy can bring. Zhang et al. [24] proposed a knowledge feedback methodology based on CAD systems to make it easier for designers to find prior eco-design knowledge that meets the requirements of the new designs they are developing. In this way, when a designer is assigned a new eco-design area, an algorithm shows similar solutions to the problem posed and facilitates adapting the solution to the new design while providing further feedback into the system.

In addition to these advances in eco-design methodologies, many studies have worked on direct applications of eco-design to different products. For example, Avadí et al. [25] proposed two eco-design strategies for conventional crop rotation. In both cases, they advocate for a change in the fertilisers used, replacing conventional mineral fertilisers with new organic fertilisers obtained from waste. Barbosa et al. [26] eco-designed an alternative product to replace traditional cotton swabs while maintaining economic and environmental viability. The product was validated through a life cycle assessment, which showed a lower environmental impact due to the raw material used in its manufacturing. Corsi et al. [27] reviewed the marine environmental impact that engineered nanomaterials can cause. In addition, they proposed an eco-design strategy for the development of new engineered nanomaterials. Duran Quintero et al. [28] identified the key elements in the eco-design of solar cultivation of Spirulina. In addition, they established the maximisation of the annual cultivation duration as the main criterion to reduce its environmental impact, as long as the solar conditions allow for the growth of the micro-algae. Longo et al. [29] performed a life cycle assessment of two possible configurations of sodium nickel chloride batteries to identify the most relevant environmental impact elements and set the path for future sustainable strategies for these products. Miettunen and Santasalo-Aarnio [30] analysed in depth the possible recycling of materials used in dye solar cells. Furthermore, using eco-design principles, they proposed substituting materials used in conventional cells, which cannot be recycled in an economically viable way, with recyclable materials that eliminate toxic gas emissions during the recycling process.

A life cycle assessment is a methodology that allows for calculating the environmental impact of any given product or process from cradle to grave [16,17]. It includes all the phases of the entire existence of a product, from its manufacture to the end-of-life recovery phase, with its negative impacts (resources, emissions, discharges, and unusable waste) and positive impacts (new jobs, reuse of components, new resources). This significant capacity to consider the environmental impact of a product as a whole makes this methodology one of the most widely used in the environmental scientific literature [31–37]. It is used to analyse the environmental impact all the way from renewable energies [38–41] to the construction industry [42,43] or food products [44].

Within the LCA methodology, different life cycle impact assessment (LCIA) methods can be used to calculate the environmental impact of the product or process under study [45]. It is common for a non-expert eye on the topic to have difficulties understanding the results obtained from an LCA and the possible differences depending on the LCIA used. The fact that there are two clearly differentiated categories of LCIA methods, midpoints and endpoints, magnifies this confusion when interpreting LCA results. The midpoint methods (i.e., CML) [46] present the results in a series of categories based on characterisation factors for different emissions, for example, CO_2 for climate change or SO_2 for acidification. On the other hand, endpoint methods (i.e., Eco-indicator 99 or ReCiPe) [47,48] weigh and group these impact categories to obtain results in several damage categories that are easier to interpret, for example, damage to the ecosystem or human health. Furthermore, these damage categories can be summed to obtain a single environmental impact value that comprises, in a balanced way, all the environmental impacts resulting from the product under study. Logically, these extra steps of weighting and grouping of general impact categories add extra uncertainty to the final LCA results.

2.2. ECO + LCA Methodology

In order to facilitate the incorporation of an LCA into the product design phase, a simple methodology (ECO + LCA) is proposed, which allows the designer to quickly analyse the multiple variables with environmental, economic, and social impact in the decisions made. This is the main contribution of designing a product with eco-design criteria (ISO 14006). The basis of this methodology is the compilation of an inventory that includes the different impacts derived from the different phases of the entire existence of a product, that is, the extraction of raw materials, transport, manufacture, use, product end of life, recovery, transport to landfill, and new raw materials.

For this purpose, firstly, a block diagram with all the processes is generated, which indicates all the inputs, known as a product life cycle inventory.

In the next step, the environmental impact of the different materials and processes that may be used in the manufacture of the product, inputs (resources), and outputs (emissions, products, by-products, and waste), are quantified in a table (see Table 1).

Table 1. Environmental impact of materials and processes.

