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Patricia Gómez Bachiller

Metodología para el diseño considerando la composición de materiales, relación con materiales críticos y diseño ecológico

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Tesis Doctoral

METODOLOGÍA PARA EL DISEÑO CONSIDERANDO LA COMPOSICIÓN DE MATERIALES, RELACIÓN CON MATERIALES CRÍTICOS Y DISEÑO ECOLÓGICO

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UNIVERSIDAD DE ZARAGOZA
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PROGRAMA DE DOCTORADO EN INGENIERÍA MECÁNICA

Tesis Doctoral

Metodología para el diseño considerando la composición de materiales, relación con materiales críticos y diseño ecológico.

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Directores: Carlos Javierre Lardiés
Daniel Elduque Viñuales

Fecha: Marzo 2019

Tesis por compendio de publicaciones

Tesis doctoral presentada como compendio de publicaciones realizadas a lo largo de la fase de desarrollo del presente trabajo de investigación.

En el siguiente listado se incluyen las referencias de las publicaciones mediante orden cronológico de aceptación y los congresos internacionales. Además en aquellas revistas indexadas JCR se indica el factor de impacto.

Revistas JCR:

- Gómez, P.; Elduque, D.; Sarasa, J.; Pina, C.; Javierre, C. Influence of the Material Composition on the Environmental Impact of surface-mount device (SMD) Transistor. ***Journal of Cleaner Production*, 2015, 107**, 722-730. **Q1**, (Q1, JCR2015: 4.959).
- Gómez, P; Elduque, D.; Sarasa, J.; Pina, C.; Javierre, C. Influence of the composition on the environmental impact of cast aluminum alloy. ***Materials*, 2016, 9(6)**, 412. **Q2** (Q2, JCR2016: 2.654).
- Gómez, P.; Elduque, D.; Pina, C.; Javierre, C. Influence of the Composition on the Environmental Impact of Soft Ferrites. ***Materials,* 2018, 11(10)**, 1789. **Q2** (Q2, JCR2017: 2.467).

Congresos internacionales

- Gómez, P; Pina, C.; Elduque, D.; Clavería, I; Javierre, C.; Sarasa, J. Environmental Assessment Tool to analyze the presence of Critical and Valuable Raw Materials. 27th EMSS 2015, European Modelling & Simulation Symposium, 21-23 Septiembre 2015, Código Proceedings publicado en Scopus: 116186, 374-381.
- Gómez, P; Elduque, D.; Pina, C.; Javierre, C.; Influence of the Composition on the Environmental Impact of Soft Ferrites. The 3rd International Electronic Conference on Materials Sciences, ECMS 2018, 14-28 Mayo 2018.
- Gómez, P; Elduque, D.; Pina, C.; Javierre, C. Design methodology considering environmental impact and critical raw materials, application on induction hobs. The 6th International workshop on simulation for energy, sustainable development and environment, 17-19 Septiembre 2018, Código Proceedings publicado en Scopus: 140582, 15-21.

Otras publicaciones en revistas:

- Gómez, P; Elduque, D.; Pina, C.; Sarasa, J.; Clavería, I; Javierre, C. Environmental Assessment Tool to analyze the presence of Critical and Valuable Raw Materials. ***Int. J. Service and Computing Oriented Manufacturing,* 2016, 2**, 205-225.

El siguiente artículo ha sido aceptado para ser publicado:

- Gómez P.; Elduque, D.; Clavería, I., Pina, C.; Javierre, C. Influence of the Material Composition of Ceramic Glass on their Environmental Impact. Pendiente de publicar por la revista ***International Journal of Precision Engineering and Manufacturing-Green Technology.*** **Q1** (Q1, JCR2017: 3.774).

Finalmente el siguiente artículo ha sido enviado:

- Gómez P.; Elduque, D.; Sarasa, J., Pina, C.; Javierre, C. Material Composition Influence of SMD Diodes on the Environmental Impact. Pendiente de publicar por la revista ***Journal of Cleaner Production.*** **Q1** (Q1, JCR2017: 5.651).

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Gracias a todos.

Resumen

La presente Tesis Doctoral “Metodología para el diseño considerando la composición de materiales, relación con materiales críticos y diseño ecológico”, es el resultado del trabajo realizado durante 5 años en el Departamento de Ingeniería Mecánica de la Escuela de Ingeniería y Arquitectura de la Universidad de Zaragoza en colaboración con BSH Electrodomésticos España.S.A. en Montañana. La realización de la misma ha sido dirigida conjuntamente por el Dr. Carlos Javierre Lardiés y el Dr. Daniel Elduque Viñuales.

En esta tesis doctoral se desarrolla una novedosa metodología con la que evaluar el impacto ambiental considerando la composición de los materiales, y prestando especial atención a la presencia de materiales críticos. El principal objetivo es desarrollar una metodología de cálculo de impacto ambiental en función de la composición, mejorando el cálculo del impacto ambiental de componentes y proporcionando resultados de mayor exactitud gracias al empleo de la composición real. Además de evaluar la influencia de la composición real en el impacto ambiental, se evaluará también la influencia de los materiales considerados críticos por la Comisión Europea.

El término crítico en materiales fue utilizado por primera vez en el año 1939. Hoy en día un material es considerado crítico cuando existe riesgo de suministro, su importancia económica es considerada mayor en comparación con la de otras materias primas y además existen consideraciones o implicaciones ambientales a tener en cuenta. Tras el último informe publicado por la Comisión Europea en 2017, 43 materiales son identificados como materiales críticos (23 materiales y 3 grupos) de los 78 analizados.

Es por ello que esta tesis doctoral se centra en los materiales críticos, siendo el principal objetivo de la misma analizar la presencia de estos materiales críticos en una cocina de inducción y la relación o influencia de estos en el impacto ambiental, analizando la variación del impacto ambiental causada por la composición de sus materiales.

El trabajo de investigación de la presente tesis doctoral consta de cuatro fases. En la primera, se ha realizado un exhaustivo trabajo de investigación del estado del arte para acotar los materiales que pueden ser considerados como críticos o candidatos a serlo. Se han analizando en profundidad los parámetros por los cuales un material es calificado como crítico, y se han estudiado dichos materiales desde la perspectiva de impacto ambiental.

En segundo lugar se plantea una metodología de trabajo para considerar el uso de los materiales críticos en el diseño, a partir de la cual es posible calcular el impacto ambiental teniendo en cuenta la composición exacta durante el desarrollo de un nuevo producto. Permitiendo conocer la influencia de cada material o cantidad de material sobre el impacto ambiental total del producto o componente desarrollado.

La principal novedad de esta metodología consiste en considerar un inventario personalizado de los componentes a evaluar durante la realización del Análisis del Ciclo de Vida, considerando la presencia de materiales críticos y estratégicos en la composición; generando una base de datos personalizada en lugar de utilizar bases de datos genéricas. Para ello se debe considerar la composición exacta de los materiales, estos datos se obtendrán a partir de información de proveedores o análisis específicos.

En la tercera fase se ha desarrollado un software informático mediante el cual aplicar la metodología con la que considerar los factores de impacto ambiental y la presencia de materiales críticos en el diseño de componentes. El software “Sustainable Electronics” permite al usuario comparar entre varios diseños considerando la composición exacta de los mismos, analizando no solo el impacto ambiental que producen sino el consumo de materiales críticos y candidatos a serlo según el último informe presentado por la Comisión Europea.

Por último, en la cuarta fase, se aplicará la metodología planteada a componentes eléctricos, electrónicos y mecánicos presentes en las cocinas de inducción desarrolladas por BSH Electrodomésticos. Entre los que se encuentran: transistores SMD, diodos, piezas de aluminio, vidrio cerámico o materiales ferríticos.

La siguiente figura muestra el resumen de todo el trabajo realizado:

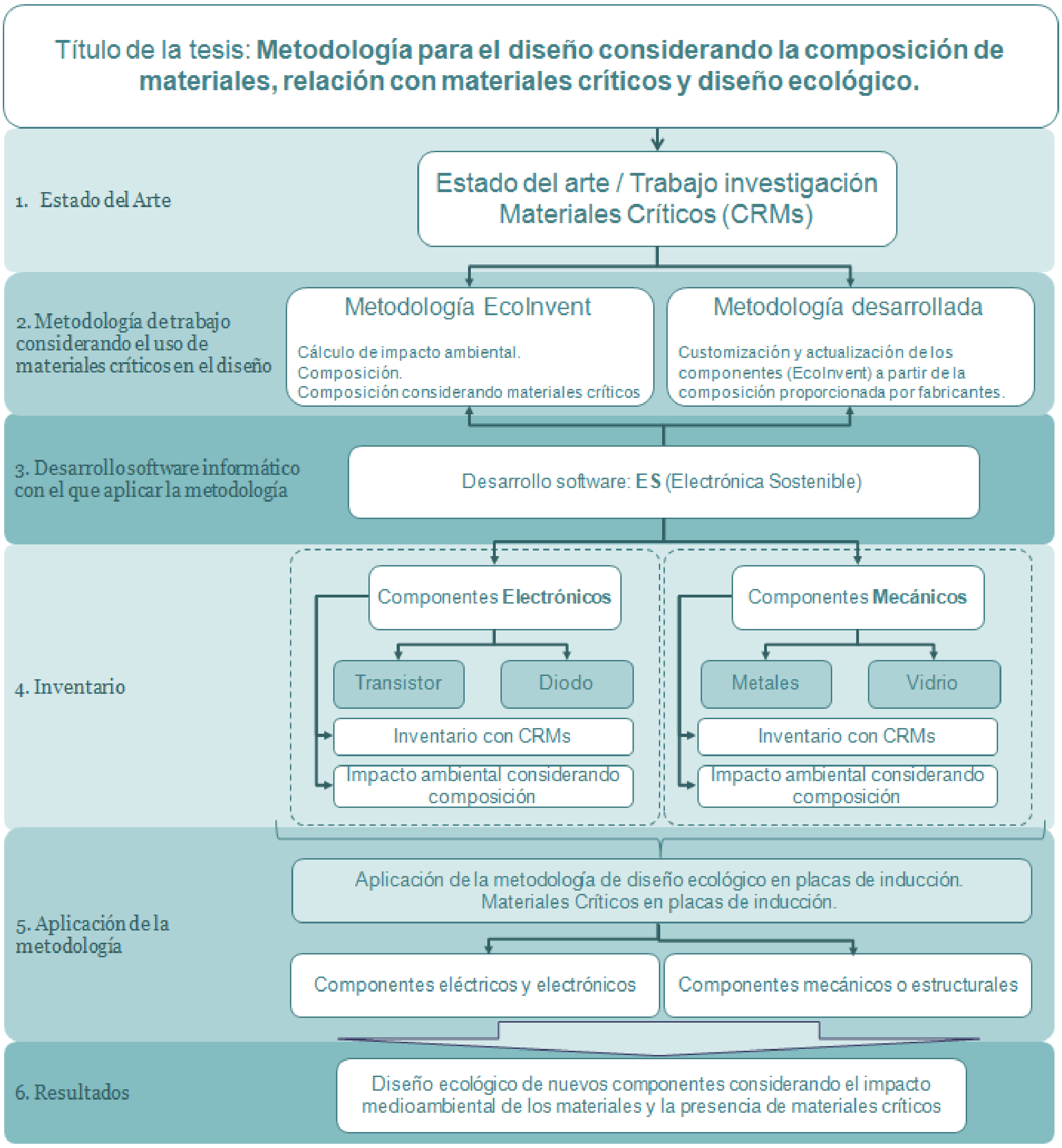

Figura 1 Resumen del trabajo realizado

Todos los resultados de esta tesis doctoral han sido difundidos a través de seis artículos científicos y tres congresos internacionales. Cuatro de los seis artículos científicos se encuentran publicados, tres de ellos en revistas JCR; otro ya ha sido aceptado para ser publicado y el último se encuentran en fase de revisión

.

Abstract

The present PhD study “Design methodology considering materials composition, relation with critical raw materials and ecodesign”, is the result of the work performed during 5 years in the Department of Mechanical Engineering in the School of Engineering and Architecture of the Universidad of Zaragoza, in collaboration with BSH Electrodomésticos España.S.A. located in Montañana. All the work has been guided by Dr. Carlos Javierre Lardiés and by Dr. Daniel Elduque Viñuales together.

In this PhD study a new methodology has been developed in order to evaluate the environmental impact considering materials composition, and taking into account the presence of critical raw materials. The main target is to develop a new methodology to assess the environmental impact depending on the composition, improving the calculation of the environmental impact of the components and achieving exact results due to the use of real composition. In addition to the influence of material composition, the influence of materials considered by the European Commission as critical raw material will be analyzed.

Critical denomination for materials was firstly used in 1939; nowadays, a material is considered as critical when it involves supply risk, when its economic importance is higher than other raw materials or when there are environmental aspects that must be taken into account. In the last report published by the European Commission in 2017, 43 materials were identified as critical raw materials (23 materials and 3 groups) from 78 analyzed materials.

That is the reason why this PhD study is focused on critical raw materials; considering the presence of critical raw material in an induction hob and the relation or influence of these materials on the environmental impact, analyzing the variation of the environmental impact due to the composition of its materials.

The research work of this PhD study is divided in four phases. In the first one, an exhaustive research work of the state of the art was done in order to limit or fix the materials candidates to be considered as critical raw materials. All the parameters that influence the criticity of a material have been analyzed, and those materials considered as critical or strategic raw materials have been studied from an environmental impact point of view.

In the second phase a new methodology that considers the use of critical raw materials when designing a new component is explained, allowing assess the environmental impact considering the exact composition during the development of a new product. It allows knowing the influence of each material or material quantity over the total environmental impact of the product or component developed.

The main innovation of this methodology consist on considering the exact inventory data of each component that will be evaluated during the development of Life Cycle Assessment; creating a customized database instead of using generic databases. In order to achieve this purpose, it is necessary to consider the exact composition of each material, which will be obtained from supplier’s information or by specific analysis.

In the third phase, a new software has been developed to implement the previous methodology, considering environmental impact aspects and the presence of critical raw materials during components design stage. The software called “Sustainable Electronics” allows the user to make a comparative among several designs. It considers their exact composition, analyzing not only their environmental impact but also the exact consumption of critical and strategic raw materials according to the last report published by the European Commission.

Finally, in the fourth stage, the methodology developed has been implemented on electrical, electronic and mechanical components; all of these components are included on induction hobs manufactured by BSH Appliances. Among mentioned components are: transistors, diodes, aluminum parts, ceramic glass or ferrite materials.

Next figure shows a summary of all the work performed:

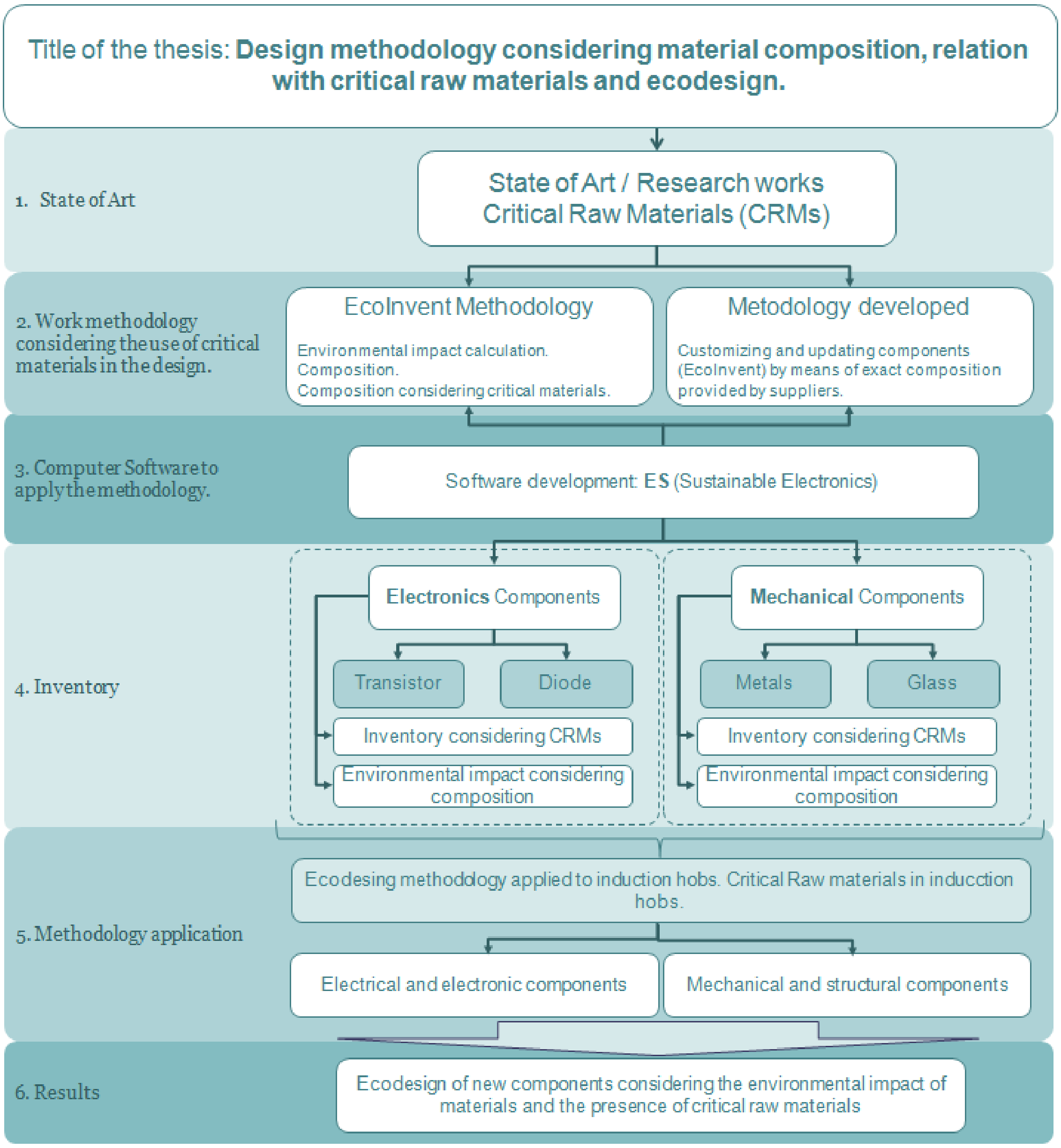

Figura 2 Summary of work

The results of this research have been exposed through six scientific papers and three international congresses. Four of the six scientific papers are already published, three of them in JCR journals; another one has been accepted to be published and the last one is in the revision step.

Introducción General

La presente tesis doctoral tiene como principal objetivo desarrollar una metodología de diseño considerando el impacto ambiental y la presencia de materiales críticos. Se evaluará el impacto ambiental en componentes utilizados en cocinas de inducción, fabricadas por BSH electrodomésticos, planteando estrategias para valorar la influencia de la composición en el impacto ambiental.

Fue en la Primera Guerra Mundial, en 1914, el momento en el que incrementó la preocupación de los Estados Unidos por el suministro de materias primas estratégicas. El primer listado de materiales con problemas de suministro para los Estados Unidos fue publicado en 1917 por C.K. Leith [1], y es el siguiente:

Tabla 1 Listado materiales 1917

Listado publicado en 1917	
Materiales con gran escasez	Estaño, níquel, platino y metales del grupo platino, antimonio, vanadio, circonio, mica, monacita, grafito, amianto, arcilla y caolín, tiza, cobalto, corundita, piedra abrasiva.
Materiales con escasez	Nitratos (excepto nitrato de potasio), carbonato de potasio, manganeso, cromita, magnesita.

Un segundo listado fue publicado tras la Primera Guerra Mundial en 1921 [2], en él se incluían los siguientes 42 materiales:

Tabla 2 Listado materiales 1921

Listado publicado en 1921
Agar, antimonio, arsénico, asfalto, madera de balsa, alcanfor, cromo, cáscaras de coco, café, grafito, cáñamo, piel, yodo, yute, capoc, aceite de linaza, fibra de manila, mercurio, mica, níquel, nuez vómica, opio, aceite de palma, fósforo, platino, nitrato de potasio, quinina, caucho, seda, manganeso, goma laca, nitrato de sodio, azúcar, sulfuro, timol, estaño, tungsteno, uranio, vanadio, lana.

A pesar de la publicación de los anteriores listados, el término crítico en materiales fue utilizado por primera vez en el año 1939, en el informe denominado “Strategic and Critical Materials Stock Piling Act” [3] [4]. Mediante el cual, la administración americana decidió acumular reservas de ciertos materiales críticos y estratégicos con relevancia militar, con el fin de asegurar el acceso inmediato a los mismos en caso de emergencia.

Tabla 3 Listado materiales 1939

Listado publicado en 1939	
Materiales estratégicos	Aluminio, antimonio, cromo, manganeso, mercurio, mica, níquel, estaño, tungsteno.
Materiales críticos	Amianto, cadmio, criolita, fluorita, grafito, yodo, platino, titanio, vanadio.
Materiales esenciales	Abrasivos, arsénico, cloro, cobre, helio, hierro, acero, plomo, magnesio, molibdeno, amoniaco, petróleo, fosfatos, potasio, refractarios, azufre, pirita, uranio, cinc, circonio.

Hoy en día un material es considerado crítico en la Unión Europea en función de su riesgo ambiental, importancia económica y riesgo de suministro; es por ello que esta Tesis doctoral se plantea con el objetivo de analizar la presencia de materiales críticos y candidatos a serlo en una cocina de inducción. Actualmente, a la hora de calificar un material como crítico, la metodología utilizada para dicha evaluación cuantitativa está basada en tres indicadores de criticidad, estos son la importancia económica, el riesgo de suministro y el riesgo medioambiental del país [5]. En consecuencia, los materiales candidatos a ser críticos son aquellos analizados por la Comisión Europea, cuyos parámetros riesgo de suministro e importancia económica se encuentran por debajo de los umbrales de criticidad establecidos. Dichos parámetros han sido calculados por numerosos expertos; se trata de parámetros que evolucionan en el tiempo y están sujetos a procesos en continuo cambio [6].

En el cálculo del primero de ellos, la importancia económica, ha de tenerse en cuenta el fin de vida del material y el valor económico del mismo en los sectores en los que surge. En la obtención del riesgo de suministro median criterios como, el valor estimado de la estabilidad en la producción del material en un país determinado, la posibilidad de sustitución de dicho material y la cantidad del mismo que es reciclada. A su vez se identifican subindicadores para valorar la disponibilidad de los recursos; estos son, el nivel de concentración de los países productores, la sustituibilidad, la reciclabilidad, el riesgo ambiental del país, el tiempo de agotamiento de las reservas, la dependencia a subproductos, la concentración, costes de explotación y de producción, capacidad minera... Por último, en el caso del riesgo ambiental del país, este valor es estimado teniendo en cuenta criterios similares al riesgo de suministro, como son la concentración del material en el país, la capacidad de dicho material para ser sustituido y el rango de reciclabilidad.

Es necesario tener en cuenta que todos estos indicadores o parámetros no son estables en el tiempo y están sujetos a procesos en continuo cambio y movimiento. El gran cambio tecnológico, factor de gran influencia actualmente, conlleva el incremento de la demanda de ciertos materiales en un momento determinado y el descenso de la demanda en otros, generando un cambio en los indicadores de riesgo para un mismo material. Al mismo tiempo el fin de vida es la última etapa del ciclo de vida de un material e incluye los diferentes escenarios de eliminación ante los que se encuentra el material: reutilización, valorización o depósito en vertedero.

Ligado al último indicador, el riesgo ambiental del país, se encuentra el concepto de ecodiseño, basado en incorporar aspectos ambientales en las fases iniciales de diseño de un producto. Dicho concepto emerge en 1990, con la necesidad de reducir el impacto ambiental de los productos, y se basa en la regla de prevención en lugar de corrección, implementando responsabilidad medioambiental en las fases de diseño. Además, el factor ecológico tiene cada vez mayor peso en las empresas, gracias a la concienciación de la sociedad de producir bienes conservando los recursos ambientales y generar la menor cantidad posible de residuos. El Análisis de Ciclo de Vida (ACV) es considerada una de las herramientas de ecodiseño más significativa, que permite evaluar las debilidades y aspectos ambientales más críticos de un producto a lo largo de toda su vida útil. Por lo que los ACV han sido implantados en numerosas industrias, tomando conciencia de la medida en que sus productos afectan al medio ambiente, permitiendo obtener un perfil ambiental del producto y al mismo tiempo identificando aquellos factores que generan un mayor impacto ambiental.

La Comisión Europea es el organismo encargado, a nivel europeo, de publicar el listado de materiales críticos, aquellos que exceden los límites de los indicadores de criticidad previamente expuestos. El primer listado de materiales críticos fue publicado en 2011, es actualizado cada tres años de acuerdo a los indicadores expuestos y con el objetivo de reflejar los cambios en el mercado, producción y nuevos desarrollos tecnológicos surgidos. En la primera evaluación, en 2011, 14 materiales fueron identificados como críticos (12 materiales individuales y 2 grupos) de los 41 analizados. El segundo informe fue publicado en 2014, en él se identificaron 20 materiales críticos (17 materiales individuales y 3 grupos) de los 54 candidatos analizados. Finalmente, el último informe fue publicado en 2017, en él se incluyen 61 materiales críticos (58 materiales individuales y 3 grupos) de los 78 materiales candidatos analizados. Son los siguientes: antimonio, barita, berilio, bismuto, borato, caucho natural, cobalto, escandio, fluorita, fosfatos, fósforo, galio, germanio, grafito natural, hafnio, helio, indio, magnesio, metales grupo platino (rutenio, rodio, paladio, iridio y platino), niobio, silicio metal, tierras raras pesadas (disprosio, erbio, europio, gadolinio, holmio, lutecio, terbio, tulio, iterbio, itrio), tierras raras débiles (cerio, lantano, neodimio, praseodimio, samario), tantalio, vanadio y wolframio.

Además del factor ecológico, las presiones sociales junto con el trabajo de la Unión Europea por disminuir el impacto ambiental han dado lugar a directivas europeas que pretenden controlar el fin de vida de productos eléctricos y electrónicos [7], promover el ecodiseño [8], [9] o incluso regular las sustancias tóxicas [10] y [11]. Otras normativas tienen como objetivo introducir el criterio de mínimo impacto ambiental en el desarrollo de productos [12].

La metodología que se propone en esta tesis doctoral está basada en el análisis de la presencia de materiales críticos y su relación con el impacto ambiental. La aplicación de la misma está íntegramente focalizada en las encimeras de inducción del grupo BSH Electrodomésticos España, dichas cocinas son diseñadas íntegramente en el centro de competencia de inducción de BSH Electrodomésticos S.A. en Zaragoza (Montañana). Se trata de un producto de gran complejidad, debido a la gran cantidad de componentes, piezas y materiales distintos con los que se fabrica.

A la hora de evaluar el impacto ambiental se utilizará el software SimaPro y la base de datos EcoInvent, cuantificando todas las fases del ciclo de vida de un producto y personalizando la base de datos genérica EcoInvent. Es decir, considerando la cantidad exacta de materiales y la presencia de materiales críticos y no críticos, la obtención de dichos materiales, los procesos de fabricación, el transporte y el fin de vida.

El análisis de la presencia de materiales críticos en las encimeras de inducción y el impacto ambiental de las mismas ha sido estudiado a lo largo de esta tesis doctoral, analizando los componentes mecánicos, eléctricos y electrónicos de las mismas. Además, se han ido realizando numerosas publicaciones científicas en varias revistas que recogen el análisis realizado y los resultados obtenidos en las distintas fases de la tesis doctoral, demostrando la gran influencia de los materiales que componen el producto sobre el impacto ambiental total del mismo, así como la influencia de la presencia de materiales críticos.

Existen materiales que contribuyen en mayor medida a incrementar los valores de impacto ambiental, especialmente los materiales presentes en componentes electrónicos, como por ejemplo, el oro, cobalto o estaño, entre otros. En el artículo publicado en la revista Journal of Cleaner Production, se analiza la composición de transistores SMD, demostrando que los componentes electrónicos son un claro ejemplo de componentes con gran cantidad de materiales críticos y materiales candidatos a ser críticos, y con un alto impacto ambiental. Se trata de elementos de gran complejidad en su composición, que conllevan un trabajo minucioso a la hora de poder determinar con exactitud la influencia de los materiales de cada componente sobre el impacto ambiental.

Igualmente se han analizado componentes mecánicos, y se han realizado dos publicaciones en la revista Materials, la primera sobre la influencia de la composición en el impacto ambiental en aleaciones de aluminio y la segunda publicación con la misma temática sobre ferritas. En dichas publicaciones se analizaban materiales incluidos en los componentes mecánicos con gran influencia sobre el impacto ambiental, como por ejemplo el cobre y el estaño, incluidos en las aleaciones de aluminio analizadas o manganeso presente en las ferritas estudiadas.

En paralelo se ha desarrollado y registrado un software informático para aplicar la metodología desarrollada. El software denominado “Electrónica Sostenible” ha sido desarrollado para que el usuario pueda analizar el impacto ambiental de un componente y realizar una valorización del uso de materiales críticos de forma sencilla. Esta herramienta informática fue publicada en el congreso “27th EMSS 2015, European Modelling & Simulation Symposium” celebrado en Italia. Tras la presentación de la misma, se publicó el artículo extendido “Environmental assessment tool to analyse the presence of critical and valuable raw materials” en la revista International Journal of Service and Computing Oriented Manufacturing [13].

Por último se presentaron en el congreso “The 6th International workshop on simulation for energy, sustainable development and environment”, en Budapest, los resultados obtenidos tras la evaluación de los componentes analizados a lo largo de toda la tesis doctoral; demostrando la importancia de considerar la composición exacta de los materiales a la hora de calcular el impacto ambiental y la influencia de considerar la composición y la presencia de materiales críticos sobre el impacto ambiental.

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Capítulo 1

Introducción

1. INTRODUCCIÓN

La tesis doctoral “Metodología para el diseño considerando la composición de materiales, relación con materiales críticos y diseño ecológico” ha sido desarrollada dentro del grupo de investigación i+ de la Universidad de Zaragoza, en el Área de Ingeniería Mecánica dentro del Departamento de Ingeniería Mecánica de la Escuela de Ingeniería y Arquitectura. Ha sido dirigida conjuntamente por el Dr. Carlos Javierre Lardiés y Dr. Daniel Elduque Viñuales. Se presenta como compendio de publicaciones, incluidas en el capítulo 9 del presente documento. En dichas publicaciones han colaborado, además de los directores de tesis, el Dr. Carmelo Pina Gadea, la Dra. Judith Sarasa Alonso y la Dra. Isabel Clavería Ambroj.

Esta memoria pretende sintetizar todo el trabajo realizado a lo largo de los 5 años de investigación; se incluye y presenta información desde objetivos y metodología de la tesis, hasta la aplicación de la metodología, conclusiones y futuras líneas de investigación.

Mediante el desarrollo de una metodología para el diseño considerando la composición de los materiales durante la fase de diseño, se podrá cuantificar la presencia de los materiales críticos y candidatos a serlo, en los productos a analizar. La fase de diseño y la selección de materiales son los momentos claves para reducir el impacto desde un punto de vista medioambiental. Es por ello que en esta tesis doctoral se pretende, por tanto, poder analizar el impacto ambiental conociendo la composición real del producto, valorando el uso de materiales críticos y determinando la influencia de estos. Para ello, mediante la realización del ACV de estos materiales, se cuantificará el impacto medioambiental, identificando los puntos clave durante el ciclo de vida del producto [14].

La consideración del impacto ambiental a la hora de diseñar un nuevo componente o producto resulta imprescindible tanto moral como legalmente, reportando además, en la mayoría de ocasiones, beneficios económicos significativos. En la actualidad existen numerosas metodologías de valorización de impacto ambiental, que analizan de formas distintas el impacto ambiental y que son aplicables a diversos sectores. A nivel científico y técnico, las más utilizadas son ReCiPe y Huella de Carbono.

Además, esta tesis doctoral se focaliza en el análisis del impacto ambiental teniendo en cuenta la composición de los materiales, y prestando atención a los materiales críticos y estratégicos, estos últimos también son descritos como candidatos a ser materiales críticos. Se trata de materiales que existen en la naturaleza y que, ya sea por su escasez, peligrosidad o coste, pueden repercutir directamente en el impacto ecológico.

El principal objetivo consiste en desarrollar una metodología para evaluar el impacto ambiental en función de la composición y la presencia de materiales críticos; se pretende mejorar el cálculo de impacto ambiental de componentes y materiales a través del conocimiento de la composición real y exacta, planteando estrategias de reducción de impacto ambiental y del consumo de materiales críticos y candidatos a serlo en el diseño.

1.1. Justificación de la tesis doctoral

Durante las últimas décadas el factor ecológico tiene cada vez mayor peso en las empresas, gracias a la concienciación de la sociedad de producir bienes conservando los recursos ambientales y generar la menor cantidad posible de residuos. La empresa BSH Electrodomésticos apuesta encarecidamente por un producto sostenible y con mínimo impacto medioambiental.

Es por ello que en este trabajo de investigación se han analizado los impactos ambientales de diversos componentes incluidos en encimeras de inducción producidos por dicho fabricante. Además, esta tesis doctoral da continuidad a tesis doctorales previas en el campo del diseño sostenible y la evaluación de impacto ambiental. En 2014 fue defendida por el Dr. Daniel Elduque Viñuales la tesis doctoral "*Estrategias en el diseño para la reducción del impacto ambiental de las encimeras de inducción*" [15]. Posteriormente, en 2015, el Dr. Víctor Manuel Camañes Vera defendió su tesis doctoral bajo el título "*Metodología para la consideración del impacto ambiental en el diseño mecánico. Herramienta para su aplicación*" [16] y el Dr. Carmelo Pina Gadea, "*Evolución del diseño mecánico de las encimeras de inducción de BSH desde el punto de vista de impacto ambiental. Propuesta de futuro*" [17].

Las encimeras de inducción, producto estudiado en esta tesis, tienen una alta relevancia debido tanto al número de ventas de las mismas, como a la cuota de mercado en continuo crecimiento en los últimos años. Se trata de aparatos muy complejos y compuestos por gran variedad de componentes electrónicos y mecánicos. Es por ello que se ha realizado un exhaustivo trabajo de evaluación de impacto ambiental tanto en componentes electrónicos como mecánicos, analizando en detalle su composición y la influencia de cada uno de los materiales que los componen sobre el impacto ambiental. Prestando especial atención a la presencia de materiales críticos y candidatos, y analizando la influencia de los mismos sobre el impacto ambiental total del producto.

Para realizar este análisis de materiales críticos en las cocinas de inducción, en relación al impacto ambiental, la colaboración entre BSH y la Universidad de Zaragoza es imprescindible. Dicha colaboración tiene lugar desde hace más de 30 años, tratando de apoyar la innovación con el fin de lograr un aprovechamiento del conocimiento científico y desarrollo tecnológico. Concretamente, en los últimos años se está realizando un exhaustivo ACV.

En el desarrollo de esta tesis doctoral, dicha colaboración resulta necesaria ya que la generación del inventario y recopilación de datos para la realización del ACV conlleva el acceso a información detallada del producto. Al mismo tiempo, resulta de gran ayuda la situación de la empresa, ya que las encimeras de inducción del grupo BSH son diseñadas y fabricadas en Zaragoza, siendo desarrolladas íntegramente en el centro de competencia de inducción de BSH Electrodomésticos España S.A. en Montañana.

Actualmente no existen numerosas publicaciones sobre ACV de electrodomésticos, y a pesar de existir publicaciones que analizan componentes electrónicos, como circuitos integrados o placas impresas, o componentes mecánicos, no es común encontrar análisis de productos donde se analice minuciosamente la electrónica, o se estudie la presencia de materiales críticos. Es por ello que la investigación de esta tesis doctoral es un tema muy novedoso y de gran interés. Se trata de un trabajo muy laborioso y detallado, en el que los resultados demuestran la gran influencia de la composición de materiales sobre el impacto ambiental y la importancia de considerar dicha composición exacta de un componente a la hora de evaluar su impacto ambiental.

Pese a que el ACV no es una metodología de reciente creación, su implementación en encimeras de inducción es un campo en el que todavía no existen grandes estudios, pero sobre el que la Unión Europea ha fijado su interés por reducir el impacto ambiental. Gracias a las recientes publicaciones, por parte de muchos fabricantes de componentes electrónicos, de información sobre la composición sus productos, se podrá realizar un análisis exhaustivo del impacto ambiental y presencia de materiales críticos en dichos componentes. Con ello se genera un valor añadido para los diseñadores, que pueden actuar en mayor medida para reducir el impacto ambiental.

Además se ha desarrollado y registrado un software informático para aplicar la metodología desarrollada, mediante el cual los desarrolladores de nuevos productos y usuarios de la herramienta podrán realizar ACVs de sus productos considerando la composición de los mismos y la presencia de materiales críticos o candidatos a serlo.

1.2. Objetivos y metodología

La principal línea de investigación de esta tesis es analizar la presencia de materiales críticos en los componentes de una cocina de inducción, estudiando y analizando la variación del impacto ambiental causada por la composición de sus componentes y planteando con ello una metodología de diseño en función de la composición de materiales.

A la hora de analizar el impacto ambiental y realizar el ACV de los materiales y productos, se tomará como referencia la base de datos EcoInvent, realizando actualizaciones y ajustes de la misma. Gracias a la colaboración entre BSH Electrodomésticos y la Universidad de Zaragoza, ha sido posible acceder a información detallada del inventario del producto y tomando como referencia la base de datos EcoInvent se ha ido mejorando el inventario, mediante la composición exacta de los materiales; lo que repercute en un ACV más conciso y detallado.

Siendo el principal objetivo de esta tesis doctoral analizar la influencia de la composición de los materiales sobre el impacto ambiental, teniendo en cuenta la presencia de materiales críticos o materiales candidatos a serlo. Para conseguir cumplir dicho objetivo ha sido necesaria la realización de los siguientes hitos:

- Análisis del estado del arte en la temática de materiales críticos.
- Análisis del estado del arte sobre impacto ambiental y evaluación del mismo.
- Aprendizaje del uso y manejo del software Simapro.
- Aprendizaje y conocimiento de la base de datos Ecoinvent.
- Aprendizaje de las metodologías ReCiPe, CML y Huella de Carbono.
- Desarrollo detallado de los inventarios.
- Aplicación de las metodologías ReCiPe, CML y Huella de Carbono; evaluando en detalle de cada uno de los componentes inventariados y analizados.
- Análisis de la presencia de materiales críticos en los componentes analizados.

Mediante el análisis de la presencia de materiales críticos en una cocina de inducción se pretende determinar la influencia de estos materiales en el impacto medioambiental. Para ello, mediante la realización de un ACV de los distintos componentes de una cocina de inducción, se cuantificará el impacto medioambiental, identificando los materiales críticos y la influencia de los mismos sobre el impacto ambiental.

Tal y como se ha comentado, resulta imprescindible la colaboración entre la Universidad de Zaragoza (Grupo i+) y BSH Electrodomésticos en esta tesis doctoral. En la que todo el estudio realizado reporta beneficios a ambas partes:

- Analizar la sostenibilidad medioambiental del producto.
- Diseño teniendo en cuenta la criticidad de los materiales.
- Mejora de costes.
- Mayor estabilidad de precios.
- Posibilidad de creación de estrategias para reducir el consumo de materiales críticos y materiales candidatos a ser críticos durante la fase de diseño del producto, reduciendo con ello el impacto ambiental.
- Posibilidad de recuperar o reciclar materiales valiosos en el fin de vida gracias al conocimiento de su presencia y cantidad en cada encimera.
- Mejorar la competitividad en el mercado; a partir de la reducción de costes gracias al ecodiseño e incremento de ingresos debido a la mejora de la imagen.

1.3. Esquema y desarrollo del documento

Tras exponer los objetivos y brevemente la metodología de esta tesis doctoral junto con la justificación de la misma, a continuación se expone la estructura que compone la presente tesis doctoral:

- Revisión del Estado del Arte.
- Metodología desarrollada.
- Software informático.
- Aplicación de la metodología.
- Conclusiones.
- Futuras líneas de investigación.
- Bibliografía.
- Publicaciones.
- Anexos.

Capítulo 2

Estado del Arte

2. ESTADO DEL ARTE

En el presente capítulo de esta tesis doctoral se realiza un exhaustivo análisis del estado del arte del término ecodiseño, técnicas de análisis de ciclo de vida y materiales considerados críticos por la Unión Europea. Asimismo, se abordarán normativas, directivas y reglamentos relacionados con el campo del diseño ecológico y la gestión ambiental.

El término ecodiseño o diseño ecológico surgió por primera vez al comienzo de los años 90, a partir de la necesidad de reducir el impacto ambiental del producto o servicio, minimizando los impactos ambientales del producto antes de ser producidos [18] [19]. Dicho concepto está basado en el principio de prevención frente al de corrección; considerando mejoras medioambientales del producto en todas las fases de su ciclo de vida, y al mismo tiempo implementando responsabilidad ambiental, creatividad e innovación actuando en la etapa de diseño [20] [21] [22].

El ciclo de vida de un producto se compone de las siguientes etapas: obtención de materia prima, fase de producción, distribución, uso y fin de vida; interrelacionadas tal y como se muestra en la siguiente figura:

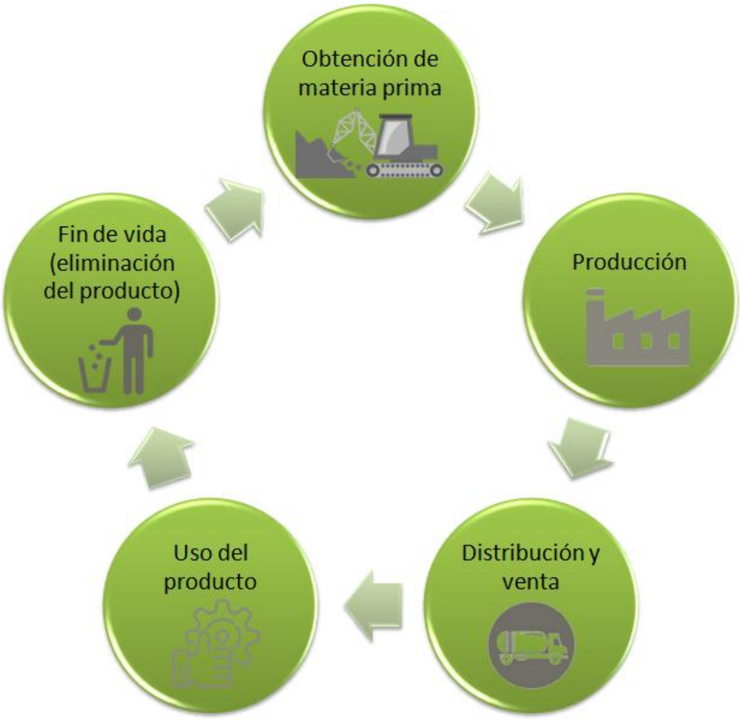


Figura 3 Etapas ciclo de vida

Para los fabricantes o desarrolladores de productos, el principal objetivo del diseño ecológico es reducir el impacto ambiental de sus productos. Aunque además de la reducción de impacto, estas medidas llevan implícitos ahorros de costes de fabricación, generando con ello una mejora en los beneficios económicos de la empresa. Entre las principales ventajas y beneficios que una empresa puede obtener implementando el ecodiseño se encuentran las siguientes: reducción del impacto ambiental del producto; aumento de la calidad e incremento de la durabilidad; mejora de la imagen tanto del producto como de la empresa y cumplimiento de las demandas de los clientes o usuarios; acceso a nuevos mercados y consumidores ambientales más exigentes; mejora del posicionamiento ante competidores; potenciación del pensamiento innovador dentro de la empresa y reducción del riesgo regulatorio anticipándose a la legislación, entre otros.