Material/Process	Impact per Kg
Material 1	XX
Material 2	XX
Process 1	XX
Process 2	XX

There are different methods, some general and others sector-based, that classify impacts by a variable number of categories. For the purposes of this article, ReCiPe endpoint (hierarchist perspective) [48] has been used. The hierarchist perspective is the one with more scientific consensus in relation to the timeframe used to define the characterisation factors of the different impact categories analysed [48]. ReCiPe endpoint allows obtaining endpoint-oriented environmental impact categories that are easier to understand and interpret. Thus, a single environmental impact can be obtained with a quantitative assessment of environmental impact points. This avoids the need to work with different impact categories with results that are not comparable with each other, or to simply keep only one impact category, such as climate change, and disregard the rest.

The software Simapro v9.2 [49] and the database Ecoinvent 3.7.1 [50] were used to obtain the environmental impact results. The software Simapro is a widely used, solid, and reliable tool that is commonly applied in life cycle analyses. Furthermore, it has the advantage of incorporating different globally accepted databases (e.g., Ecoinvent), which can be used as data sources to study the environmental impact of different materials and processes.

The database Ecoinvent is one of the most used in the LCA field, as it incorporates a wide range of datasets, thus covering the basic aspects of any LCA. In addition, these datasets are localized in a way that a distinction can be made between geographical locations. For instance, different datasets can be selected to calculate the generated impact of generating 1 kWh of energy in Spain or in China.

The environmental impact values in Tables 1–3 were obtained by using Simapro and selecting the corresponding dataset within the Ecoinvent database, that is, based on the material, process, transport, or waste treatment used in the specific product design.

Table 2. Environmental impact of transports.

Transport	Impact per kgkm
Transport Type 1	X
Transport Type 2	X

Table 3. Environmental impact of waste treatments.

Waste Treatment	Impact per kg
Waste Treatment 1	X
Waste Treatment 2	X

In addition to the environmental impact table for materials and processes, environmental impact tables for possible means of transport (see Table 2) and end-of-life (see Table 3) must also be made.

From these tables, the designer will only have to fill in the data corresponding to each design to be analysed to automatically obtain the estimation of the environmental impact of the design. This allows the designer to perform as many iterations as necessary until a green design [51–53] product is obtained (see Table 4). In addition, for each alternative design, the associated economic costs must also be assessed. In this way, the design as a whole is considered from the economic perspective of the decisions to the environmental implications in the choice of materials and possible end-of-life treatments.

Table 4. Environmental impact of the design.

Material	Weight	Active	Fab/Us Imp.	Distance	Transport	Transport Imp.	Waste Treatment	Waste Imp.	Total Imp.
Mat1	X	YES		X	Trans1		Treat1		
Mat2	X	NO		X	Trans2		Treat2		
	ALTERNATIVE SCENARIO PRICE: XXX€								IMP

The proposed methodology was applied to the case study of a conventional desk. The starting point was a conventional design of a 180 × 80 cm desk with a height of 72 cm and made with chipboard wood and steel legs.

3. Results

The results obtained from applying the ECO + LCA methodology to a conventional desk design case study are presented below.

The first step was to calculate the environmental impact associated with the different materials used, the transportation needed, and their end-of-life (see Tables 5–7).

Table 5. Environmental impact of materials and processes for the case study.

Material/Process	Impact per Kg
Steel	9.58×10^{-1}
Aluminium	1.51×10^{0}
PVC	2.32×10^{-1}
Chipboard Wood	1.06×10^{-1}
Wood	1.16×10^{-1}
Paperboard	1.25×10^{-1}

Table 6. Environmental impact of transports for the case study.

Transport	Impact per kgkm
Lorry 16–32 t	1.65×10^{-5}
Transoceanic Transport	1.34×10^{-6}
Aircraft	1.02×10^{-4}

Table 7. Environmental impact of waste treatments for the case study.

Waste Treatment	Impact per kg
Inert Material Landfill	2.10×10^{-3}
Aluminium Landfill	2.19×10^{-3}
Steel Landfill	1.15×10^{-3}
PVC Landfill	6.48×10^{-2}
Chipboard Wood Landfill	6.40×10^{-3}
Wood Landfill	8.92×10^{-4}
Municipal Incineration	3.12×10^{-2}
Aluminium Recycling	-1.01×10^{0}
Steel Recycling	-1.50×10^{-1}
Chipboard Wood Recycling	-3.19×10^{-2}
Wood Recycling	-8.50×10^{-2}

Table 5 shows the possible materials and/or manufacturing processes used or studied for the possible design of the conventional desk analysed in this case study. If a certain material or process was to be used in the design, it was then included in the tables to obtain its environmental impact according to the ReCiPe LCIA.