El consumo de materiales, uso de sustancias peligrosas, consumo de energía y agua, residuos, ruidos, olores, emisiones atmosféricas…son temas ambientales clave. Su identificación y evaluación durante todo el ciclo de vida del producto proporciona una idea global de la interacción del mismo con el medio ambiente. Es por ello que durante la última década, el diseño de nuevos productos está siendo fuertemente influenciado por la legislación medioambiental [23] [24]. Numerosas leyes y normativas han surgido con el principal objetivo de reducir el impacto ambiental de productos y servicios a partir del diseño ecológico, prueba de ello son la normativa ISO 14006 [12], que incluye directrices para la incorporación del ecodiseño o las directivas EuP Directive: 2005/32/CE y ErP Directive: 2009/125/CE que establecen requisitos de diseño ecológico aplicables a productos que utilizan energía o productos relacionados con la energía, respectivamente [8] [9]. Además de las directivas focalizadas en reducir los residuos de aparatos eléctricos y electrónicos [7] o regular el uso de sustancias tóxicas [10] [11].

Existen numerosos artículos y estudios relacionados con la importancia de considerar la composición material de un producto a la hora de diseñar ecológicamente. Es por ello que se ha realizado una extensa búsqueda de información relacionada con el concepto de ecodiseño, así como documentación sobre la consideración de los materiales a la hora de diseñar ecológicamente. En productos electrónicos [22] [25], componentes de automoción [26] o polímeros [27] se ha implementado la metodología de diseño ecológico a la hora de desarrollar nuevos productos.

Además del concepto de diseño ecológico, la temática en torno a la cual se desarrolla esta tesis doctoral está focalizada en los materiales críticos. Actualmente, las materias primas son cruciales para la economía mundial, constituyen la base para una industria potente, y a partir de las mismas se producen un amplio rango de objetos y aplicaciones utilizadas en el día a día, así como todas las nuevas tecnologías.

El continuo cambio tecnológico en el que vivimos junto con el rápido crecimiento de economías emergentes ha generado un incremento en la demanda de ciertos metales y minerales. En Europa, con el objetivo de gestionar este importante crecimiento, la Comisión Europea puso en marcha la Iniciativa Europea sobre materias primas en 2008, donde una de las acciones prioritarias fue establecer una lista de Materiales Críticos a nivel europeo. En la actualidad, el poder acceder sin obstáculos y de manera segura a estas materias primas es un gran reto para la Unión Europea. De modo que para conseguir llevar a cabo este reto, la Comisión Europea creó un listado vivo de materiales considerados críticos para la Unión Europea, ya sea por su importancia económica o por el riesgo asociado al suministro de los mismos.

Tal y como se ha comentado, esta preocupación por los materiales críticos e interés por hacer frente a los mismos, presenta carácter mundial. Sin embargo, las estrategias planteadas muestran diferencias dependiendo de la región. Mientras que en Europa, se ha optado por una política de diálogo con los países ricos en recursos de materiales críticos; Japón y Estados Unidos apuestan por iniciativas de investigación y desarrollo [28] [29]. En el caso de Australia y China, en cambio, promueven las actividades mineras locales e intentan proteger sus propios recursos [30].

Además, en el caso de Europa, la metodología implantada por la Unión Europea para establecer el listado de materiales críticos se basa en las pautas que se expondrán a continuación para determinar los parámetros: importancia económica (IE) y riesgo de suministro (RS) [31] [32].

La importancia económica es calculada considerando tanto el fin de vida del material analizado, como el valor económico en los sectores en que dicho material es utilizado. En el caso del riesgo de suministro, se considera el valor estimado de la estabilidad de la producción de dicho material en un país determinado, la posibilidad de que dicho material pueda ser sustituido por otro y la cantidad del mismo que es reciclada. Mediante dichos parámetros es determinada la criticidad de un material, estableciendo con ello el listado de materiales críticos. Dicho listado incluye los materiales sin orden de magnitud en la criticidad de los mismos.

El parámetro importancia económica (EI), tiene como objetivo proporcionar información sobre la importancia de un material para la economía de la Unión Europea en términos de aplicaciones de uso final. La importancia económica es modificada por el índice de sustitución (SI), relacionado con el rendimiento técnico y económico de los materiales sustitutivos para aplicaciones individuales. Se obtiene a partir de la siguiente fórmula:

$$EI = \Sigma_s(A_S * Q_S) * SI_{EI}$$

Donde:

EI = importancia económica
A_S= participación de utilización de una materia prima en un sector determinado.
Q_S= el valor añadido de un sector.
SI_{EI} = índice de sustitución de un material relacionado con la importancia económica.
$_S$ = denota sector

En el caso del índice de sustitución (SI_{EI}) para un material candidato, es calculado utilizando parámetros de coste de sustitución asignados a cada material, multiplicados por la participación de cada sustituto en una aplicación determinada y al mismo tiempo por la participación en la aplicación final. Es decir:

$$SI_{EI} = \Sigma_i\Sigma_a SCP_{i,a} * \text{sub-share}_{i,a} * \text{share}_a$$

Donde:

SI = Índice de sustitución.
i = describe un material sustituto.
a = describe una aplicación individual del material candidato.
SCP = parámetro del coste de sustitución.
Share = participación de las materias primas en la aplicación final.
Sub-share = la sub participación de cada sustituto en cada aplicación.

El parámetro riesgo de suministro (SR) refleja el riesgo de una disrupción en el suministro de un material en la Unión Europea. Se basa en la concentración del suministro primario de los países productores de materias primas, considerando el desempeño de sus gobiernos y aspectos comerciales. En función de la dependencia de las importaciones (IR) de la Unión Europea, considerando proveedores globales y países de los que la Unión Europea adquiere materias primas. El riesgo de suministro (SR) se mide en la etapa “cuello de botella” del material, momento en el que presenta el mayor riesgo de suministro para la Unión Europea; considerando la sustitución y el reciclaje como medidas de reducción de riesgos.

De modo que la metodología propone la siguiente fórmula para el parámetro riesgo de suministro:

$$SR = [(HHI_{WGI,t})_{GS} * \frac{IR}{2} + (HHI_{WGI,t})_{EUsourcing}(1- \frac{IR}{2})] * (1-EoL_{RIR}) * SI_{SR}$$

Donde:
SR = riesgo suministro
GS = suministro global.
$EU_{sourcing}$ = abastecimiento real del suministro a la UE.
HHI = índice Herfindahl-Hirschman (utilizado como aproximación para la concentración del país)
WGI = índice de gobernabilidad mundial.
t = ajuste de parámetro WGI
EoL_{RIR} = tasa de entrada de reciclaje al final de su vida útil.
SI_{SR} = índice de sustitución relacionado con el riesgo de suministro.
IR = dependencia de las importaciones

El último de estos parámetros, dependencia de las importaciones (IR) de un material candidato a ser material crítico, es calculado como:

$$\textbf{Dependecia de la importación (IR)} = \frac{\textbf{Importación — Exportación}}{\textbf{Producción domestica} + \textbf{Importación} - \textbf{Exportación}}$$

Por su parte, el índice HHI_{WGI} se ajusta mediante un parámetro comercial y calculado del siguiente modo:

$$(HHI_{WGI,t})_{GS \text{ or } EUsourcing} = \Sigma_c (S_c)^2 WGI_C * t_c$$

Donde:

S_c = participación del país c en el suministro global de la materia prima.

WGIc = índice de gobernanza mundial escalado del país c.

La variable t se calcula del siguiente modo:

$$t_c = (ET\text{-}TA_C \text{ ó } EQ_C \text{ ó } EP_C \text{ ó } EU_C)$$

Donde:

tc = variable relacionada con el comercio del país c para una materia prima candidata (RM).

$ET\text{-}TA_C$ = parámetro que refleja una tasa de exportación impuesta (%) por país c, posiblemente mitigado por un acuerdo comercial (AT) en vigor.

EQ_C = parámetro que refleja una cuota física de exportación impuesta por el país c.

EP_C = parámetro que refleja una prohibición de exportación introducida por el país c para una materia prima candidata.

EU_C = parámetro c de los países de la UE para una materia prima igual a 0.8.

La tasa de entrada de reciclaje al fin de vida, EOL_{RIR}, se entiende como el ratio de reciclaje desde chatarra antigua hasta la demanda europea de una materia prima candidata. Es decir, las entradas de material primario y secundario.

$$EOL_{RIR} = \frac{\text{Entrada de materia prima secundaria de la UE (desde chatarra)}}{\text{Entrada materia prima primaria de la UE+Entrada materia prima secundaria de la UE}}$$

El índice de sustitución específico (SI_{SR}) de un material candidato es calculado como la media geométrica de tres parámetros (SP, SCr and SCo) asignados a cada material sustituto, multiplicados por la sub-aportación de cada sustituto en una aplicación determinada, y añadiendo la cuota de fin de uso.

$$SI_{SR} = \Sigma_i \left[(SP_i * SCr_i * SCo_i)^{1/3} * \Sigma_a (\text{Sub-share}_{i,a} * \text{Share}_a)\right]$$

Donde:

i = denota un material sustituto individual.

a = aplicación individual de un material candidato.

SP = producción sustituta. Refleja la producción global de material y de material sustituto; como un indicador de si las cantidades de material sustituto están disponibles

SCr = la criticidad de un material sustituto tiene en cuenta si este fue crítico en el anterior listado de la UE.

SCo = la co-producción sustituta tiene en cuenta si un material sustituto es un producto primario o si se extrae como co-produto o producto secundario.

Share = la aportación de los materiales candidatos en una aplicación final.

Subshare = la subaportación de cada sustituto en cada aplicación

En la lista de materiales considerados críticos por la Unión Europea se encuentran materias primas que exceden los límites de ambos parámetros, importancia económica y riesgo suministro. El primer informe fue presentado por la Comisión Europea en 2011, comprometiéndose a actualizarlo cada 3 años debido al gran cambio tecnológico en el que nos encontramos actualmente y con ello las continuas fluctuaciones en la demanda de materiales. En el primer informe 12 materiales y 2 grupos de materiales fueron identificados como críticos entre los 41 analizados [33]. Fueron los siguientes:

- Antimonio.
- Berilio.
- Cobalto.
- Fluorita.
- Galio.
- Germanio.
- Grafito.
- Indio.
- Magnesio.
- Metales Grupo Platino.
- Niobio.
- Tantalio.
- Tierras Raras.
- Tungsteno.

Posteriormente, en 2014, la Comisión Europea actualizó y publicó un nuevo informe en el que se analizaron 54 materiales, de los cuales 17 materiales y 3 grupos de materiales fueron considerados como críticos [34]. Son los siguientes:

- Antimonio.
- Berilio.
- Cobalto.
- Fluorespato.
- Galio.
- Germanio.
- Grafito.
- Indio.
- Magnesio.
- Niobio.
- Metales Grupo Platino.
- Tierras Raras pesadas.
- Tierras Raras ligeras.
- Tungsteno.
- Borato.
- Cromo.
- Carbón de coque.
- Magnesita.
- Roca fosfática.
- Metal de silicio.

Finalmente, en 2017 la Comisión Europea publico el último informe hasta el momento, en el que identificaron 43 materiales críticos (23 materiales y 3 grupos) de los 78 analizados [35] [36].

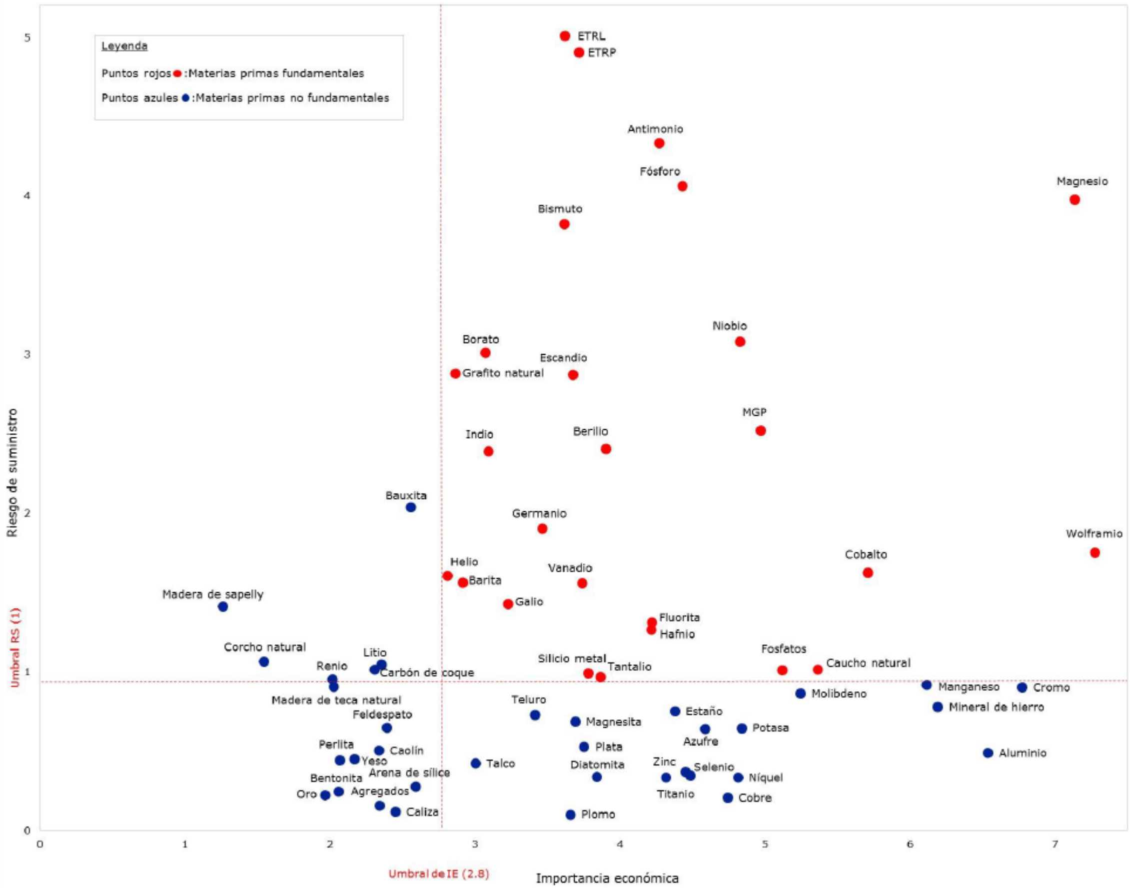


Figura 4 Evaluación criticidad 2017 - Importancia económica y riesgo de suministro [37]

Por primera vez los niveles de criticidad y los materiales considerados críticos están disponibles a nivel de materia prima, es decir aparecen los 15 elementos del grupo tierras raras divididos en dos subcategorías, tierras raras pesadas y ligeras; y 5 metales del grupo platino. Son los siguientes:

- Antimonio.
- Barita.
- Berilio.
- Bismuto.
- Borato.
- Caucho natural.
- Cobalto.
- Escandio.
- Fluorita.
- Fosfatos.
- Fósforo.
- Galio.
- Germanio.
- Grafito natural.
- Hafnio.
- Helio.
- Indio.
- Magnesio.

- Metales Grupo Platino (Rutenio, Rodio, Paladio, Iridio y Platino).
- Niobio.
- Silicio metal.
- Tierras Raras pesadas (Disprosio, Erbio, Europio, Gadolinio, Holmio, Lutecio, Terbio, Tulio, Iterbio, Itrio).
- Tierras Raras débiles (Cerio, Lantano, Neodimio, Praseodimio, Samario).
- Tantalio.
- Vanadio.
- Wolframio.

El análisis realizado sobre el riesgo de suministro de los 78 materiales candidatos a críticos en 2017 demuestra que China es el mayor productor mundial de los materiales considerados críticos. No obstante, países como Rusia o Sudáfrica aparecen como los mayores productores a nivel mundial de metales del grupo platino; EEUU de berilio y helio; y Brasil de niobio [38].

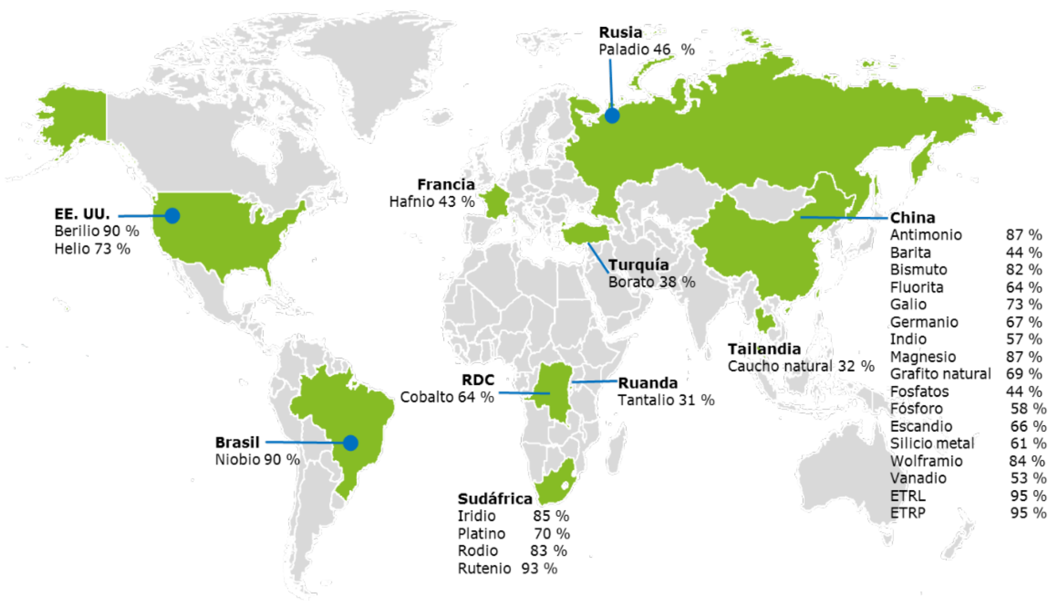


Figura 5 Productores mundiales de materiales críticos [37]

A pesar de que China sea el mayor productor a nivel mundial, los principales proveedores de materiales considerados críticas a la unión Europea son Kazajistán, suministrador de fósforo y Rusia, proveedor de escandio y vanadio con cuotas de abastecimiento de 77%, 67% y 60% respectivamente. Dicho análisis de abastecimiento de la Unión Europea incluye únicamente 37 de los 43 materiales críticos, ya que materiales como el berilio o metales del grupo platino apenas son suministrados a la Unión Europea.

Actualmente, se aprecia un importante crecimiento en la demanda de aparatos eléctricos y electrónicos, debido principalmente a su bajo coste y accesibilidad; ya que se trata de productos cada vez más eficientes. En consecuencia, la población puede permitirse comprar nuevos productos eléctricos y electrónicos con mayor frecuencia, reemplazando la tecnología con la que contaban por otra nueva y generando con ello nuevos residuos eléctricos y electrónicos. En el año 2010, los países de la Unión Europea produjeron aproximadamente 6,5 millones de toneladas de residuos eléctricos y electrónicos; en 2015 fue estimada una producción de los mismos de 12 millones de toneladas. Estas cifras se estima que se incrementarán entre un 16 y un 28% cada cinco años, como consecuencia de las nuevas tecnologías cada vez más económicas [39] [40].

Tomando conciencia del concepto de ecodiseño y de cómo sus productos afectan al medio ambiente, el ACV ha sido implementado por muchas empresas, industrias y negocios. Esta técnica de valorización de impacto ambiental evalúa de forma sistemática los impactos ambientales, contemplando todo el ciclo de vida del producto desde la obtención de la materia prima hasta su final de vida. El concepto de ecodiseño supone para el fabricante, reducir el impacto del producto y además un ahorro de costes de fabricación; generando con ello una mejora de los beneficios.

A la hora de evaluar el impacto ambiental de un producto se realiza un ACV, se trata de una técnica mediante la cual evaluar cuantitativamente todos los parámetros que generan un impacto ambiental en el producto a lo largo de todo el ciclo de vida del mismo, desde la adquisición de la materia prima hasta el fin de vida del producto, pasando por las etapas de producción y uso. Donde las normativas UNE-EN ISO 14040 y 14044 establecen la metodología y los requerimientos para su realización [41] [42].

Se han desarrollado numerosos métodos de cálculo de impacto ambiental, entre los que cabe destacar los siguientes:

- CML.
- ReCiPe.
- Ecological Scarcity 2013.
- EDIP 2003.
- EPD (2013).
- ICLD 2011.
- IPCC 2013 GWP 100a.
- USEtox.
- Cumulative Energy Demand.
- Water footprint.

Hoy en día, la mayoría de estos ACV utilizan bases de datos genéricas como EcoInvent para evaluar el impacto ambiental de sus productos.

A lo largo de los años, esta metodología de ACV ha sido implementada para analizar el impacto ambiental de todo tipo productos en numerosas áreas: construcción [44] [45] [46]; dispositivos electrónicos desde telefonía móvil y ordenadores personales [47] [48] [49] [50] hasta memorias flash [51] y otros componentes electrónicos [52] [53] [54] [55]; contenedores de residuos [56]; tejidos [57]; embalajes de alimentación y bebidas [58] [59] o producción de bebidas [60]. Además numerosos materiales han sido analizados mediante esta metodología: plásticos [61], aluminio [62], acero [63], plomo [64] u hormigón [65] [66].

En el campo de los electrodomésticos, existen estudios en los que se analiza el impacto ambiental a lo largo del ciclo de vida en productos como neveras [67] [68], lavadoras [69] [70], microondas [71], lavavajillas [72], hornos [73] o encimeras de inducción [74] [75]. Sin embargo, no existen estudios en los que se evalúe la influencia de la composición de los componentes y la presencia de materiales críticos como principal influencia en los valores de impacto ambiental.

Concretamente, esta tesis doctoral analiza un tipo muy específico de electrodoméstico, como son las encimeras de inducción. La inducción es una tecnología de cocinado de reciente creación, en la que el calor es creado directamente en el recipiente debido a la generación de campos magnéticos. A pesar de no ser la tecnología más popular entre las cocinas eléctricas, se trata de una exitosa innovación para el cocinado; las cifras demuestran que entre 2002 y 2008 el número de unidades vendidas se fue ampliando sobre un 24% anual, incrementando progresivamente el número de unidades vendidas desde que esta tecnología fue incluida en el mercado [76].

2.1. Síntesis, justificación y aportaciones

Como se ha explicado previamente, las materias primas constituyen un pilar muy importante en la economía Europea, ya que a partir de las mismas se generan todos los materiales que componen los productos que utilizamos a diario en nuestras vidas. Tan importante o imprescindible como la creación de estos materiales es el acceso a los mismos y el impacto que generan sobre el medio ambiente.

De la importancia de considerar los materiales pensando en el medioambiente surge el concepto de ecodiseño, cuyo principal objetivo es incluir aspectos ambientales en las primeras fases de diseño de un producto. Junto con este concepto de diseño sostenible, el hilo conductor de esta tesis doctoral serán los materiales críticos, materiales que, ya sea por su importancia económica o riesgo de suministro, resultan cruciales para la economía de Europa. A día de hoy y cada vez más, las empresas e industrias toman conciencia de la influencia de sus productos sobre el medioambiente; implementando en sus negocios ACVs de sus productos.

Considerando los anteriores detalles, es posible justificar que el principal interés de esta tesis doctoral consiste en analizar la presencia de materiales críticos en componentes mecánicos y electrónicos, presentes en el inventario de una cocina de inducción; analizando la influencia de considerar la composición exacta de los materiales a la hora de evaluar el impacto ambiental.

En la metodología de diseño desarrollada, se considera la composición de materiales exacta de los componentes a analizar a la hora de evaluar el impacto ambiental de los mismos; basándose en la tesis doctoral "Estrategias en el diseño para la reducción del impacto ambiental de las encimeras de inducción" del Dr. Daniel Elduque Viñuales [15]. Analizando además en esta nueva metodología la presencia de materiales críticos en la composición, y considerándolos a la hora diseñar un nuevo componente.

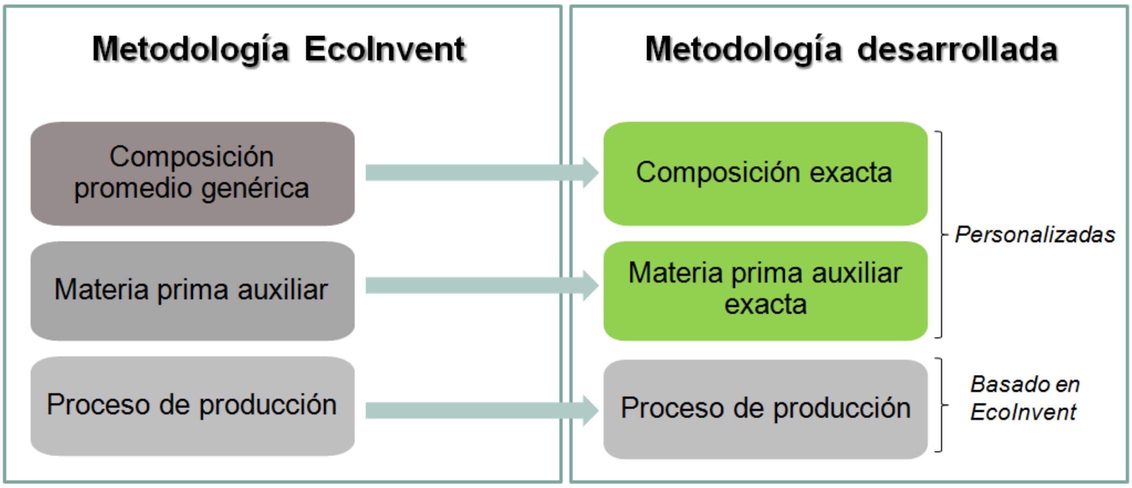


Figura 6 Comparativa metodologías

Este análisis de impacto ambiental ha sido realizado en componentes mecánicos y electrónicos: piezas de plástico, metales, componentes eléctricos y electrónicos, vidrios cerámicos… Entre todos los estudiados, hay que recalcar que los componentes electrónicos son los que presentan mayor porcentaje de materiales críticos incluidos en su composición. Se trata de materiales de pequeñas dimensiones cuyo cómputo y evaluación global implica gran complejidad, ya que conlleva un trabajo muy detallado y minucioso a la hora de determinar la composición exacta requerida para evaluar posteriormente la influencia de la composición de cada componente sobre el resultado final de impacto ambiental.

Por ello, la principal aportación de esta tesis consiste en el análisis de la presencia de materiales críticos y candidatos a serlo en componentes mecánicos y electrónicos presentes en las cocinas de inducción; evaluando la influencia de la composición sobre el impacto ambiental en dichos componentes.

Capítulo 3

Metodología

3. METODOLOGÍA

Esta tesis doctoral pretende desarrollar una nueva metodología cuyo principal objetivo es evaluar la influencia de la composición de los materiales sobre el medio ambiente, considerando la presencia de materiales críticos y su relación con el diseño ecológico durante la etapa de diseño. Fomentando el diseño ecológico y considerando la presencia de materiales críticos en las primeras fases del ciclo de vida del producto, es decir, durante la selección de materias primas y evaluación de las mismas. La implementación de la misma se ha focalizado en la industria de los electrodomésticos, donde la reducción del impacto ambiental de los productos conlleva un incremento de la competitividad de los mismos en el mercado; ya que una ligera reducción del impacto ambiental de un producto puede llegar a generar importantes mejoras para las compañías o fabricantes de dichos productos, incrementando los beneficios y al mismo tiempo la competitividad de la compañía [20] [77].

Existen diversas técnicas de gestión ambiental, tal y como indican las normas ISO sobre gestión ambiental y análisis de ciclo de vida [41] [42], como evaluación del riesgo, evaluación del desempeño ambiental, auditoría ambiental y evaluación del impacto ambiental, además del ACV. Actualmente existen numerosos modelos de Evaluación de Ciclo de Vida mediante bases de datos profesionales como EcoInvent, desarrollada por Swiss Centre y considerada como una de las bases de datos más utilizadas para realizar ACVs [78]. La metodología de ACV es implementada considerando el ciclo de vida completo del producto, desde la extracción de la materia prima hasta el tratamiento al final de la vida útil del producto, pasando por la producción de energía y fabricación. De modo que se realiza un estudio exhaustivo, analizando en detalle materiales, procesos, consumo de energía, transporte, uso, fin de vida… que afectan al producto completo a lo largo de su vida. Sin embargo, la principal debilidad de las bases de datos es que son muy genéricas, por lo que no se ajustan a productos específicos. Es por ello que la metodología desarrollada en esta tesis doctoral está basada en realizar un ACV con bases de datos adaptadas y mejoradas a partir de la composición exacta de materiales de los componentes a analizar.

Esta nueva metodología, basada en un estudio de ACV, se subdivide en cuatro fases: definición del objeto, análisis del inventario, evaluación de impacto e interpretación. Evaluando los impactos ambientales en todas las etapas del ciclo de vida e implementando mejoras focalizadas en la fase del análisis de inventario. Estas mejoras en el inventario y en consecuencia en la evaluación de impacto se muestran en línea con las características esenciales de un ACV, en las que se plantea que la metodología de ACV está abierta a incluir novedades científicas y mejoras en el estado de la técnica.

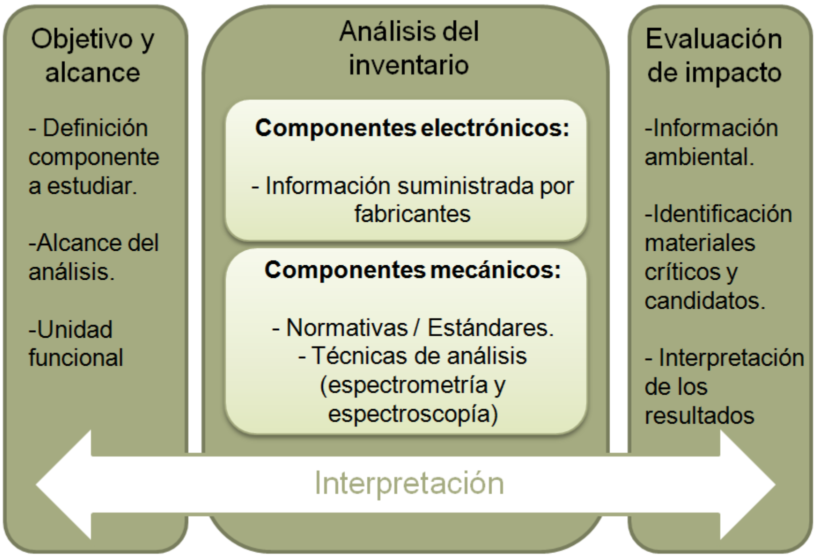


Figura 7 Metodología - Fases ACV

En la fase de análisis de inventario se obtendrá información de diversas fuentes, en función del tipo de componente a analizar. Aunque la base de datos EcoInvent incluye numerosos materiales y componentes, estos incluyen composiciones genéricas que en muchas ocasiones no se corresponden con la composición exacta de los materiales a analizar. Esto genera inseguridades y desconfianza en los resultados de impacto ambiental que se obtienen y supone el principal objetivo de la metodología desarrollada en esta tesis doctoral. Además, en la metodología planteada se consideran no solo los materiales presentes en el final de vida del producto, sino el consumo total de materiales y la generación de residuos y deshechos durante la fabricación.

El inventario del ciclo de vida ha sido realizado a través de EcoInvent v3.4 (desarrollado por Swiss Centre for Life Cycle Inventories), modelizando el ACV con SimaPro 8.4 (desarrollado por Pré consultants), y siguiendo en todo momento las metodologías ReCiPe, CML y Huella de Carbono [43]. La metodología ReCiPe combina los métodos midpoint y endpoint para validar los sistemas CML y Eco Indicador99, combinando las ventajas de ambos; y la metodología Huella de Carbono establece una relación entre las emisiones de gas que generan efecto invernadero y la cantidad de CO_2 con el mismo efecto [79].

Además se analizarán las siguientes categorías de impacto ambiental: Abiotic depletion, Abiotic depletion (fossil fuels), Acidification, Eutrophication, Global warming (GWP 100), Ozone layer depletion (ODP), Human toxicity, Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity y Photochemical oxidation. El inventario necesario para el ACV ha sido desarrollado utilizando EcoInvent v3, una de las bases de datos más utilizadas y desarrollada por Swiss Centre for Life Cycle Inventories.

A la hora de realizar el análisis del inventario del ciclo de vida, será necesario establecer el objeto o componente a estudiar y el propio alcance del análisis; siguiendo con la recopilación de datos y validación de los mismos. En la presente metodología, la realización de inventario se llevará a cabo dependiendo del componente a evaluar. Se distinguirá entre componentes electrónicos y mecánicos; dentro de estos últimos se han seguido varias vías, en función de los datos publicados por los fabricantes y la viabilidad de los mismos.

El inventario de componentes electrónicos como diodos o transistores ha sido realizado completando y mejorando la base de datos EcoInvent a partir de información suministrada por los fabricantes, incluyendo información de todas las piezas que forman dichos componentes.

En el caso de componentes mecánicos distinguimos distintas vías a la hora de llevar a cabo el análisis de inventario. Para la evaluación de impacto ambiental de aleaciones de aluminio o aceros, el inventario de los mismos puede obtenerse a partir de su composición definida en estándares y normativas, o mediante técnicas de espectroscopía y espectrometría de análisis metales. Las técnicas o métodos de análisis de composición de metales son variadas, se clasifican dependiendo de la excitación primaria con la que se incide en la muestra a analizar y la respuesta generada. Estas son algunas de ellas: Espectroscopía Fotoelectrónica de rayos X (XPS), Espectroscopía Electrónica Auger (AES), Espectrometría de Masas de Iones Secundarios por Tiempo de Vuelo (TOF-SIMS), Espectrometría de dispersión de energía de rayos X (EDX).

Durante la obtención del inventario de las ferritas evaluadas, los porcentajes de composición son obtenidos a partir de estándares. Sin embargo, el inventario de los vidrios cerámicos no pudo obtenerse a partir de datos de proveedor, ni normativa publicada. La composición de los siete tipos de vidrio cerámico analizados fue obtenida mediante un espectrómetro secuencial de fluorescencia de rayos X de Thermo Electron, serie ARL modelo ADVANT-XP, con tubo de rayos X de Rodio y programa UNIQUANT para análisis semicuantitativo sin patrones.

Una vez recopilados y validados los datos de inventario, será necesario establecer una relación de los mismos con la unidad funcional, calculando la suma total del inventario y ajustando los límites del sistema. Tras la fase de análisis del inventario tendrán lugar las fases de evaluación de impacto ambiental del ciclo de vida e interpretación del mismo, tal y como establece la norma sobre gestión ambiental [41] [42].

La metodología desarrollada en esta tesis doctoral es una metodología innovadora, que permite a los ingenieros calcular el impacto ambiental en el momento en que desarrollan sus productos, considerando la composición exacta de los materiales y componentes y siendo conscientes en todo momento de la influencia que generan pequeños cambios de la composición de los materiales sobre el impacto ambiental total. Esta metodología ha sido aplicada a números componentes tanto electrónicos como mecánicos presentes en encimeras de inducción, que posteriormente serán presentados y donde se demuestra como la presencia en pequeñas cantidades de por ejemplo metales preciosos incrementan en gran medida el impacto ambiental.

A la hora de implementar la metodología planteada, en las fases de evaluación de impacto ambiental e interpretación, se ha desarrollado un software informático que tiene como principal objetivo permitir al usuario calcular el impacto ambiental y el consumo de materias primas, determinando la cantidad de materiales críticos utilizados dentro de un componente o producto. Esta herramienta informática ayudará al usuario a comparar ágilmente, de manera rápida y sencilla, entre varios diseños en función de la composición exacta de los materiales, analizando y evaluando el impacto ambiental de los mismos y la presencia de materiales críticos y candidatos a serlo.

La presencia y contenido total de materiales críticos y candidatos a serlo se obtendrá a partir del ciclo de vida, considerando los materiales críticos incluidos en las materias primas de los componentes, los materiales críticos a considerar durante los procesos de producción y distribución, además del fin de vida; alcanzando así el siguiente esquema:

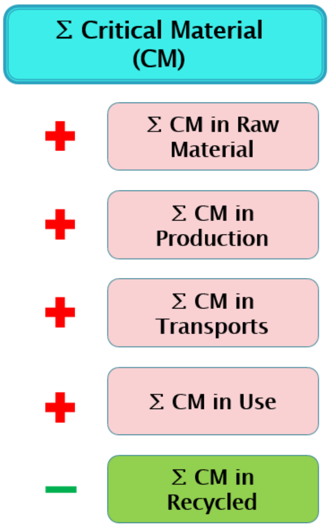


Figura 8 Cálculo de materiales críticos

En el capítulo 4 de la presente memoria se explica detalladamente el desarrollo, funcionamiento e implementación de este software informático. En el capítulo 5, la metodología expuesta durante el presente capítulo ha sido implementada a componentes de encimeras de inducción. Este tipo de encimeras es considerado un producto de gran complejidad, formado por una gran variedad de materiales y componentes: placas electrónicas, piezas metálicas, soportes plásticos, vidrio cerámico o cableado.

Figura 9 Componentes placa de inducción - Vista superior

Figura 10 Componentes placa de inducción - Vista inferior

Figura 11 Componentes placa de inducción – Embalaje y accesorios

Es necesario analizar el impacto ambiental producido por cada uno de los componentes eléctricos, electrónicos y mecánicos de la encimera de inducción, para analizar el porcentaje que cada uno de ellos produce sobre el impacto total del aparato y de ese modo poder evaluar la influencia de cada material sobre el impacto ambiental total del producto.

Por un lado, entre los componentes electrónicos de una placa de inducción se encuentran placas electrónicas (PCBs), diodos, transistores o resistencias; por otro, en el caso de componentes metálicos, se incluyen piezas de aluminio, acero inoxidable, hierro o cobre. Además, tal y como se ha comentado, entre los componentes mecánicos también se incluyen piezas plásticas y de vidrio cerámico; que junto con los anteriores constituyen una estructura compleja de producto.

La gran cantidad de piezas y materiales distintos utilizados para fabricar las encimeras de inducción hacen que la metodología previamente expuesta haya sido desarrollada para este producto, considerando además la presencia de materiales críticos y candidatos a serlo, junto con la influencia de los mismos sobre los cálculos de impacto ambiental.

Capítulo 4

Software Informático

4. SOFTWARE INFORMÁTICO

En la actualidad, gran parte de los ACV se realizan mediante bases de datos profesionales como EcoInvent. Sin embargo, la mayoría de estas bases de datos no son adecuadas para productos o componentes específicos. El software informático desarrollado en esta tesis doctoral está basado en un modelo de ACV que, mediante la utilización de bases de datos customizadas, evalúa el impacto ambiental y cuantifica, además, el contenido de materiales críticos.

La metodología previamente planteada es utilizada por el software informático desarrollado, considerando diferentes finales de vida para calcular la cantidad de materiales críticos e impacto ambiental. El ACV se calcula mediante las metodologías de evaluación de impacto ReCiPe Endpoint e IPCC 2013 Huella de Carbono.

Esta herramienta informática ha sido desarrollada con el objetivo de poder realizar una valorización del uso de materiales críticos de forma fácil y rápida; particularizándose para un tipo de componentes específicos: los componentes eléctricos y electrónicos. Este tipo de componentes ha sido elegido debido a la gran cantidad de materiales críticos que utilizan este tipo de componentes. Esta herramienta guiará al usuario ayudándole, asesorándole de manera rápida y sencilla a introducir datos y aportar sugerencias en caso de desconocimiento de los datos, y presentando los resultados estructuradamente y de manera fácilmente entendible. Se pretende que dicho software sea fácilmente extrapolable a componentes mecánicos o estructurales [13].

Se trata de una herramienta tipo CAE (ingeniería asistida por ordenador) que permite al usuario calcular el contenido de materiales críticos de un proyecto o componente y calcular el impacto ambiental del mismo. Mediante dicha herramienta el usuario podrá comparar entre varios diseños o propuestas para un mismo proyecto y elegir el óptimo.

El lenguaje de programación utilizado para el desarrollo de esta herramienta ha sido VisualBasic.NET, que permite una fácil instalación en dispositivos con sistema operativo Windows. Esta herramienta fue desarrollada conjuntamente con Ignacio Alecha, formando parte de su Proyecto Fin de Carrera "*Metodología para la consideración de los materiales críticos en el diseño de componentes. Aplicación a componentes eléctricos y electrónicos*".

Las funciones generales de la herramienta son las siguientes:

- Permite calcular el contenido de materiales críticos de un componente y el impacto ambiental del mismo:
    - El usuario dispone de distintos tipos de inventario relacionados con el proyecto a analizar, tales como componentes, placas, procesos, conexiones, etc. Es el software quien solicita al usuario la selección de varios de dichos datos de inventario para crear un nuevo proyecto. Una vez seleccionados, se solicitará el peso y las unidades a incorporar al proyecto; completados los datos de inventario seleccionados, el programa es capaz de realizar los cálculos.
    - La base de datos del software informático consta de dos tablas y varios ficheros de texto. La tabla 1 contiene la configuración de los materiales considerados críticos, además de los materiales candidatos a ser materiales críticos en el siguiente informe a publicar por la Unión Europea. Para cada material se definen las siguientes características: ID, nombre, crítico o estratégico, peso máximo y porcentaje máximo. Se muestra una tabla general de consulta, que contiene los datos requeridos por cada uno de los elementos disponibles para la creación del proyecto e información relativa al contendido de materiales críticos, impacto o datos generales. Por último, los ficheros de texto permitirán gestionar los textos en las ayudas que se muestran al usuario, cuando se solicita información mediante los botones de ayuda.