Similarly, Table 6 shows the environmental impacts of the possible transport of materials involved in the design of the product to be produced. If a certain material requires road transport to the manufacturing plant, this type of transport should be included.

Table 7 includes the environmental impact of the possible waste treatment systems for the different materials used in the manufacture of the product design.

Based on these initial data, the impact associated with each proposed design was calculated. Table 8 and Figure 1 show the results obtained for the case study of a conventional desk with truck transport and basic waste treatment, discharge in landfill, or incineration at municipal facilities. Entering the necessary data is very simple; it is only about selecting the materials, the type of transport, and waste treatment from the drop-down menus and filling in the weights and transport distances.

Table 8. Results of conventional desk scenario.

Material	Weight	Active	Fab/Use Imp.	Distance	Transport	Transport Imp.	Waste Treatment	Waste Imp.	Total Imp.
Steel	6.70×10^{0}	YES	6.42×10^{0}	10	Lorry 16–32 t	1.10×10^{-3}	Landfill	7.73×10^{-3}	6.43×10^{0}
Aluminium	5.60×10^{0}	YES	8.45×10^{0}	10	Lorry 16–32 t	9.22×10^{-4}	Landfill	1.22×10^{-2}	8.46×10^{0}
PVC	3.00×10^{-1}	YES	6.96×10^{-2}	10	Lorry 16–32 t	4.94×10^{-5}	Landfill	1.94×10^{-2}	8.91×10^{-2}
Chipboard Wood	3.15×10^{1}	YES	3.35×10^{0}	10	Lorry 16–32 t	5.19×10^{-3}	Landfill	2.02×10^{-2}	3.55×10^{0}
Wood	3.60×10^{1}	NO	0.00×10^{0}	10	Lorry 16–32 t	0.00×10^{0}	Landfill	0.00×10^{0}	0.00×10^{0}
Paperboard	3.00×10^{0}	YES	3.74×10^{-1}	10	Lorry 16–32 t	4.94×10^{-4}	Incineration	9.36×10^{-2}	4.68×10^{-1}
CONVENTIONAL DESK PRICE: €149.35									1.90×10^{1}

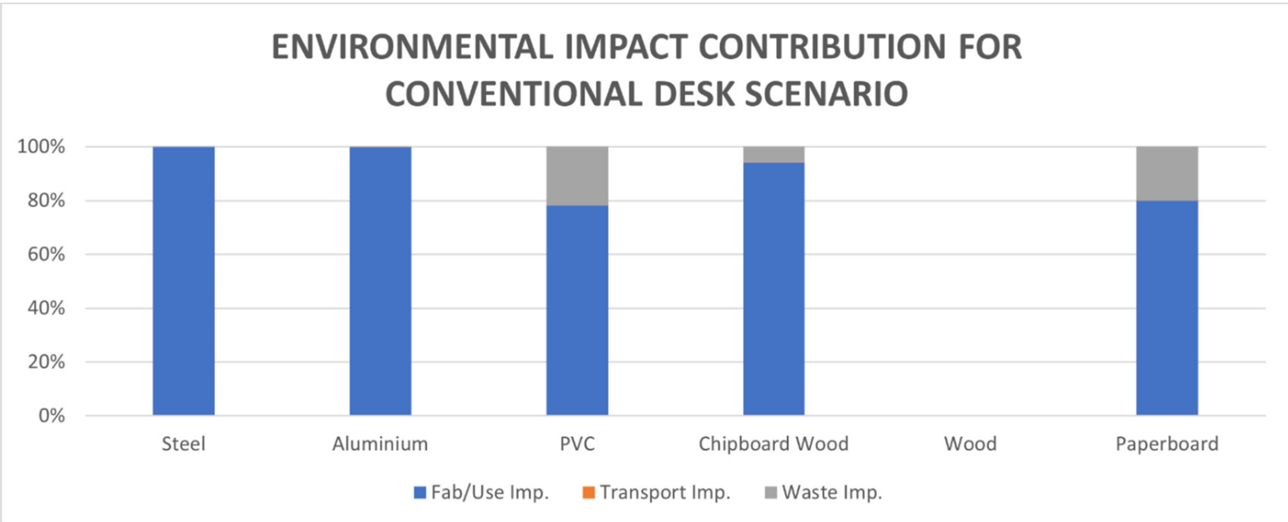

Figure 1. Environmental impact contribution for conventional desk scenario.

According to the results obtained for the base case, the environmental impact of the initial design would be 1.90×10^{1} pt.

With this starting point, it is easy to start assessing different potential designs/scenarios. For instance, Table 9 and Figure 2 show the results of using wood instead of chipboard, and in this case, from an American supplier, including sea transport. This choice would increase the environmental impact by almost one point, with a total impact of 1.99×10^{1} pt.

Table 9. Results of American wood desk scenario.

Material	Weight	Active	Fab/Use Imp.	Distance	Transport	Transport Imp.	Waste Treatment	Waste Imp.	Total Imp.
Steel	6.70×10^0	YES	6.42×10^0	10	Lorry 16–32 t	1.10×10^{-3}	Landfill	7.73×10^{-3}	6.43×10^0
Aluminium	5.60×10^0	YES	8.45×10^0	10	Lorry 16–32 t	9.22×10^{-4}	Landfill	1.22×10^{-2}	8.46×10^0
PVC	3.00×10^{-1}	YES	6.96×10^{-2}	10	Lorry 16–32 t	4.94×10^{-5}	Landfill	1.94×10^{-2}	8.91×10^{-2}
Chipboard Wood	3.15×10^1	NO	0.00×10^0	10	Lorry 16–32 t	0.00×10^0	Landfill	0.00×10^0	0.00×10^0
Wood	3.60×10^1	YES	4.19×10^0	5000	Transoceanic Transport	2.41×10^{-1}	Landfill	3.21×10^{-2}	4.46×10^0
Paperboard	3.00×10^0	YES	3.74×10^{-1}	10	Lorry 16–32 t	4.94×10^{-4}	Incineration	9.36×10^{-2}	4.68×10^{-1}
AMERICAN WOOD DESK PRICE: €188.21									1.99×10^1

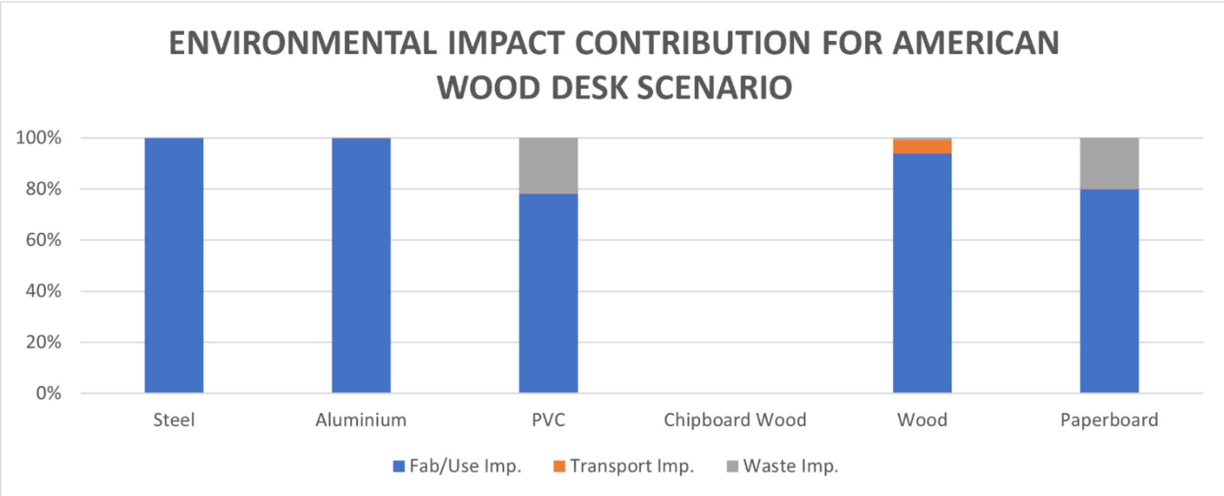

Figure 2. Environmental impact contribution for American wood desk scenario.

If the option of using wood instead of chipboard is considered, though including a local supplier, along with the scenario of possible recycling this wood at the end of its useful life (see Table 10 and Figure 3), the results vary significantly. The environmental impact is thus reduced by 2.4×10^0 pt., as the total impact of the desk is 1.66×10^1 pt.