- Permite gestionar la base de datos.
    - El usuario es capaz de crear o editar datos de inventario basados en otros, o borrar datos de inventario. A diferencia de otras herramientas informáticas este software permite al usuario analizar el impacto ambiental customizando el inventario incluido en dicha base de datos.
- La usabilidad de la herramienta es elevada, ya que además de su sencilla navegabilidad a través de la interfaz de usuario se han incluido ayudas para mejorar el manejo de la misma.
- El programa guarda los proyectos en ficheros .TXT, permitiendo al usuario la exportación e importación de los mismos.

Una vez instalado el software en el dispositivo, a través del icono "ES" en la barra de Inicio de Windows se accede al software informático y aparece el siguiente menú con las opciones "New Project", "Load Project", "Database" y "Help".

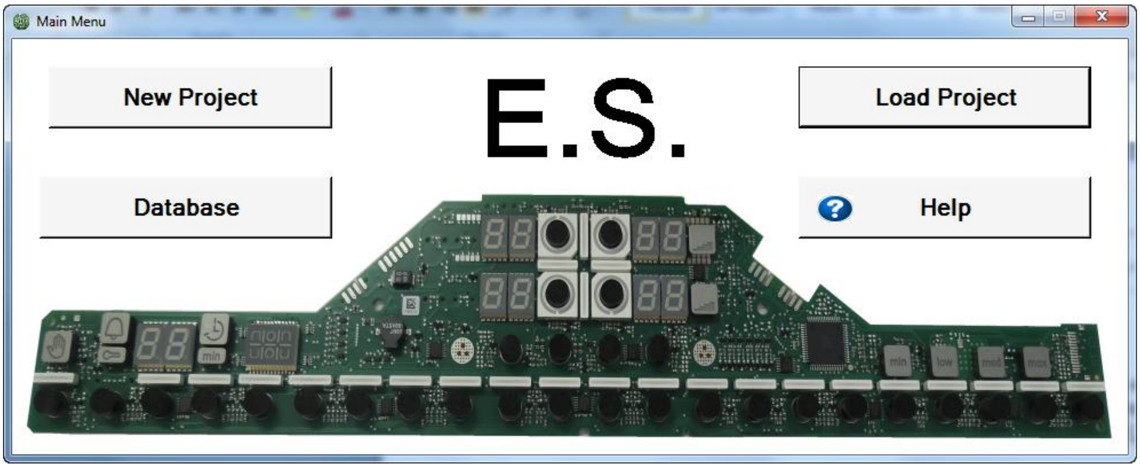
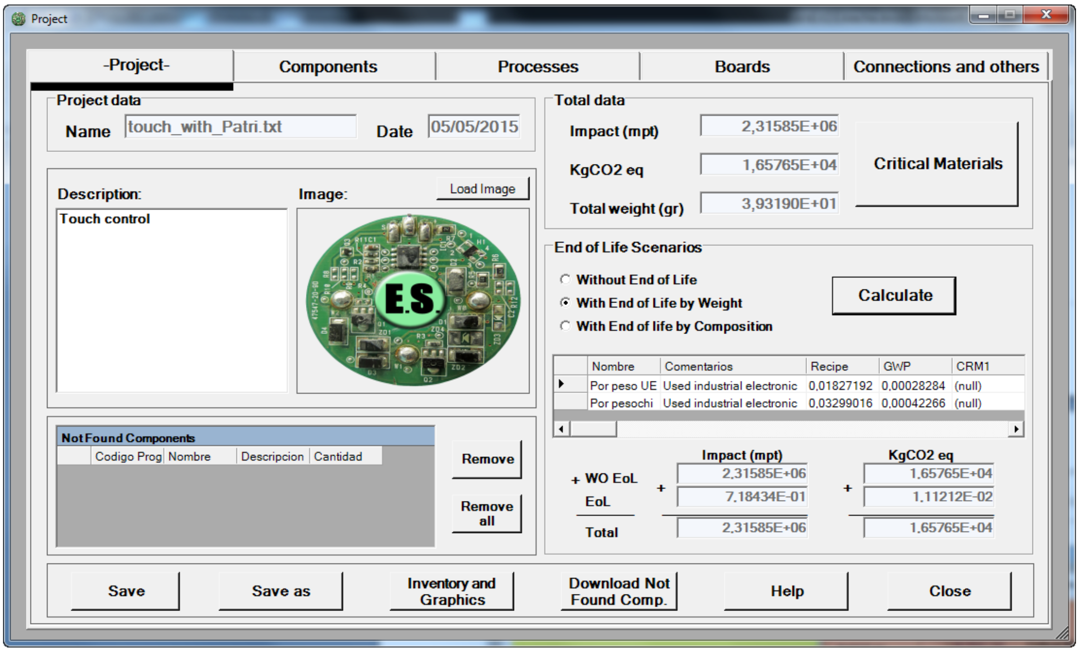


Figura 12 Pantalla principal software E.S.

- New Project: a través de este comando el usuario puede crear un nuevo proyecto. El programa solicita nombre y ubicación para el fichero de texto con la información del nuevo proyecto.
- Load Project: este comando permite acceder a un proyecto creado previamente.
- Database: permite al usuario crear, editar o borrar datos de inventario.
- Help: el comando help o ayuda tiene la finalidad de proporcionar al usuario una navegación más sencilla a través del programa, guiándole a través de cada una de las pantallas.

Una vez creado un nuevo proyecto, el usuario podrá gestionar los datos del inventario del proyecto navegando por las pestañas: Project, Components, Processes, Boards y Connections and others. Mediante estas pestañas el usuario podrá añadir nuevos componentes, procesos, placas, conexiones y otros al proyecto.

En la pantalla Project se muestran los datos generales, datos totales y resultados del proyecto. Además en la parte inferior de la pantalla existe una amplia botonera que ofrece al usuario las siguientes opciones: *Save, Save as, Inventory ad Graphics, Download Not Found Comp, Help and Close.*



Project data

Name: touch_with_Patri.txt

Date: 05/05/2015

Description: Touch control

Image:

Total data

Impact (mpt): 2,31585E+06

KgCO2 eq: 1,65765E+04

Total weight (gr): 3,93190E+01

End of Life Scenarios

○ Without End of Life
● With End of Life by Weight
○ With End of life by Composition

Nombre	Comentarios	Recipe	GWP	CRM1
Por peso UE	Used industrial electronic	0,01827192	0,00028284	(null)
Por pesochi	Used industrial electronic	0,03299016	0,00042266	(null)

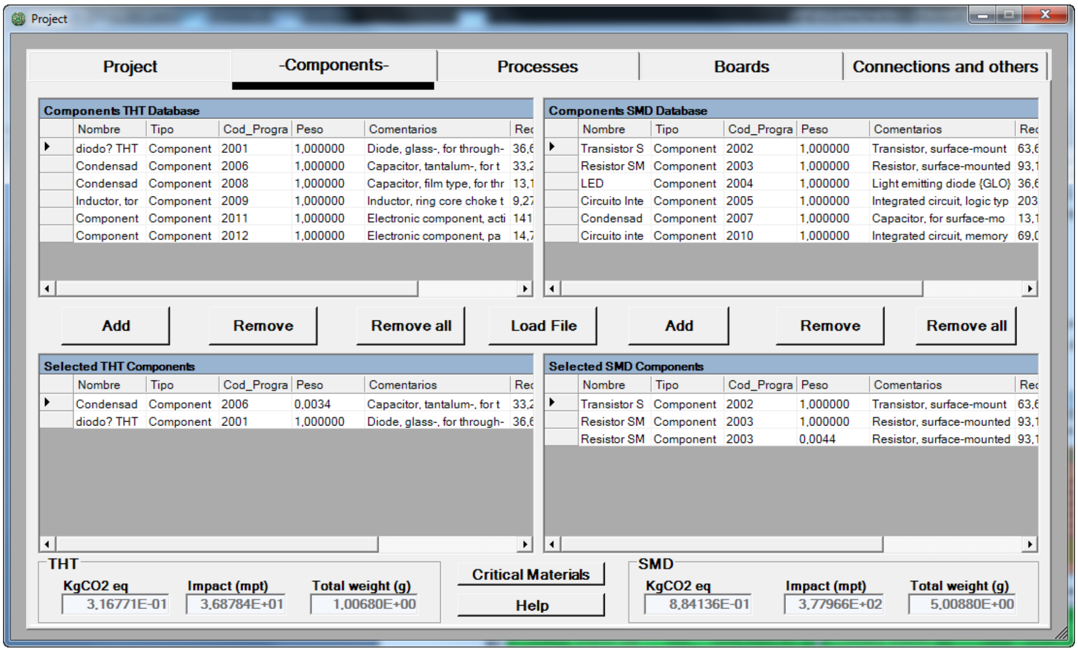
Not Found Components

Codigo Prog	Nombre	Descripcion	Cantidad

	Impact (mpt)	KgCO2 eq
+ WO EoL	2,31585E+06	1,65765E+04
EoL	7,18434E-01	1,11212E-02
Total	2,31585E+06	1,65765E+04

Figura 13 Pantalla "Project"

En la pantalla "Components" se muestran dos tablas de datos junto con sus correspondientes tablas de selección. Además existe la opción "Load File", mediante la cual el usuario puede realizar una carga masiva de componentes.



Components THT Database

Nombre	Tipo	Cod_Progra	Peso	Comentarios	Rec
diodo? THT	Component	2001	1,000000	Diode, glass-, for through-	36,6
Condensad	Component	2006	1,000000	Capacitor, tantalum-, for t	33,2
Condensad	Component	2008	1,000000	Capacitor, film type, for thr	13,1
Inductor, tor	Component	2009	1,000000	Inductor, ring core choke t	9,27
Component	Component	2011	1,000000	Electronic component, acti	141
Component	Component	2012	1,000000	Electronic component, pa	14,7

Components SMD Database

Nombre	Tipo	Cod_Progra	Peso	Comentarios	Rec
Transistor S	Component	2002	1,000000	Transistor, surface-mount	63,6
Resistor SM	Component	2003	1,000000	Resistor, surface-mounted	93,1
LED	Component	2004	1,000000	Light emitting diode {GLO}	36,6
Circuito Inte	Component	2005	1,000000	Integrated circuit, logic typ	203
Condensad	Component	2007	1,000000	Capacitor, for surface-mo	13,1
Circuito inte	Component	2010	1,000000	Integrated circuit, memory	69,0

Selected THT Components

Nombre	Tipo	Cod_Progra	Peso	Comentarios	Rec
Condensad	Component	2006	0,0034	Capacitor, tantalum-, for t	33,2
diodo? THT	Component	2001	1,000000	Diode, glass-, for through-	36,6

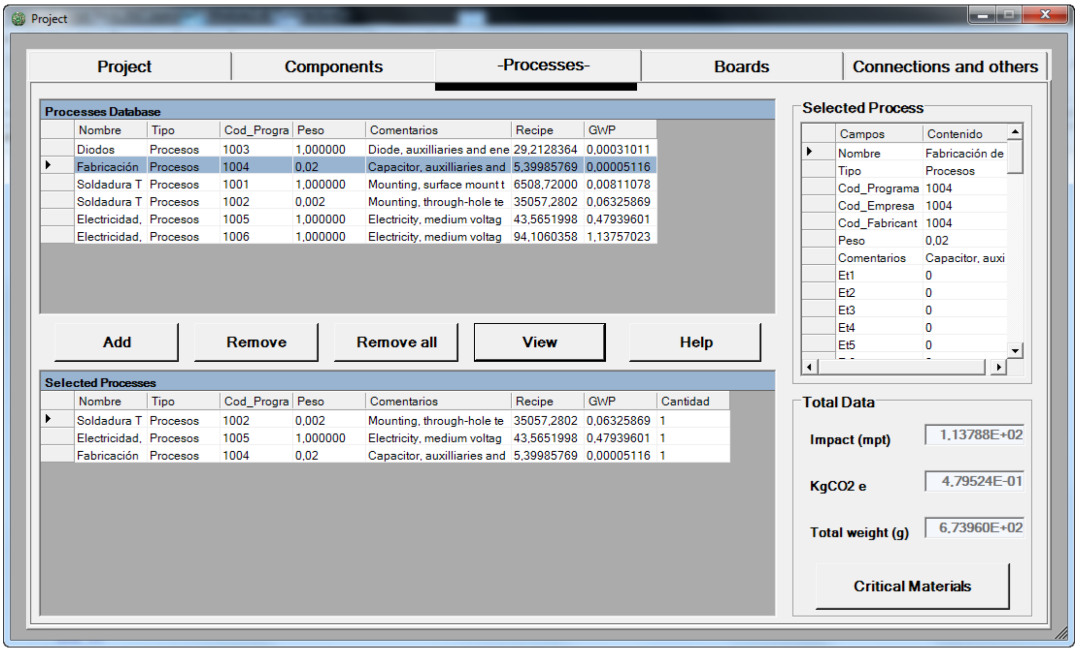
Selected SMD Components

Nombre	Tipo	Cod_Progra	Peso	Comentarios	Rec
Transistor S	Component	2002	1,000000	Transistor, surface-mount	63,6
Resistor SM	Component	2003	1,000000	Resistor, surface-mounted	93,1
Resistor SM	Component	2003	0,0044	Resistor, surface-mounted	93,1

	KgCO2 eq	Impact (mpt)	Total weight (g)
THT	3,16771E-01	3,68784E+01	1,00680E+00
SMD	8,84136E-01	3,77966E+02	5,00880E+00

Figura 14 Pantalla "Components"

En la pantalla “Processes” se incluyen dos tablas, la situada en la parte superior contiene los datos de inventario que pueden añadirse al proyecto, y la situada en la parte inferior contiene los datos ya incluidos en el proyecto. Asimismo, en la zona derecha de esta pantalla puede visualizarse el contenido de los elementos y el resumen de datos totales.



Processes Database

Nombre	Tipo	Cod_Progra	Peso	Comentarios	Recipe	GWP
Diodos	Procesos	1003	1,000000	Diode, auxilliaries and ene	29,2128364	0,00031011
Fabricación	Procesos	1004	0,02	Capacitor, auxilliaries and	5,39985769	0,00005116
Soldadura T	Procesos	1001	1,000000	Mounting, surface mount t	6508,72000	0,00811078
Soldadura T	Procesos	1002	0,002	Mounting, through-hole te	35057,2802	0,06325869
Electricidad,	Procesos	1005	1,000000	Electricity, medium voltag	43,5651998	0,47939601
Electricidad,	Procesos	1006	1,000000	Electricity, medium voltag	94,1060358	1,13757023

Selected Processes

Nombre	Tipo	Cod_Progra	Peso	Comentarios	Recipe	GWP	Cantidad
Soldadura T	Procesos	1002	0,002	Mounting, through-hole te	35057,2802	0,06325869	1
Electricidad,	Procesos	1005	1,000000	Electricity, medium voltag	43,5651998	0,47939601	1
Fabricación	Procesos	1004	0,02	Capacitor, auxilliaries and	5,39985769	0,00005116	1

Selected Process

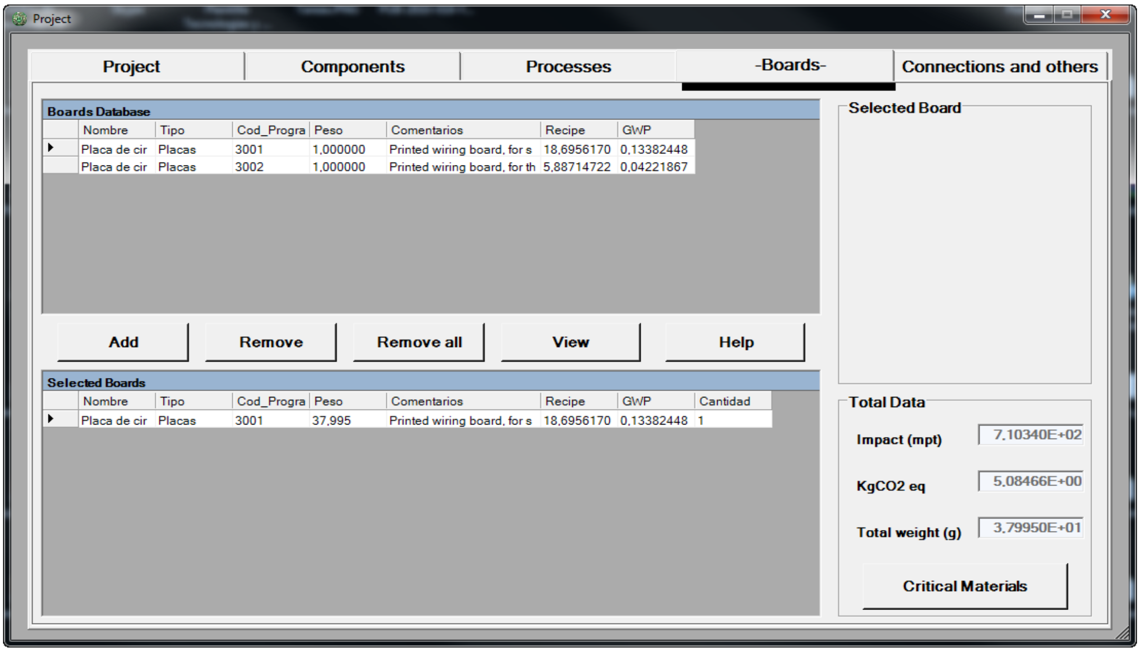
Campos	Contenido
Nombre	Fabricación de
Tipo	Procesos
Cod_Programa	1004
Cod_Empresa	1004
Cod_Fabricant	1004
Peso	0,02
Comentarios	Capacitor, auxi
Et1	0
Et2	0
Et3	0
Et4	0
Et5	0

Total Data

Impact (mpt) 1,13788E+02
KgCO2 e 4,79524E-01
Total weight (g) 6,73960E+02

Figura 15 Pantalla "Processes"

La pantalla “Boards”, al igual que en la anterior, incluye dos tablas donde se incluyen datos de inventario disponibles para añadir en el proyecto (tabla superior de la pantalla) y datos incluidos en el mismo (tabla inferior de la pantalla).



Boards Database

Nombre	Tipo	Cod_Progra	Peso	Comentarios	Recipe	GWP
Placa de cir	Placas	3001	1,000000	Printed wiring board, for s	18,6956170	0,13382448
Placa de cir	Placas	3002	1,000000	Printed wiring board, for th	5,88714722	0,04221867

Selected Boards

Nombre	Tipo	Cod_Progra	Peso	Comentarios	Recipe	GWP	Cantidad
Placa de cir	Placas	3001	37,995	Printed wiring board, for s	18,6956170	0,13382448	1

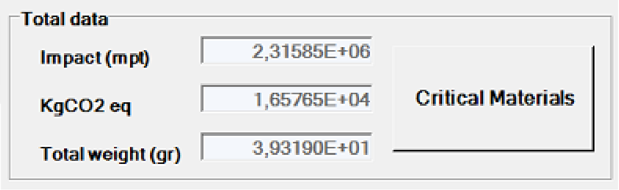
Total Data

Impact (mpt) 7,10340E+02
KgCO2 eq 5,08466E+00
Total weight (g) 3,79950E+01

Figura 16 Pantalla "Boards"

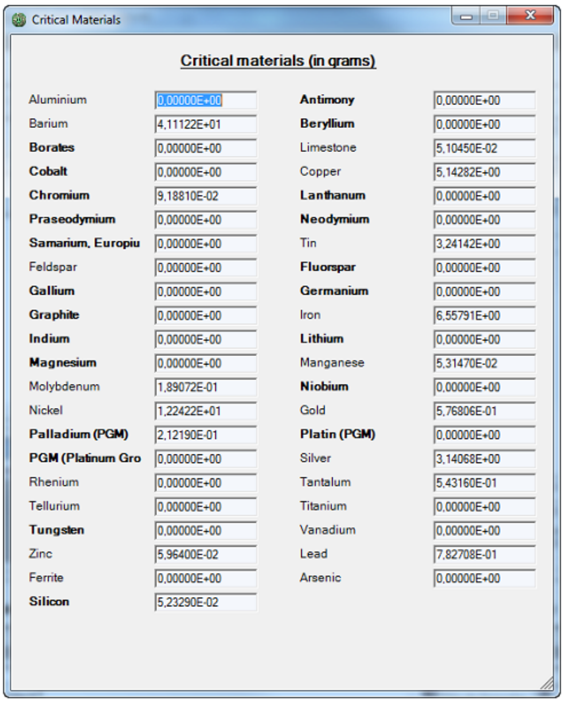
El software “Sustainable Electronics” permite a ingenieros e investigadores analizar diferentes alternativas con el principal objetivo de reducir el impacto ambiental y disminuir el uso de materiales críticos, mostrando la cantidad total de materiales críticos y candidatos a serlo en cada componente, proceso, placa o conexión. De modo que el usuario es capaz de tomar una decisión a la hora de diseñar un nuevo componente considerando la presencia de materiales críticos y el impacto ambiental.

En la pantalla Project, previamente explicada, el software presenta los resultados de manera clara y concisa, proporcionando en todo momento una fácil y rápida interpretación de los mismos por parte del usuario. Además de los resultados de valores de impacto ambiental, se muestra la posibilidad de acceder a un listado de materiales críticos y candidatos a serlo, con los porcentajes de los mismos.