Table 10. Results of wood desk + recycling scenario.

Material	Weight	Active	Fab/Us Imp.	Distance	Transport	Transport Imp.	Waste Treatment	Waste Imp.	Total Imp.
Steel	6.70×10^0	YES	6.42×10^0	10	Lorry 16–32 t	1.10×10^{-3}	Landfill	7.73×10^{-3}	6.43×10^0
Aluminium	5.60×10^0	YES	8.45×10^0	10	Lorry 16–32 t	9.22×10^{-4}	Landfill	1.22×10^{-2}	8.46×10^0
PVC	3.00×10^{-1}	YES	6.96×10^{-2}	10	Lorry 16–32 t	4.94×10^{-5}	Landfill	1.94×10^{-2}	8.91×10^{-2}
Chipboard Wood	3.15×10^1	NO	0.00×10^0	10	Lorry 16–32 t	0.00×10^0	Landfill	0.00×10^0	0.00×10^0
Wood	3.60×10^1	YES	4.19×10^0	10	Lorry 16–32 t	5.93×10^{-3}	Recycling	-3.06×10^0	1.13×10^0
Paperboard	3.00×10^0	YES	3.74×10^{-1}	10	Lorry 16–32 t	4.94×10^{-4}	Incineration	9.36×10^{-2}	4.68×10^{-1}
WOOD DESK + RECYCLING PRICE: €170.21									1.66×10^1

If instead of wood, a cheaper version using chipboard is chosen and the option of final recycling is also considered (see Table 11 and Figure 4), the impact is also reduced compared to the base case (1.21×10^0 pt.), but it does not reach the values of the case with wood and recycling. The total impact of the desk would be 1.78×10^1 pt.

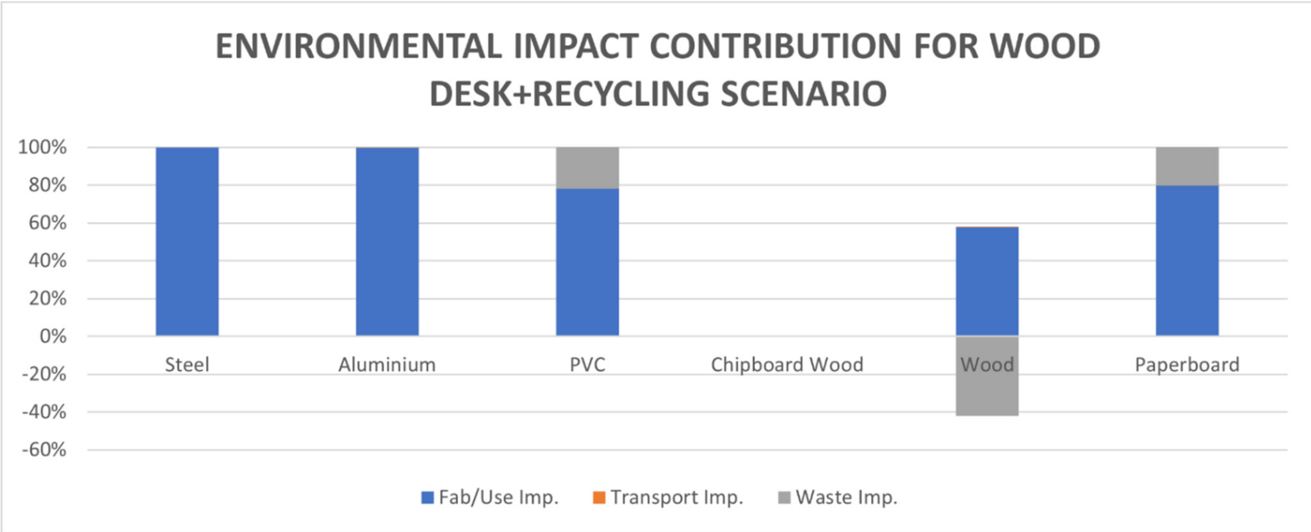

Figure 3. Environmental impact contribution for wood desk + recycling scenario.

Table 11. Results of chipboard wood desk + recycling scenario.