Impact (mpt)	2,31585E+06
KgCO2 eq	1,65765E+04
Total weight (gr)	3,93190E+01

Figura 17 Resultados – Pantalla “Project”



Critical materials (in grams)

Aluminium	0,00000E+00	**Antimony**	0,00000E+00
Barium	4,11122E+01	**Beryllium**	0,00000E+00
Borates	0,00000E+00	Limestone	5,10450E-02
Cobalt	0,00000E+00	Copper	5,14282E+00
Chromium	9,18810E-02	**Lanthanum**	0,00000E+00
Praseodymium	0,00000E+00	**Neodymium**	0,00000E+00
Samarium, Europiu	0,00000E+00	Tin	3,24142E+00
Feldspar	0,00000E+00	**Fluorspar**	0,00000E+00
Gallium	0,00000E+00	**Germanium**	0,00000E+00
Graphite	0,00000E+00	Iron	6,55791E+00
Indium	0,00000E+00	**Lithium**	0,00000E+00
Magnesium	0,00000E+00	Manganese	5,31470E-02
Molybdenum	1,89072E-01	**Niobium**	0,00000E+00
Nickel	1,22422E+01	Gold	5,76806E-01
Palladium (PGM)	2,12190E-01	**Platin (PGM)**	0,00000E+00
PGM (Platinum Gro	0,00000E+00	Silver	3,14068E+00
Rhenium	0,00000E+00	Tantalum	5,43160E-01
Tellurium	0,00000E+00	Titanium	0,00000E+00
Tungsten	0,00000E+00	Vanadium	0,00000E+00
Zinc	5,96400E-02	Lead	7,82708E-01
Ferrite	0,00000E+00	Arsenic	0,00000E+00
Silicon	5,23290E-02		

Figura 18 Pantalla "Critical Materials"

Capítulo 5

Aplicación de la metodología.

5. APLICACIÓN DE LA METODOLOGÍA.

A la hora de implementar la metodología expuesta en el capítulo 3 “Metodología” de esta tesis doctoral, es necesario actualizar la base de datos EcoInvent, generando una base de datos personalizada y más exacta. Dicha base de datos se modeliza a partir de la introducción de datos sobre los materiales obtenidos de proveedores y fabricantes, o mediante análisis internos de los propios materiales realizados en la Universidad de Zaragoza.

Además, para realizar un ACV íntegro, es imprescindible analizar en detalle no solo materiales, tal y como se ha expuesto previamente, sino procesos, energía consumida, transportes, uso y fin de vida entre otros; ya que todo ello afecta al producto total y a su vida útil.

A partir de la metodología desarrollada en esta tesis doctoral, se ha analizado la influencia de la composición y la presencia de materiales críticos sobre el impacto ambiental en componentes mecánicos y electrónicos incluidos en las encimeras de inducción fabricadas por BSH.

El principal objetivo de la aplicación de esta metodología es demostrar la influencia de considerar la composición material exacta sobre el impacto ambiental total del producto; para ello los siguientes componentes han sido analizados: diodos, transistores, piezas de aluminio, de acero, vidrio cerámico y ferritas.

5.1. Componentes electrónicos

Debido al continuo cambio tecnológico en el que nos encontramos, existe un incremento en la demanda de componentes eléctricos y electrónicos y en consecuencia, las ventas de estos componentes se han visto incrementadas exponencialmente. El incremento en la demanda de los productos eléctricos y electrónicos, junto con los bajos costes de los dispositivos electrónicos ha generado un gran avance de esta tecnología y en consecuencia grandísimas cantidades de basura eléctrica y electrónica (WEEE).

El estudio e implementación de la metodología a componentes electrónicos se focaliza en diodos y transistores, ambos componentes están incluidos en las placas electrónicas de las encimeras de inducción analizadas.

5.1.1. Diodos

Los diodos son componentes semiconductores simples, dispositivos no lineales formados por dos electrodos, ánodo y cátodo [80]. Aunque las encimeras de inducción están compuestas por numerosos tipos de diodos y una gran cantidad de estos, la implementación de la metodología se ha centrado en diodos tipo SMD (tecnología de montaje superficial). Este tipo de diodos están compuestos por dos terminales, permitiendo a la corriente circular en una sola dirección y proporcionando un voltaje estable entre los terminales [81] [82] [83].

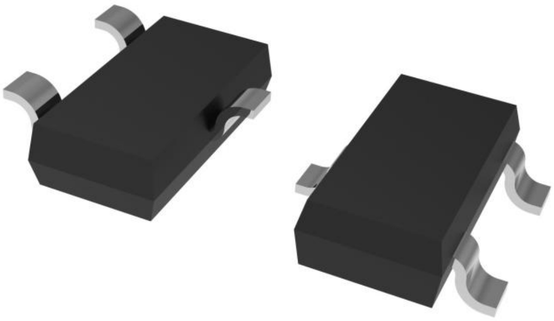


Figura 19 Vistas diodo SMD SOT23

En este estudio se han analizado los diodos SMD incluidos en la tabla 4, entre los que se encuentra el diodo de la base de datos EcoInvent; cuyos tamaños son aproximadamente 3x2.5x1.1 mm y una potencia de consumo entre 250 mW y 350 mW. El peso de este tipo de diodos SMD es de 8 miligramos, sin embargo su composición incluye materiales como estaño, plata, oro, níquel, antimonio o manganeso; donde los mayores valores de impacto ambiental son creados por el oro, seguidos de la plata y el manganeso. Además, el impacto ambiental creado por estos materiales es muy dañino, a pesar de las pequeñas cantidades en las que se encuentran.

Tabla 4 Diodos analizados

Diodos analizados	
EcoInvent	BCW65ALT1G
BAT17	BFS 17P E6327
BZX84B10LT1G	MMBD4148SE
BZX84C20	PMBD354
CMPD1001A	PESD3V3S2UAT
PLVA650A	BZX84-B10
AZ23C10	MMBZ5221B
BAS17	MMBZ5V6B
DDZX10C	PLVA659A
ESDA14V2L	BZX84_A2V4

Para poder llevar a cabo el análisis de impacto ambiental, el inventario de cada uno de los diodos se introduce en el programa SimaPro. Dichos inventarios se obtienen a partir de las hojas de especificaciones aportadas por cada proveedor de diodos. A partir del inventario, mediante la herramienta informática SimaPro y siguiendo la metodología desarrollada se obtienen los impactos ambientales de cada uno de los diodos a través de 11 categorías. En la tabla 5 se presentan los resultados de impacto ambiental de 10 diodos SMD y embalaje SOT23. El resultado, en porcentaje, se ha obtenido considerando los valores de EcoInvent como referencia 100%.

Tabla 5 Impacto ambiental diodos estudiados

Impact category	**EcoInvent**	**BAT17**	**BZX84B10LT1G**	**BZX84C20**	**CMPD1001A**	**PLVA650A**	**AZ23C10**	**BAS17**	**DDZX10C**	**ESDA14V2L**
Abiotic depletion	100%	486,6%	8,5%	1153,6%	1254,3%	600,2%	1027,5%	53,3%	554,0%	1632,8%
Abiotic depletion (fossil fuels)	100%	103,5%	96,5%	110,7%	113,2%	104,8%	111,3%	98,1%	104,3%	118,9%
Global warming (GWP100a)	100%	102,3%	96,1%	108,8%	111,1%	103,5%	109,6%	97,5%	103,2%	116,6%
Ozone layer depletion	100%	109,9%	88,8%	112,9%	118,1%	104,8%	116,2%	93,2%	103,5%	130,7%
Human toxicity	100%	66,9%	15,1%	141,9%	150,8%	78,0%	123,7%	17,0%	70,8%	186,9%
Fresh water aquatic ecotoxicity	100%	67,4%	14,4%	147,4%	156,8%	80,1%	128,4%	16,3%	72,9%	194,8%
Marine aquatic ecotoxicity	100%	76,2%	36,6%	135,3%	142,3%	85,5%	121,3%	38,2%	80,2%	170,6%
Terrestrial ecotoxicity	100%	222,0%	80,9%	447,4%	470,7%	258,7%	391,1%	83,2%	237,9%	569,8%
Photochemical oxidation	100%	102,0%	110,3%	119,8%	120,9%	116,9%	121,5%	110,7%	115,8%	128,9%
Acidification	100%	98,9%	105,2%	121,5%	122,6%	114,5%	122,0%	105,7%	113,7%	132,8%
Eutrophication	100%	70,3%	20,3%	144,4%	153,4%	81,8%	127,0%	22,3%	75,1%	189,0%

Tras introducir los inventarios de cada uno de los diodos en SimaPro, es posible concluir que el impacto ambiental de los diodos SOT23 analizados varía en función de la composición material. Considerando el impacto ambiental de EcoInvent como referencia (100%), el impacto ambiental de los diodos analizados varía desde 8.5% hasta 1632.8% dependiendo del contenido de oro incluido en la composición.

Analizando más en detalle los diodos con mayor y menor impacto ambiental, es posible concluir que tras el oro, los materiales que mayor influencia tienen sobre el impacto ambiental son la plata y el níquel. A pesar de que ninguno de ellos es considerado material crítico por la Comisión Europea, se trata de materiales con gran impacto para el medio ambiente. No obstante, la presencia de materiales críticos en los diodos con mayor impacto ambiental es notable; este es el caso de los siguientes materiales: antimonio, cobalto, magnesio y arena de sílice, presente en los diodos ESDA14V2L, CMPD1001A y AZ23C10.

5.1.2. Transistores

Desde su descubrimiento e invención, los transistores son considerados los componentes electrónicos más importantes, debido al importante avance que reportaron a la industria electrónica. Se trata de componentes esenciales e imprescindibles para los dispositivos electrónicos debido a su bajo consumo eléctrico [84].

Actualmente el principal objetivo de la mayoría de los fabricantes de transistores consiste en reducir el tamaño de los mismos, reduciendo con ello el impacto ambiental e incrementando la competitividad de sus productos en el mercado. Por consiguiente, todo esto repercute directamente en un incremento de los beneficies y una reducción de los costes [85].

El estudio realizado en esta tesis doctoral acerca de transistores se ha focalizado en transistores SMD (tecnología de montaje superficial) incluidos entre los componentes electrónicos de las encimeras de inducción, el tamaño aproximado es de 3 mm x 1.74 mm x 3 mm y 8 miligramos de peso. Se ha analizado el impacto ambiental de numerosos transistores SMD (Tabla 6) mediante la metodología desarrollada, como una herramienta de comparación alimentada por información suministrada por los fabricantes en términos de impacto ambiental. Con ello, se mejora la selección de transistores durante el diseño electrónico, debido a la posibilidad de examinar la influencia de la composición sobre el impacto ambiental [86].

Tabla 6 Transistores analizados

Transistores analizados	
EcoInvent	BCR191
BC817#1	BC847PN
47B	BC847B
BCR108	BCR858
BCR533	FJY3002R
BC847A	FJX3007R
BCX70J	FJX3014R
FJV3110R	SMBTA06
BC817#2	BC817UE6327
BC817-25	ZSOT2

A la hora de realizar este estudio, un detallado estudio de la composición a partir de las hojas de especificaciones de los fabricantes de 11 transistores ha sido realizado y publicado en una revista de alto impacto. En dicho estudio se incluye la composición exacta de cada una de las piezas que componen estos transistores: un chip unido al marco de plomo mediante cables de unión y protegido del ambiente mediante un encapsulado epoxy, tal y como puede verse en la siguiente imagen:

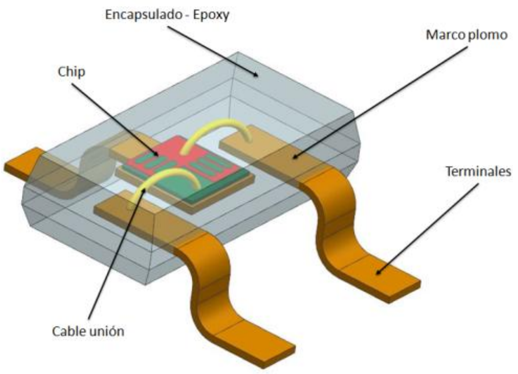


Figura 20 Vista esquemática componentes transistor SMD SOT23

En el inventario detallado de cada uno de los transistores se observa que las cantidades de determinados materiales varían considerablemente de unos proveedores a otros. Este es el caso de materiales como el oro, arsénico, cromo, silicio, titanio y plata, que no están incluidos en la base de datos genérica EcoInvent, y sin embargo sí que lo están en la mayoría de los transistores analizados. Por el contrario, materiales como el cobre, resina epoxy, aluminio, hierro o níquel, sí que aparecen incluidos en la base de datos EcoInvent pero no lo hacen en varios de los transistores analizados.

Una vez introducidos los inventarios de cada uno de los transistores en SimaPro, se puede concluir que el impacto ambiental de los transistores SMD SOT23 analizados varía sustancialmente en función de la composición material. La adquisición de materias primas representa entre un 20,3% y un 99,9% del impacto ambiental en la mayor parte de las categorías. Por el contrario, el impacto ambiental generado por el proceso productivo es normalmente menor, siendo los tratamientos de fin de vida los que menor impacto ambiental generan, con valores de aproximadamente 0,1% del total. Demostrando así la gran influencia de la composición de materiales de los transistores SMD SOT23 analizados sobre el impacto ambiental.

Se ha observado que la presencia de metales preciosos, especialmente oro, incrementan en gran medida la carga de impacto ambiental en la mayoría de las categorías; creando desde el 53,8% del impacto en la categoría *photochemical oxidation* hasta el 98,9% en la categoría *human toxicity* en uno de los transistores analizados, tal y como puede observarse en la siguiente tabla:

Tabla 7 Impacto ambiental detallado transistor

Impact category	Gold	Electricity consumption	Nickel	Tin	Silver	Electronic component factory	Copper	Others	Total
Abiotic depletion	97,533%	0,001%	0,018%	0,273%	2,150%	0,012%	0,012%	0,001%	100%
Abiotic depletion (fossil fuels)	74,604%	18,463%	0,677%	1,091%	1,180%	0,794%	0,112%	3,079%	100%
Global warming (GWP100a)	74,805%	17,525%	0,756%	1,069%	1,426%	1,004%	0,105%	3,311%	100%
Ozone layer depletion (ODP)	80,023%	11,974%	0,565%	0,891%	1,761%	1,035%	0,832%	2,918%	100%
Human toxicity	98,936%	0,228%	0,146%	0,014%	0,259%	0,099%	0,108%	0,210%	100%
Fresh water aqu. ecotox.	98,882%	0,285%	0,203%	0,017%	0,239%	0,083%	0,102%	0,189%	100%
Marine aquatic ecotox.	98,618%	0,532%	0,149%	0,029%	0,259%	0,107%	0,105%	0,200%	100%
Terrestrial ecotoxicity	77,900%	14,926%	3,251%	0,824%	0,576%	0,613%	0,150%	1,761%	100%
Photochemical oxidation	53,773%	13,172%	23,276%	2,543%	2,609%	1,345%	0,919%	2,363%	100%
Acidification	69,780%	8,638%	15,165%	1,817%	2,004%	0,764%	0,750%	1,081%	100%
Eutrophication	98,694%	0,483%	0,118%	0,040%	0,273%	0,082%	0,106%	0,204%	100%

Además, utilizando un transistor SMD de la base de datos EcoInvent como referencia, los impactos ambientales varían desde 0,48 veces hasta 167 veces el de referencia, principalmente dependiendo de la cantidad de contenido de oro.

El consumo de este metal precioso y el consumo energético generan la mayor parte del impacto ambiental total. Sin embargo, muchos de los transistores analizados contienen materiales como cobalto o silicio, considerados materiales críticos por la Comisión Europea en 2017 o el cromo en 2014., pero que no generan un impacto ambiental destacable en los transistores estudiados.

5.2. Componentes mecánicos

Los componentes mecánicos y estructurales resultan imprescindibles para cualquier tipo de encimera de inducción. Las principales funciones de estas piezas mecánicas son las siguientes: posicionamiento de componentes tanto electrónicos como no electrónicos (placas electrónicas, cables, inductores…) y fijación de los mismos durante toda la vida útil del producto. En el caso de las ferritas su principal función consiste en incrementar el acoplamiento entre el bobinado del inductor y el recipiente, apantallando los campos magnéticos y actuando como concentrador de flujo.

En las encimeras de inducción se incluyen numerosos componentes mecánicos, como piezas metálicas de aluminio o acero inoxidable, piezas plásticas, vidrio cerámico, ferritas… Por lo que en esta sección se analizan la mayor parte de estos materiales y componentes, estudiando además la contribución de los mismos sobre el impacto ambiental total del producto.

5.2.1. Aluminio

En este capítulo han sido analizados seis tipos de aleaciones de aluminio, con el fin de conocer la influencia de la composición sobre el medio ambiente [87]. La composición de las aleaciones de aluminio están definidas por estándares como los siguientes: normativa europea EN 1706:2011 [88], japonesa H5302 [89], británica BS 1490 [90], francesa NF EN 755-3-2008 [91], o americana AA ASTM B179-14 [92]. El trabajo realizado consiste en actualizar la base de datos EcoInvent v3 con la composición exacta de las aleaciones mostradas en la tabla 8, siguiendo la metodología desarrollada, con el objetivo de realizar una evaluación de impacto ambiental más precisa.

Los tipos de aleaciones de aluminio analizadas son las siguientes:

Tabla 8 Aleaciones aluminio analizadas

Aleaciones aluminio analizadas
$AlSi_9$
$Al\ Si_9Cu_3(Fe)(Zn)$
$Al\ Si_{10}Mg(Fe)$
$AlSi_9Cu_3Zn_3Fe$
$Al\ Si_5Mg$
$Al\ Si_{12}Cu_1(Fe)$

Una vez analizados, y tras realizar una comparativa de los mismos, es posible confirmar la influencia que tiene la composición sobre el medio ambiente. Por ello, es necesario resaltar la importancia de la selección de materiales, ya que esto repercutirá directamente sobre los costes, propiedades mecánicas del componente y sobre el impacto ambiental [93].

Materiales como níquel, titanio, plomo o estaño varían considerablemente de unas aleaciones de aluminio a otras; incluso llegando a no incluirse en la composición de la aleación de aluminio de la base de datos EcoInvent $AlMg_3$. Por el contrario, la presencia de cromo solamente está incluida en EcoInvent y en la aleación $AlSi_9Cu_3(Fe)(Zn)$. En el caso del aluminio, principal componente en las aleaciones analizadas, y otras materias primas como silicio, cobre y magnesio, están presentes en diferentes cantidades en cada aleación [94].

Entre las aleaciones de aluminio analizadas, la aleación $AlSi_9Cu_3Zn_3Fe$, reporta el mayor impacto ambiental bajo la metodología ReCiPe (1.01 puntos por kg). Es la aleación AlSi9 la que menor impacto ambiental genera bajo esta misma metodología (0.61 puntos por kg). Además, realizando una comparativa entre todas las aleaciones analizadas, se puede concluir que la presencia de materiales como cobre o estaño en la composición, influye en gran medida al incremento de impacto ambiental.

Finalmente, es importante resaltar la presencia de magnesio, silicio y cromo en la mayoría de las aleaciones analizadas. Los dos primeros, magnesio y silicio, se encuentran incluidos en el listado de materiales críticos publicado por la Comisión Europea en 2017. En el caso del cromo, es considerado material estratégico o candidato a ser material crítico en el mismo informe.

5.2.2. Acero

El acero es ampliamente utilizado entre el inventario mecánico de las encimeras de inducción analizadas, ya que la mayoría de los elementos estructurales están fabricados con este material. En componentes de las encimeras de inducción como el marco interno, marco estético, tornillos y muelles se utiliza acero.

De manera similar a la seguida en el apartado anterior sobre el aluminio, en este caso se han analizado alrededor de 180 tipologías de aceros; todos ellos han sido evaluados considerando su composición exacta y siguiendo la metodología desarrollada en esta tesis doctoral [95].

Los impactos ambientales de los aceros analizados varían entre 0.238 puntos por kg y 0.6763 puntos por kg bajo la metodología ReCiPe; siendo el acero inoxidable el que mayor impacto ambiental genera. Los elementos que influyen en mayor medida sobre el impacto ambiental son silicio, cromo y boro. El primero de ellos, silicio, considerado material crítico por la Comisión Europea y el segundo, cromo, candidato a serlo tras el último informe presentado en 2017 [5].

5.2.3. Vidrio cerámico

Los vidrios cerámicos son utilizados en multitud de aplicaciones, como aplicaciones ópticas, médicas y dentales. En esta tesis doctoral el vidrio cerámico analizado es utilizado en las encimeras de inducción; se trata del único componente visible por parte del usuario una vez instalado. Es esta última aplicación una de las más atractivas en el mercado, debido a su facilidad de limpieza y su bajo coeficiente de expansión térmica [96].

Las características principales de este componente son la dureza, densidad, resistencia térmica, conductividad eléctrica y facilidad de limpieza; donde el proceso de fabricación y la composición repercuten directamente en las mencionadas características de este tipo de vidrio [97]. Es por ello que en función de las anteriores características y dependiendo de la composición, existen numerosos tipos de vidrio. Cualquier modificación en la composición o en el proceso productivo repercute directamente en las propiedades del vidrio cerámico [98] [99]. Además existen gran cantidad de tamaños, estéticas y colores entre los que el usuario puede elegir a la hora de seleccionar su placa de inducción.

En esta ocasión, se ha analizado el impacto ambiental de siete tipos de vidrios cerámicos, estudiando la composición exacta de los mismos, la presencia de materiales críticos y candidatos a ser críticos, y evaluando la influencia de dicha composición sobre el impacto ambiental total de cada tipo de vidrio cerámico. Siguiendo la metodología desarrollada en esta tesis doctoral, mediante la utilización de la composición exacta de cada uno de los tipos de vidrios cerámicos a analizar, ha sido posible realizar una evaluación de impacto ambiental más precisa y con ello se ha podido estudiar más detalladamente la influencia del contenido de cada material sobre dicho impacto.

La composición exacta de cada tipo de vidrio cerámico es un tema confidencial y considerado como conocimiento propio de cada fabricante. Al contrario que en otros componentes incluidos en las encimeras de inducción, en esta ocasión no ha sido posible consultar la composición en las hojas de especificaciones publicadas en Internet por los fabricantes. En este componente y con el objetivo de conseguir los valores exactos de la composición de cada tipo de vidrio, los siete tipos han sido analizados mediante un espectrómetro de rayos X por fluorescencia de Thermo Electron, series ARL modelo ADVANT-XP, como el que puede verse en la Figura 14.

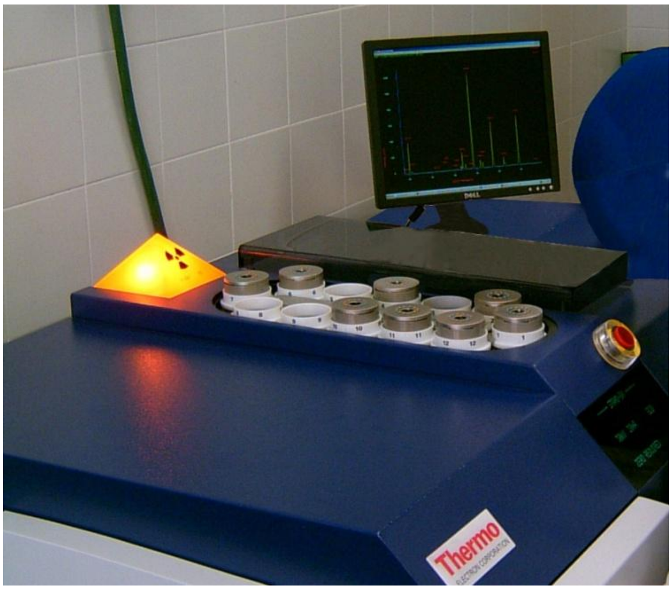


Figura 21 Espectrómetro de rayos X Thermo Electron

Mediante este equipo ha sido posible detectar presencia de materiales críticos como barita o magnesio, incluidos en la composición de la mayoría de los tipos de vidrios analizados. Estos materiales son incorporados en la composición de los vidrios cerámicos debido a sus propiedades ópticas y mecánicas. Además de estos materiales críticos también se han detectado materiales estratégicos o candidatos a ser materiales críticos, como aluminio, litio, estaño, titanio y zinc; la presencia de todos ellos repercute directamente en el incremento del impacto ambiental.

En el caso del estaño, se trata de un material que contribuye en gran medida a incrementar los valores de impacto ambiental. Tal y como puede verse en la gráfica 15, bajo la metodología ReCiPe el mayor impacto ambiental es generado por el vidrio cerámico tipo B, con 0.6079 puntos. De los cuales el 81.1% es generado por la presencia de litio, con únicamente un 0.74% del total de la composición.

Por el contrario, en el caso del vidrio cerámico tipo C con un impacto ambiental de 0.1693, la ausencia de estaño genera alrededor de un 80% menos de impacto ambiental que en el vidrio cerámico tipo B bajo la misma metodología, ReCiPe.

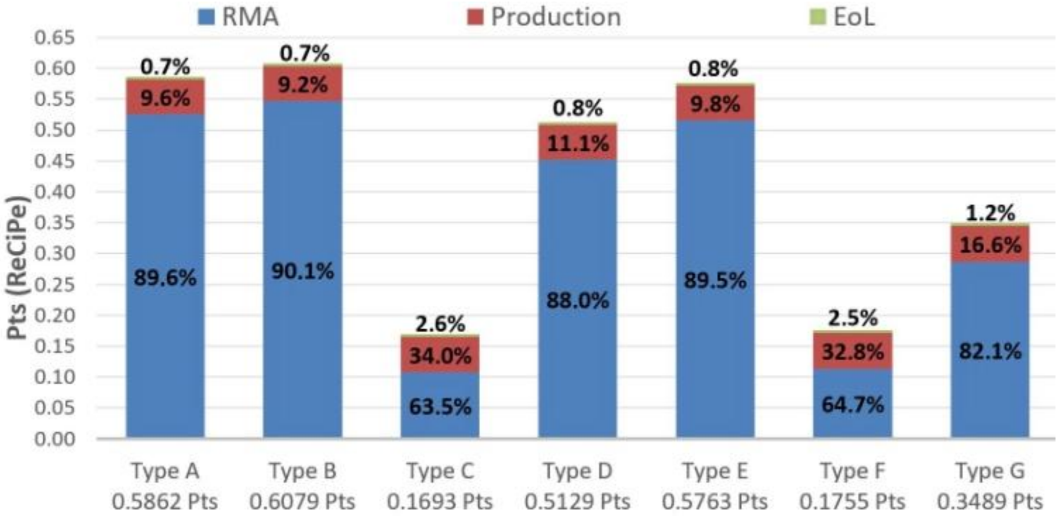


Figura 22 Impacto ambiental vidrios cerámicos (metodología ReCiPe)

Mediante la metodología Huella de Carbono, los materiales que en mayor medida contribuyen a incrementar el impacto ambiental son el neodimio, estaño y litio. Sin embargo otros como aluminio, titanio o circonio también contribuyen a incrementar los valores de impacto ambiental bajo esta metodología. Tal y como puede verse en la figura 16, los mayores valores de impacto ambiental son generados por los vidrios cerámicos tipo A y G. Se trata de vidrios cerámicos con elevada presencia de aluminio, litio y titanio, entre otros. En ambos, el contenido de litio es del 3.5% del total de la composición, generando un 19.6% del total de impacto ambiental en el vidrio cerámico tipo A y un 20.15% en el vidrio cerámico tipo G.

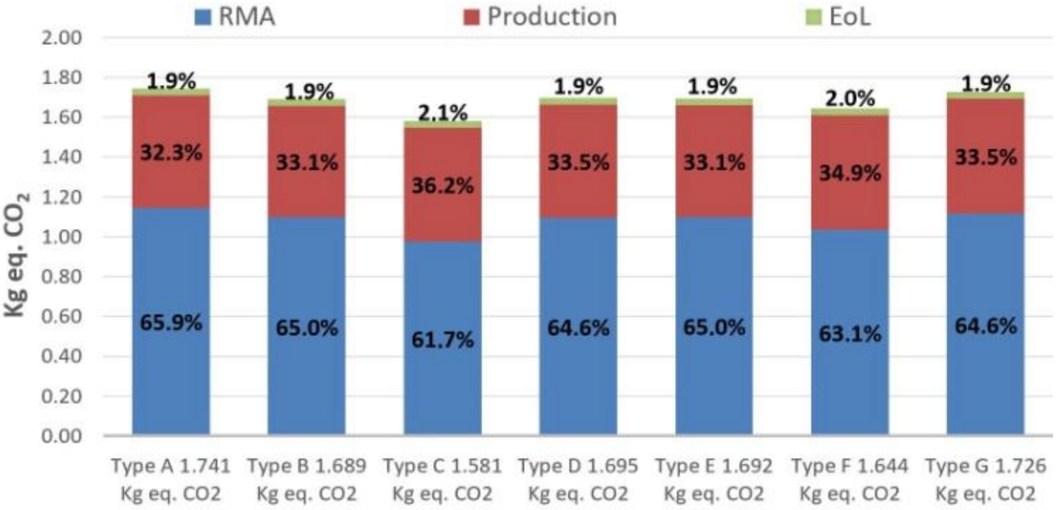


Figura 23 Impacto ambiental vidrios cerámicos (metodología Huella de Carbono)

Por el contrario, en ambas metodologías ReCiPe y Huella de Carbono, la arena de sílice es el material que menor contribuye a incrementar el impacto medioambiental. Este material, a pesar de estar incluido en la composición de todos los vidrios cerámicos analizados y suponer entre un 58% y un 63% de sus composiciones, es prácticamente irrelevante para el impacto ambiental que generan.

5.2.4. Ferritas

Las ferritas son componentes cerámicos compuestos de óxidos de hierro y cationes metálicos como el cobalto, aleaciones de manganeso-zinc, níquel-zinc o hierro [100]. Estos componentes son utilizados principalmente en dispositivos electrónicos como transformadores, electroimanes o inductores electrónicos [101].

Las principales propiedades de las ferritas son su baja coercitividad con gran resistividad, baja permeabilidad y bajas pérdidas [102]. Estas propiedades son el resultado de una formulación química y una estructura determinada. Siendo, igualmente, el principal propósito de este estudio demostrar la importancia de considerar la composición exacta de los componentes a la hora de analizar el impacto ambiental de los mismos [103]. Para ello se han comparado los resultados de impacto ambiental obtenidos considerando la base de datos EcoInvent y customizando la misma con la composición exacta de dos tipos de ferritas: manganeso-zinc (MnZn) y níquel-zinc (NiZn).

Ambos tipos de ferrita analizados, MnZn y NiZn, presentan propiedades similares: baja coercitividad con alta resistividad, pérdidas bajas y alta permeabilidad. Los dos tipos son utilizados para aplicaciones de alta frecuencia y comparten un área de trabajo común con frecuencias entre 10^{-2} y 1 MHz y permeabilidad inicial de alrededor de 10^{3} [104]. Además, materiales como el manganeso, níquel y zinc, incluidos en la composición de las ferritas estudiadas, están incluidos y calificados como materiales críticos en el último informe presentado por la Comisión Europea en 2017.

Este estudio demuestra la importancia de considerar la composición exacta de materiales a la hora de evaluar el impacto ambiental de ambas ferritas, MnZn y NiZn [105]. Para ello, se ha utilizado "Ferrite production {GLO}" de EcoInvent como referencia, actualizándola con los rangos de composición de las ferritas analizadas.

En la tabla 9, en el caso de las ferritas MnZn, bajo la metodología ReCiPe, el impacto ambiental varía un 41.5%, desde 1570 mPt/Kg hasta 2220 mPt/Kg en función de la composición seleccionada. En el caso del impacto ambiental con la base de datos EcoInvent es más de 2700 mPt/Kg, es decir 72% mayor que el mínimo impacto ambiental considerando la composición exacta basada en óxido de hierro y 21.5% mayor que el máximo impacto ambiental con la composición basada en óxido de magnesio. Bajo la metodología Huella de Carbono, se observa una variación del 26%, con valores de impacto ambiental desde 1.025 hasta 1.292 kg CO_2 eq. por Kg. Valores significativamente distintos a los obtenidos con base de datos de EcoInvent, donde se obtienen 1.54 kg CO_2 eq. por Kg. Analizando globalmente y en detalle los resultados de ambas metodologías, puede concluirse que las variaciones en los resultados de impacto ambiental son creadas principalmente por las diferencias en la cantidad de manganeso utilizado.

Tabla 9 Impacto ambiental mínimo, máximo y medio - Ferritas MnZn

	Fe_2O_3 (%)	ZnO (%)	MnO (%)	ReCiPe (mPt/Kg)	IPCC 2013 (Kg CO_2 eq)
Mínimo	76.5	6.5	17.0	1571.6	1.025
Medio	70	10	20	1833.3	1.156
Máximo	68	7.5	24.5	2223.9	1.292

En las ferritas NiZn, tal y como puede verse en la tabla 10, los valores de impacto ambiental varían casi un 520% bajo la metodología ReCiPe, desde 272 hasta 1.682 mPts/Kg. Y alrededor de un 270% bajo la metodología Huella de Carbono, desde 0.94 hasta 3.46 Kg CO_2 eq. por Kg. En el caso de comparar con la base de datos EcoInvent, los valores de impacto de la ferrita NiZn son siempre menores que los de EcoInvent bajo la metodología ReCiPe; pero pueden ser mayores o menores en la metodología Huella de Carbono en función del contenido de níquel.

Tabla 10 Impacto ambiental mínimo, máximo y medio - Ferritas NiZn

	Fe_2O_4 (%)	ZnO (%)	NiO (%)	ReCiPe (mPt/Kg)	IPCC 2013 (Kg CO_2 eq)
Mínimo	68.5	28.6	2.9	271.9	0.935
Medio	69	16	15	976.6	2.195
Máximo	70	3.2	26.8	1681.8	3.455

Las ferritas NiZn son más sensibles al contenido de níquel que las MnZn al contenido de manganeso. Factor a tener en cuenta por científicos e ingenieros que realizan análisis de ciclo de vida; ya que esto puede ayudarles en la selección de un tipo u otro de ferrita considerando el impacto medioambiental.

Este estudio resalta la importancia de considerar la composición exacta a la hora de calcular el impacto ambiental. Además, tal y como se ha explicado, comparando ambas ferritas bajo la metodología ReCiPe, la mayor parte de las ferritas NiZn presentan menor impacto ambiental que las MnZn. Sin embargo, no ocurre lo mismo bajo la metodología Huella de Carbono.

Capítulo 6

Conclusiones

6. CONCLUSIONES

- Una vez finalizadas las distintas fases del trabajo de investigación, se han extraído numerosas conclusiones, la mayoría de ellas han sido publicadas en artículos de revistas de alto impacto.

- Tal y como se explicaba al comienzo de esta memoria, la presente tesis doctoral se ha dividido en 4 etapas; en primer lugar se ha realizado un extenso trabajo de investigación sobre los materiales denominados críticos en la Unión Europea, focalizando el análisis desde una perspectiva medioambiental. En la segunda fase se planteaba una metodología de trabajo considerando dichos materiales críticos en el diseño de componentes; para lo cual en la tercera fase se desarrollo una herramienta informática mediante la cual aplicar dicha metodología. Por último, en la cuarta fase, se ha llevado a cabo la aplicación de la metodología a componentes de una encimera de inducción.

  Es posible concluir que la primera fase de esta tesis doctoral ha estado viva durante todo el transcurso de la misma, ya que ha ido actualizándose durante toda la investigación debido al continuo cambio tecnológico en el que vivimos y a las actualizaciones periódicas por parte de la Comisión Europea del listado de materiales críticos y de la metodología para determinar la criticidad de un material.

  En segundo lugar tras el planteamiento de la metodología de trabajo desarrollada en la segunda fase ha sido posible calcular el impacto ambiental de diversos componentes (mecánicos o estructurales y electrónicos), teniendo en cuenta la presencia de materiales críticos y considerando la composición exacta de los distintos componentes. Esto ha permitido conocer la influencia de cada material y de las cantidades de los mismos sobre el medioambiente. Tal y como se exponía en el planteamiento, la principal novedad que conlleva esta metodología radica en el inventario detallado y personalizado de los componentes a evaluar a la hora de llevar a cabo el ACV; para lo cual en base a lo expuesto anteriormente se considera la composición exacta de los componentes suministrada por los propios proveedores o a partir de análisis y estudios específicos.

  En la tercera fase se desarrolló la herramienta informática “Sustainable Electronics”, mediante la cual es posible aplicar la metodología planteada. Dicha herramienta permite al usuario evaluar el impacto ambiental de componentes considerando la presencia de materiales críticos; permitiéndole además, comparar entre distintos diseños considerando la composición material exacta de los mismos.

  Tras la segunda y tercera fase de esta tesis doctoral, una vez planteada la metodología de trabajo y desarrollada la herramienta informática mediante la cual aplicar dicha metodología considerando la presencia de materiales críticos y candidatos a serlo durante el diseño de componentes, ha sido necesario implementar los listados de materiales críticos actualizados a la herramienta informática desarrollada tras cada publicación por parte de la Comisión Europea.
  Además, debido al continuo cambio tecnológico en el que nos encontramos, ha sido necesario tener en cuenta que los parámetros a la hora de establecer la criticidad de los materiales han ido cambiando, de ahí que los listados publicados no sean estables en el tiempo.
  Esta herramienta informática ha sido utilizada como primera evaluación de impacto ambiental y presencia de materiales críticos en los componentes electrónicos estudiados (diodos y transistores). Estos artículos y la utilización del software en los mismos han servido además como doble chequeo de la herramienta, ya que mediante dicha primera evaluación de cada uno de los componentes se actualizaba la base de datos de este software informático, y a partir del mismo se obtenían los valores de impacto ambiental y contenido de materiales críticos que

también eran evaluados posteriormente mediante SimaPro y la base de datos EcoInvent. A lo largo de la presente tesis doctoral, siguiendo la metodología desarrollada, la base de datos EcoInvent ha sido continuamente modificada y mejorada en las diversas evaluaciones de componentes, a partir de fichas técnicas y hojas de especificaciones suministradas por los proveedores; así como análisis de componentes y materiales realizados por parte de Universidad de Zaragoza.

- En último lugar, en la cuarta fase, recae el mayor peso de toda la investigación realizada, ya que la metodología planteada ha sido implementada en componentes incluidos en placas de inducción desarrolladas por BSH; componentes mecánicos y electrónicos (diodos y transistores SMD, piezas de aluminio, aceros, vidrio cerámico y materiales ferríticos). Tanto los componentes mecánicos como electrónicos que ensamblan las cocinas de inducción son considerados componentes de gran complejidad y de los que nunca se había entrado tan en detalle desde el punto de vista medioambiental. Tras la evaluación, siguiendo la metodología, de cada uno de los componentes destacan las siguientes conclusiones:

  - **Diodos:** El impacto ambiental de los diodos SMD analizados durante la tesis doctoral refleja la gran influencia de la composición material sobre dicho impacto. Considerando el diodo de la base de datos EcoInvent como referencia, llegan a obtenerse impactos ambientales hasta 165 veces mayores variando únicamente la composición material de los mismos. Además, la presencia de materiales críticos como antimonio, cobalto o magnesio, junto con la existencia de metales preciosos, como oro o plata, en la composición incrementan sustancialmente los valores de impacto ambiental.

  - **Transistores:** En el estudio realizado sobre transistores SMD, la metodología EcoInvent fue utilizada como una herramienta comparativa frente a la información suministrada por los proveedores en términos de impacto ambiental; observando variaciones en el impacto ambiental de los transistores SMD analizados en función de dicha composición. La extracción de la materia prima representa entre el 20.3% y el 99.9% del impacto total en la mayoría de las categorías ambientales analizadas. Por el contrario, el impacto ambiental de cada transistor creado mediante los procesos productivos es normalmente menor; siendo el menor de todos el obtenido de los tratamientos de fin de vida, con valores de aproximadamente 0.1%. Lo que demuestra nuevamente la gran influencia de la composición material de los transistores SMD sobre el impacto ambiental.

  - **Aluminio:** La influencia de la composición de 6 tipos de aleaciones de aluminio sobre el impacto ambiental ha sido analizada. A la hora de realizar una evaluación del impacto ambiental más exacta, el ACV realizado mediante la metodología ReCiPe Endpoint ha sido mejorado con los rangos de composición material de las distintas aleaciones analizadas; obteniendo con ello los impactos ambientales mínimos, máximos y medios. En general, los valores de impacto ambiental alcanzan valores casi duplicados, en función de la composición seleccionada; siendo los elementos que más contribuyen a incrementar el impacto ambiental de estas aleaciones el cobre y el estaño.

  - **Acero:** Dentro del inventario mecánico de una cocina de inducción existen numerosos componentes fabricados con acero, entre ellos tornillos, marco interno o muelles. Todos ellos realizados a partir de hasta 5 tipos distintos de acero, cuya composición e impacto ambiental han sido analizados a partir de la metodología desarrollada. Se han obtenido incrementos de hasta casi 3 veces los valores de impacto bajo la metodología ReCiPe, donde el mayor impacto ambiental es creado por el acero inoxidable; siendo los materiales que mayor contribuyen a dicho impacto: sílice, cromo y boro.

  - **Vidrio cerámico:** Se ha realizado un exhaustivo estudio de la influencia de la composición de los vidrios cerámicos sobre el impacto ambiental de las encimeras de inducción. Mediante el análisis de la composición de varios tipos de vidrio cerámico, se observa como pequeñas variaciones en la composición material de los mismos generan importantes diferencias en los valores de impacto ambiental. Con ello se ha demostrado la importancia de considerar la composición exacta de los materiales a la hora de evaluar el impacto ambiental de un componente o producto. Elementos como estaño, litio o titanio son los que en mayor medida contribuyen a incrementar el impacto ambiental. Otros como barita o magnesio, junto con neodimio, también se incluyen en la composición de los vidrios cerámicos analizados y se encuentran incluidos en el listado de materiales críticos publicado por la Comisión Europea.

  - **Ferritas:** El impacto ambiental de dos tipos de ferritas, manganeso-cinc (MnZn) y níquel-cinc (NiZn), ha sido evaluado; analizando la influencia que su composición material tiene sobre el impacto ambiental. Esto permitirá a científicos e ingenieros comparar ambos tipos de ferritas no solo desde el punto de vista de propiedades técnicas y coste, sino también comparando su impacto sobre el medio ambiente. Ambos tipos de ferritas están compuestas principalmente por óxido de hierro, además de un amplio rango de componentes entre los que se encuentran manganeso y níquel; cuya presencia afecta no solo a las propiedades magnéticas sino también al impacto de las mismas sobre el medio ambiente. Ya que se trata de materiales con gran influencia sobre el impacto ambiental y cuyo riesgo de suministro se ha incrementado durante los últimos años, generando con ello una preocupación entre los fabricantes de la Unión Europea.