Material	Weight	Active	Fab/Use Imp.	Distance	Transport	Transport Imp.	Waste Treatment	Waste Imp.	Total Imp.
Steel	6.70×10^0	YES	6.42×10^0	10	Lorry 16–32 t	1.10×10^{-3}	Landfill	7.73×10^{-3}	6.43×10^0
Aluminium	5.60×10^0	YES	8.45×10^0	10	Lorry 16–32 t	9.22×10^{-4}	Landfill	1.22×10^{-2}	8.46×10^0
PVC	3.00×10^{-1}	YES	6.96×10^{-2}	10	Lorry 16–32 t	4.94×10^{-5}	Landfill	1.94×10^{-2}	8.91×10^{-2}
Chipboard Wood	3.15×10^1	YES	3.35×10^0	10	Lorry 16–32 t	5.19×10^{-3}	Recycling	-1.00×10^0	2.35×10^0
Wood	3.60×10^1	NO	0.00×10^0	10	Lorry 16–32 t	0.00×10^0	Recycling	0.00×10^0	0.00×10^0
Paperboard	3.00×10^0	YES	3.74×10^{-1}	10	Lorry 16–32 t	4.94×10^{-4}	Incineration	9.36×10^{-2}	4.68×10^{-1}
CHIPBOARD WOOD DESK + RECYCLING PRICE: €149.35									1.78×10^1

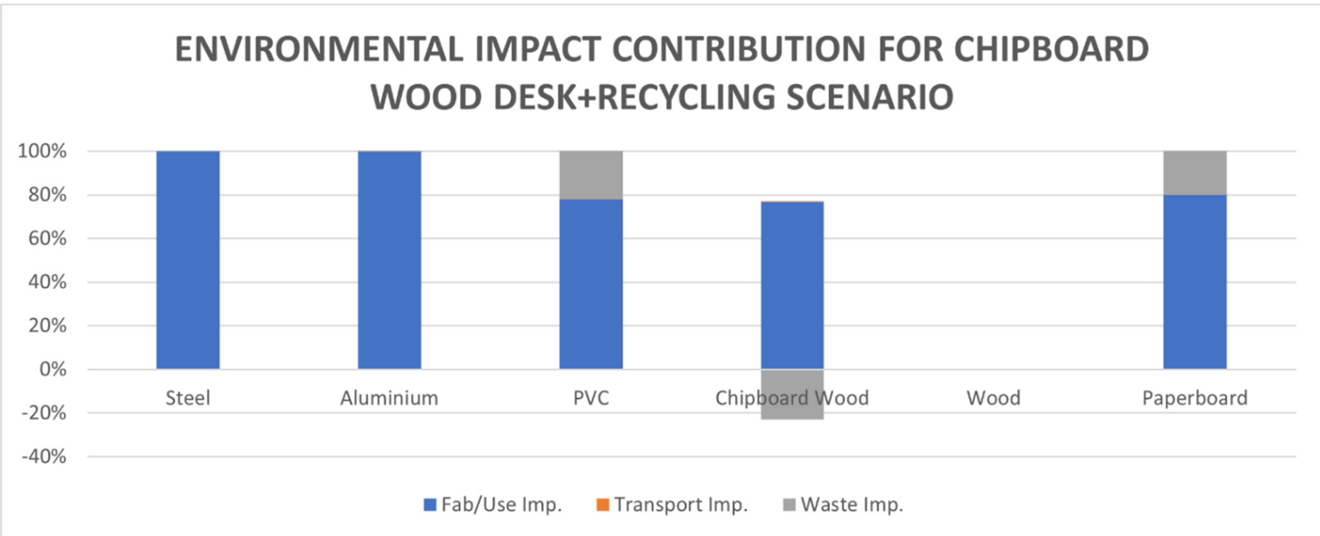

Figure 4. Environmental impact contribution for chipboard wood desk + recycling scenario.

If, in addition to choosing wood and facilitating the option of its final recycling, the amount of material needed to manufacture the desk is reduced by 30% in wood and 20% in metal, the environmental impact would decrease by 5.7×10^0 pt. The total impact of this design would be 1.33×10^1 pt. (see Table 12 and Figure 5). The reduction in materials presented in this scenario maintains the minimum requirements of the desk design but changes the shape of the desk by making it round instead of the original square and thus eliminating part of the trims. With these modifications, the materials and the final weight of the table are reduced while the basic dimensions of 180 × 80 cm are maintained but with a narrower central area.

Table 12. Results of chipboard wood desk + reduced materials + recycling scenario.

Material	Weight	Active	Fab/Use Imp.	Distance	Transport	Transport Imp.	Waste Treatment	Waste Imp.	Total Imp.
Steel	5.36×10^{0}	YES	5.14×10^{0}	10	Lorry 16–32 t	8.82×10^{-4}	Landfill	6.18×10^{-3}	5.14×10^{0}
Aluminium	4.48×10^{0}	YES	6.76×10^{0}	10	Lorry 16–32 t	7.38×10^{-4}	Landfill	9.80×10^{-3}	6.77×10^{0}
PVC	3.00×10^{-1}	YES	6.96×10^{-2}	10	Lorry 16–32 t	4.94×10^{-5}	Landfill	1.94×10^{-2}	8.91×10^{-2}
Chipboard Wood	2.21×10^{1}	NO	0.00×10^{0}	10	Lorry 16–32 t	0.00×10^{0}	Landfill	0.00×10^{0}	0.00×10^{0}
Wood	2.52×10^{1}	YES	2.93×10^{0}	10	Lorry 16–32 t	4.15×10^{-3}	Recycling	-2.14×10^{0}	7.94×10^{-1}
Paperboard	3.00×10^{0}	YES	3.74×10^{-1}	10	Lorry 16–32 t	4.94×10^{-4}	Incineration	9.36×10^{-2}	4.68×10^{-1}
WOOD DESK + REDUCED MATERIALS + RECYCLING									1.33×10^{1}
PRICE: €132.30									

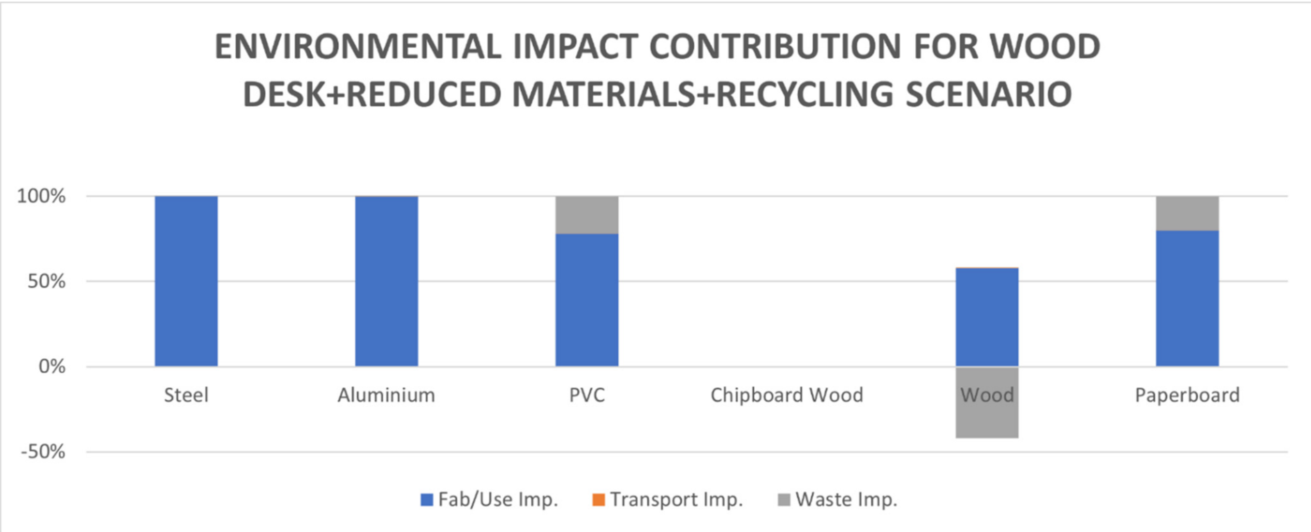

Figure 5. Environmental impact contribution for wood desk + reduced materials + recycling scenario.

A conflictive phase that indirectly affects this circular economy is still pending—the standardisation of impacts according to the world region in which all or part of the processes takes place, where energy consumption clearly appears as a polluting villain and demonstrates the need for an energy transition towards a circular and digital economy.

4. Discussion

The proposed methodology allows for the eco-design of products based on the LCA methodology but in a more simplified and direct manner. Compared to other eco-design methodologies that apply a complete LCA [25,27,28], the proposed methodology focuses on providing a simplified life cycle inventory, which, however, includes all phases of product life—the extraction of raw materials, transport, manufacturing processes, and waste treatment at the end of its useful life. In this way, once the materials, processes, transport, and waste treatment that can be used in the design have been established, the designer is free to propose alternatives in a simple and smooth way, without having to rely on an LCA specialist.

To achieve an effective transition to a circular economy, at least part of the barriers slowing down the implementation of circular economy concepts in companies must be removed from the equation [2,3]. One of these barriers is the specialised knowledge needed in the LCA area to be able to design new products that comply with the ideas of circular economy, which analyses products from cradle to grave in an attempt to reduce their environmental impact in all phases of their life cycle. If with the proposed methodology, the need for LCA experts is limited, companies might see it as an easier way to get started with the principles of a circular economy.

In addition, a successful transition to a circular economy also requires that the end-customer can easily assess the environmental improvement of one product over another [22]. The use of an endpoint LCIA leads to environmental impact results in a single, dimensionless value without the need for the end-customer to get confused with different impact categories that are complex to explain in a simple manner. For instance, Figure 6 shows a simple graphical comparison of the different environmental impacts and prices of each of the alternatives studied for the traditional desktop case study. In this way, the end-customer would have a clear, visual, and easy-to-interpret presentation of each of the alternatives, and thus would be able to assess the advantages/disadvantages in each case.

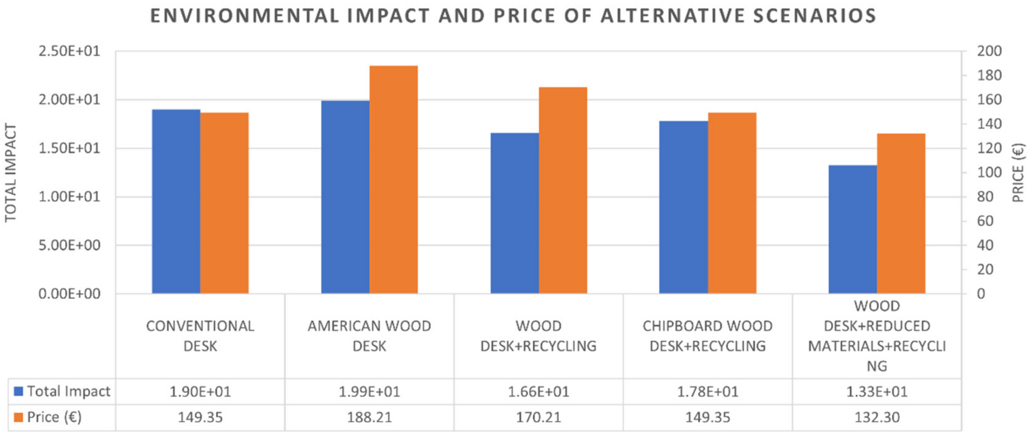

Figure 6. Environmental impact and price of alternative scenarios analysed.

5. Conclusions

The need to move towards a circular economy model makes it necessary to develop methodologies to address it from the initial phase of product design and development. For this reason, in this article, we propose a simple and easy-to-apply methodology to combine eco-design and LCA as an essential part of product development.

The basis of this methodology is the compilation of an inventory that includes the different impacts derived from all the phases of the entire existence of a product, that is, the extraction of raw materials, transport, manufacture, use, product end of life, recovery, transport to landfill, and new raw materials. This is achieved in a simple way and facilitates the incorporation of design alternatives, use scenarios, and end-of-life.

This ECO + LCA methodology was applied to a case study of a conventional desk design. Four alternative scenarios were analysed, achieving environmental improvements ranging from 1.21×10^0 pt. to 5.74×10^0 pt., and starting from a base design with a total environmental impact of 1.90×10^1 pt. Of the different scenarios analysed, the last one (WOOD DESK + REDUCED MATERIALS + RECYCLING) presents not only a better environmental performance but also a lower economic cost thanks to the reduction in materials used in its manufacturing. If, in addition, the significant advantages of choosing products designed with an environmental cradle-to-grave perspective are successfully conveyed to the customers, it would be a step forward for the circular economy to advance and become established in all aspects of society.

Based on this proposed methodology, future studies will include more complex aspects of the LCA methodology, such as the allocation of by-products or co-products in a way that is relatively simple and easy to use for a designer who is considering different alternatives in the initial design phase of a product.

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