- Tal y como se planteaba en los objetivos iniciales de esta tesis doctoral, queda patente la importancia de considerar la composición exacta de materiales a la hora de calcular el impacto ambiental de un componente. Además, mediante la aplicación de la metodología propuesta es posible conocer los materiales críticos y materiales candidatos a ser críticos presentes en los distintos componentes analizados, la cantidad de los mismos y la influencia que poseen sobre el impacto ambiental total del componente o producto analizado.
  Es por ello que esta tesis doctoral ha permitido analizar la sostenibilidad ambiental de las placas de inducción desarrolladas y producidas en la planta del grupo BSH en Zaragoza (Montañana) con gran exactitud. Además el conocimiento de los resultados medioambientales y la influencia de los distintos materiales sobre el impacto ambiental total hacen posible que los desarrolladores de placas de inducción puedan diseñar sus componentes, tanto mecánicos como electrónicos, considerando la criticidad de los materiales a utilizar, pudiendo elegir entre distintas alternativas de materiales en función de la composición de los mismos; mejorando al mismo tiempo los costes y permitiendo obtener estabilidad en los precios de los materiales utilizados en sus componentes.
  Llegando más al detalle de la cuestión sería posible incluso recuperar o reciclar materiales valiosos al final de la vida útil del producto, gracias al conocimiento de su presencia y además de la cantidad de los mismos en cada encimera de inducción. Consiguiendo con ello mejorar la competitividad en el mercado, incrementando los beneficios y en paralelo disminuyendo los costes. Por todo ello, a partir de la metodología desarrollada, los resultados obtenidos y las conclusiones extraídas, ingenieros y desarrolladores de componentes serán capaces de evaluar como pequeñas modificaciones en la composición y propiedades de los materiales, provocan grandes cambios sobre el impacto ambiental.

Capítulo 7

Futuras líneas de investigación

7. FUTURAS LÍNEAS DE INVESTIGACIÓN

A continuación se incluyen futuras líneas de investigación y trabajo adicional al realizado durante esta tesis doctoral. Permitiendo continuar con el trabajo realizado, actualizándolo y ampliando temas interesantes que la presente tesis doctoral no haya podido abarcar.

Tras desarrollar la metodología expuesta en esta tesis doctoral y los resultados obtenidos tras la implementación de la misma, es posible plantear las siguientes nuevas líneas de investigación debido al gran interés social que actualmente existe en los campos de ecodiseño y materiales críticos.

De acuerdo al desarrollo temporal de los listados de materiales críticos presentados por la Comisión Europea cada 4 años, sería interesante actualizar la herramienta informática desarrollada a partir de futuros listados publicados sobre materiales críticos.

Actualizando con estos nuevos listados los estudios ya realizados a los componentes electrónicos y mecánicos de las cocinas de inducción. También implementar esta metodología a nuevos componentes como polímeros e incluso a otros de otros componentes presentes en productos distintos a la inducción. En el caso de los aceros analizados, ampliar e implementar la metodología a otros tipos de aceros distintos a los aceros inoxidables analizados.

De igual modo que en componentes estructurales o mecánicos, existen numerosos componentes electrónicos que podrían ser analizados. Siguiendo el hilo conductor de la presente tesis doctoral, mediante el análisis de la composición de dichos componentes electrónicos sería interesante analizar la influencia de dicha composición sobre el impacto ambiental total del componente.

Finalmente, todos los análisis de evaluación de impacto ambiental realizados a componentes mecánicos y electrónicos podrán ser actualizados en un futuro a partir de nuevas actualizaciones de la base de datos EcoInvent. Realizando nuevas comparativas entre las composiciones exactas obtenidas de cada componente y las nuevas actualizaciones de EcoInvent.

Capítulo 8

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Capítulo 9

Publicaciones

9. PUBLICACIONES

9.1. Journal of Cleaner Production: Influence of the material composition on the environmental impact of surface-mount device (SMD) transistors

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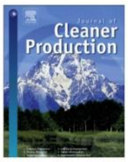

Influence of the material composition on the environmental impact of surface-mount device (SMD) transistors

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ABSTRACT

The aim of this study is to better elucidate the influence of surface-mount device (SMD) transistor material composition on the environmental impact of such transistors. A life cycle assessment (LCA) has been performed in which the EcoInvent dataset was updated with material compositions provided by several manufacturers. The influence of the material composition has been studied, providing a more precise understanding of the environmental impact. The software used to develop the LCA model was SimaPro 8.0.3.14, developed by Pré Consultants. The LCA was calculated with the CML methodology. In addition, a life cycle inventory was developed using EcoInvent v3.

The EcoInvent methodology was used as a comparison tool for information provided by the manufacturers in terms of environmental impact, thus improving transistor selection in electronics design. The environmental impact of an SMD transistor can vary substantially with respect to material composition. Raw material acquisition represent between 20.3% and 99.9% of the total impact in most environmental categories. By contrast, the environmental impact of each transistor created due to part production is usually lower. The lowest environmental impact comes from the end of life treatments, values for which are approximately 0.1%.

This environmental impact study demonstrates the large influence of transistor material composition for those analyzed herein.

1. Introduction

The concept of ecodesign arose at the beginning of 1990s from the need for reducing environmental impacts of various. This concept is based on the rule of prevention instead of correction and implements creativity, innovation and environmental responsibility in the design stage (Plouffe et al., 2011) (Aoe, 2007) (Platcheck et al., 2008).

In the electronics industry, it is important to measure the environmental performance of a product in order to reduce environmental impact, which also provides another aspect to market competitiveness for manufacturers, i.e., companies look to improve their profits and at the same time save costs (Plouffe et al., 2011) (Borchardt et al., 2011).

One of the most important advances in the electronics industry was the invention of the union transistor, which took place in 1951, by William Schockley (Malvino, 1999). The transistor is a semiconductor device mainly used to amplify electronic signals. It can be used for many digital and analog purposes including amplification, regulation of voltage, switching and signal modulation.

Transistors have had an enormous impact on modern society, as nearly all of the electronic devices we use rely on transistors. As transistors have become an essential component to any electronics device, manufactures continue to try to reduce their size. State-of-the-art transistors are in fact microscopic in size, and their electric power consumption is very low (Hischier et al., 2007).

There are two main methods of soldering transistors on an electronic circuit board: through-hole mounting technology and surface mounting technology (SMT). Components using the SMT

List of abbreviations: ETSI, European Telecommunications Standards Institute; GWP100y, Global Warming Potential referred to 100 years; ICT, Information and Communication Technologies; LCA, Life Cycle Assessment; ODP, Ozone layer Depletion; PP, Part Production; RMA, Raw Material Acquisition; SMD, Surface-Mount Device; SMT, Surface Mounting Technology; WEEE, Waste of Electrical and Electronic Equipment.

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approach are known as surface-mounted devices (SMD) (Sharon Mui Ling et al., 2014). Through-hole technology requires holding the circuit board to place the components that cross through all layers. In contrast, SMDs are soldered on the circuit board or assembled with a small amount of adhesive on the underside, without the necessity of holding the circuit board (Vianco, 2001) (Liu, 2001).

There has been a recent trend toward SMDs rather than through-hole devices due to needs for devices with reduced size and weight, which are thus more compact and portable. Additionally, reducing cost and improving reliability is also important (Koshal, 1993). The smaller size and shorter connections of SMT make it more amenable to these design goals, and the mechanical strength of the assembly is greater as well.

Furthermore, depending on several factors, such as the application requirements of the transistors, there are many types of encapsulation. Once again, due to size constraints, there has been progress in encapsulation of microelectronic devices toward reducing packaging size (Strauss, 1998) (Lau, 2014).

There is an increasing demand for electronic devices due to cheaper, accessible and more efficient products and also to surging data traffic due to cloud services (Concoran and Andrae, 2014). Accordingly, many people can afford to buy new devices, replacing other technologies and generating new waste of electrical and electronic equipment (WEEE). In 2010, European countries produced approximately 6.5 million tons of WEEE, with an estimate 12 million tons for 2015. These figures will increase 16–28% every five years as a result of new cheaper technologies (Ongondo et al., 2011) (Queiruga et al., 2012).

Consequently, the European Union has implemented several laws focused on WEEE reduction, such as the WEEE Directive, to improve the recycling of electric and electronic equipment thus reducing the disposal of waste (European Parliament, 2012). As a means to increase energy efficiency, directives related to energy-using products (EuP) (European Parliament, 2005) and energy-related products (ErP) (European Parliament, 2009) were developed to protect the natural environment. This study shows the environmental impact of SMD transistors according to the WEEE Directive, which accounts for the generated waste being treated in a European WEEE treatment plant.

There is also a large concern in society about materials that have substantial environmental impact. These materials are considered critical materials due to shortage or supply risk, economic vulnerability and ecological risk (Commission, 2014). Due to technological change, the demands for particular materials are volatile as one demand for one material may quickly increase while another decreases, which can lead to changes in risk indicators for a particular material. It is necessary to take into account all of these considerations when determining the criticality of a material (Chapman et al., 2013) (Binnemans et al., 2013) (Graedel and Nuss, 2014).

Therefore, the main objective of this study is to determine the influence of the material composition on the environmental impact of SMD transistors. To do that, life cycle assessment (LCA) has been used to quantify the environmental impact, identifying the main types of environmental impact along the life cycle.

LCA has been implemented by many industries and businesses to better understand how their products affect the natural environment. Several electrical and electronic products have LCA studies (Andrae et al., 2004), such as, integrated circuit products (Taiariol et al., 2001), integrated circuit packaging technologies (Andrae and Andersen, 2011), telecommunications exchange technologies (Andrae et al., 2000) and optical fiber networks (Andrae, 2012).

Further, several authors analyzed the environmental impact of products from flash memories (Boyd et al., 2011) to personal computers or mobile phones (Andrae and Andersen, 2010) (Yao et al., 2010) (Moberg et al., 2014), including silicon wafer processing for microelectronic chips (Schmidt et al., 2012), computational logic (Boyd et al., 2009), smartphones (Andrae and Vaija, 2014) (Andrae, 2015) and FED TVs (Hischier, 2015). Other studies were focused on the environmental impact of information and communication technologies (ICT) (Arushanyan et al., 2014) (Stiel and Teuteberg, 2014) (Börjesson Rivera et al., 2014) or domestic induction hobs (Elduque et al., 2014); also recently, Sikdar published a LCA of electronic components used in Wi-Fi access points and Ethernet switches (Sikdar, 2013) (Sikdar, 2010).

Although other authors wrote studies about semiconductor production processes (Boyd et al., 2010), this LCA is focused on the material composition of each transistor and the influence they have on the environmental impact. To carry out the LCA, information from several manufacturers has been gathered. Recently, a Technical Specification to carry out LCA of electronic products focused on ICT Equipment, Networks and Services was published by the European Telecommunications Standards Institute (ETSI). This document has been used as a guide in this research (ETSI, 2011).

2. Materials and methods

2.1. Dataset improvement methodology for electronic components

Most recent LCA studies use generic datasets from databases such as EcoInvent to evaluate electronic products. The EcoInvent database covers several types of parts, including SMD transistors. This database provides a system characterization for transistors produced on a global scale that includes material composition and an estimation of the productions efforts: auxiliaries, energy, emissions, waste, infrastructure, etc (Hischier et al., 2007). Manufacturers have started to publish material composition datasheets for electronic components (Technologies, 2014) (Fairchild, 2014), and the aim of this study is to use that information to evaluate the influence of the material composition on the natural environment. Our approach is similar to that of Andrae and Andersen (Andrae and Andersen, 2011), who compared the environmental impacts of integrated circuit packaging technologies based on manufacturer information on the material composition and masses of subparts; however, our study is focused more specifically on analyzing the differences using EcoInvent part data.

Therefore, in this paper, the dataset provided by EcoInvent is updated with material composition provided by manufacturers. To achieve a more precise environmental impact assessment, the production processes and waste generation for each transistor has been analyzed using the EcoInvent methodology and applying it to the information provided by the manufacturers.

For the different construction elements of an SMD transistor (chip, lead frame, encapsulation, etc.), material efficiency and waste generation data provided by EcoInvent for "Transistor, surface-mounted {GLO}| production" have been applied to several SMD transistors. This allows us to estimate the overall raw material acquisition, not only considering the materials present in the final transistors but also the overall material consumption and waste generation. Using the original EcoInvent dataset, the overall amount of non-used raw materials needed for the production processes, which ends up as waste, is also obtained. All of these data are introduced into the EcoInvent dataset, preserving production efforts and updating raw material consumption and waste generation. To improve the comparison between transistors, the EcoInvent dataset has been modified by substituting tin–lead solder for lead-free solder, as most modern transistors are lead-free due to legislation changes (Abtew and Selvaduray, 2000).

This makes possible the use of the information currently supplied by manufacturers of material content and the adaptation of this information to assess the environmental impact while taking into account the system characterization of EcoInvent. Recently, (Zhu and Andrae, 2014) showed a system and methodology for performing cost effective LCA of information and communication technology (ICT) equipment based on material content and in conformance with ETSI TS 103 199. Therefore, the LCAs of different SMD transistors can be performed and compared with the EcoInvent dataset with the objective of evaluating the influence of the material composition on the environmental impact. Doing so enables electronic engineers to choose between different transistors from an environmental point of view.

2.2. LCA methodology

2.2.1. Goal and scope definition

The aim of this LCA is to analyze the influence of the differences in the material composition on the environmental impact results between different SOT23 SMD transistors. This analysis can be used as a comparison tool to improve transistor selection considering its environmental impact.

2.2.2. Functional unit

In the developed LCA, the functional unit has been defined as one transistor with a SOT23 package with an NPN structure, with dimensions of 3.0 mm × 1.75 mm × 1.3 mm and power consumption 200–300 mW. Current gains for the transistors studied in this study are between 70 and 160; maximum values for collector currents are between 100 nA and 100 mA. The chosen reference mass flow is 1 g. The LCA accounts for the material composition of the component, waste produced in the production process, energy consumption and end of life. However, in end of life calculations, the transistor is assumed to be integrated into a circuit board, as transistors are manufactured and soldered in integrated circuit boards together with other components, e.g., diodes, resistors and capacitors.

From the information provided by several manufacturers and the commercial database, the environmental impact has been analyzed with respect to SMD transistor material composition.

2.2.3. System boundaries

The main goal of this paper is to study the environmental impact created by different types of transistors, studying and analyzing the variation of the environmental impact caused by their material composition.

To analyze the environmental impact of each transistor and compare them, a LCA model has been developed. It includes the following stages (Fig. 1): the production of raw materials and energy consumption (Stage A, following ETSI nomenclature), manufacture and production processes (Stage B1) and finally end-of-life (Stage D2). Distribution to consumers and the use phase are not included in the studied product system, as they are not directly related to material composition of transistors and strongly dependent on the electronic board in which the transistor is used. Other generic processes included in the studied product system are G1 (Transport and Travel), G2 (Electricity), G3 (Fuels) and G5 (Raw Material Acquisition).

2.2.4. Inventory data and cut-off criteria

A life cycle inventory has been developed using EcoInvent v3, one of the most used databases developed by Swiss Centre for life cycle inventories. The inventory data and cut-off criteria are based on EcoInvent.

2.2.5. Assumptions

SimaPro 8.0.3.14, developed by Pré Consultants, was used to develop the LCA model. LCA was implemented with CML – IA baseline V.3.01 methodology. Additionally, the following impact categories have been used to avoid subjectivity: abiotic depletion, abiotic depletion (fossil fuels), acidification, eutrophication, global warming (GWP100y), ozone layer depletion (ODP), human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation.

Disposal of SMD transistors must comply with the WEEE Directive; therefore, they must be collected at the end of their life. It is assumed that the boards where the transistors are soldered are going to be treated in a WEEE treatment plant; thus, the following EcoInvent dataset has been used for all of the transistors: Used printed wiring boards (waste treatment) {GLO}| treatment of scrap printed wiring boards, shredding and separation. This dataset has been used as a reasonable proxy for the aim of this study, but if the

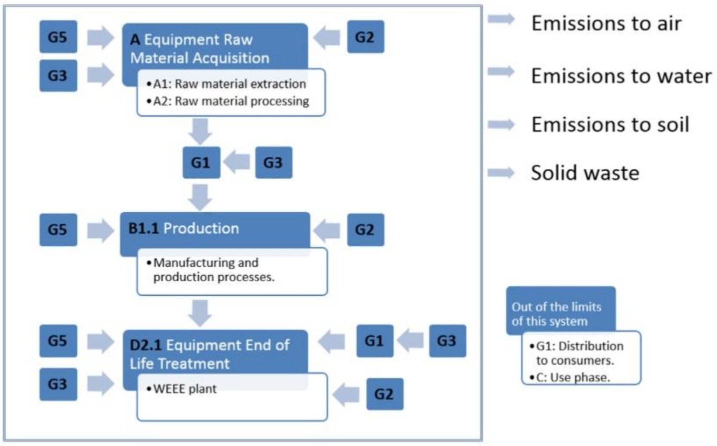

Fig. 1. System boundaries.

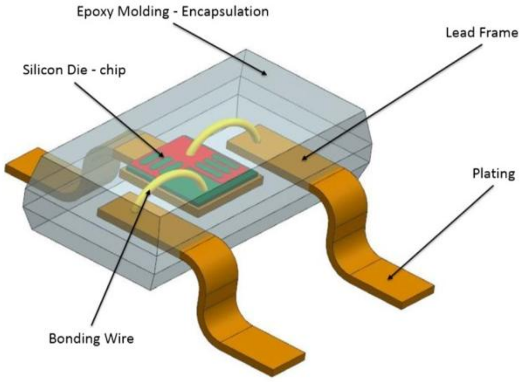

Fig. 2. Schematic view of the parts of a transistor SMD SOT23.

end-of-life phase were more relevant, it should be analyzed with primary data instead of using this EcoInvent's dataset.

3. Life cycle inventory

The aim of this article is to study the environmental impact created by different types of transistors and to examine the influence of their material composition.

To perform this study, the detailed material composition of several transistors have been obtained from manufacturers, including information of their constituent parts. These parts (lead frame, plating, bonding wire, encapsulation, silicon die) are shown in Fig. 2. As shown in the figure, a chip or die is bonded to the lead frame with bonding wires, while this chip is protected from the environment by the epoxy molding or the encapsulation (Vishay Electronic, 2014).

Material content datasheets that have been used to analyze the environmental impact of SMD SOT23 transistors were provided by manufacturers. The SMD type transistor dataset provided by EcoInvent has been analyzed, along with the calculated material composition of 11 different transistors. The results of material composition with respect to 1 g of transistor are shown in Table 1.

Table 1 also shows a detailed inventory of the material composition of each transistor. The quantity of some materials varies considerably from some suppliers to others. This is the case for gold, arsenic, chromium, silicon, titanium and silver. The EcoInvent transistor dataset does not include these elements despite them being present in most of the studied transistors. Additionally, there are materials that the EcoInvent dataset include that are not actually found in some of the studied transistors, such as cooper, epoxy resin, aluminum, iron or nickel.

Table 2 shows the studied transistors and the material inputs needed for manufacturing 1 g of each transistor. This allows us to calculate the amount of transistor used, not only considering 1 g of final transistor but also taking into account the complete raw materials inputs and the waste generation. The values have been calculated using the EcoInvent methodology, applying it to every manufacturer dataset. The life cycle inventory for each SMD transistor has been developed to compare these results with EcoInvent. In this way, the influence of the material composition on the environmental impact can be evaluated with more precision. The methodology used to develop the transistor LCAs by EcoInvent considers an input of raw material acquisition (RMA) of 5.80 g for each gram of transistor manufactured (a waste amount of 4.80 g unused raw material). However, transistors such as the SMBTA06 model require 3.35 g, and in BC817#2 transistors, the amount of material is higher, 6.25 g.

Table 3 shows the most relevant EcoInvent datasets that have been used to characterize the inputs of the transistors. These datasets have been selected following the EcoInvent guidelines (Hischier et al., 2007).

4. Results and discussion

After introducing the life cycle inventory in SimaPro, several results have been calculated with the aim of analyzing the environmental impact of all of the selected transistors. The influence of the material composition, production processes and end of life have been studied. Finally, a more detailed study of the environmental impact for three particular transistors is shown.

Table 1
Material composition for 1 g of studied SMD transistors.

Material (g)	EcoInvent	BC817#1	BC847B	BCR108	BCR533	BC847A	SMBTA06	BCX70J	FJV3110R	BC817#2	BC817-25	ZSOT23
Gold	0,00E+00	2,80E-03	1,96E-03	1,87E-03	3,38E-03	1,96E-03	3,43E-03	1,96E-03	2,29E-03	0,00E+00	2,10E-03	1,04E-02
Arsenic	0,00E+00	8,00E-06	3,00E-06	6,00E-06	1,50E-05	3,00E-06	1,40E-05	3,00E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Silicon chip	1,52E-02	6,71E-03	2,84E-03	4,86E-03	1,23E-02	2,84E-03	1,21E-02	2,84E-03	5,56E-03	1,06E-02	1,06E-02	3,70E-02
Chromium	0,00E+00	9,90E-04	9,33E-04	9,26E-04	9,96E-04	9,33E-04	9,96E-04	9,33E-04	0,00E+00	7,00E-04	7,00E-04	6,65E-04
Silicon metallurgical	0,00E+00	6,60E-05	6,20E-05	6,20E-05	6,60E-05	6,20E-05	6,60E-05	6,20E-05	8,17E-04	8,00E-04	8,00E-04	7,98E-04
Titanium	0,00E+00	3,30E-04	3,11E-04	3,09E-04	3,32E-04	3,11E-04	3,32E-04	3,11E-04	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Copper	4,58E-01	3,29E-01	3,10E-01	3,07E-01	3,30E-01	3,10E-01	3,30E-01	3,10E-01	0,00E+00	3,81E-02	3,70E-02	3,90E-02
Carbon black	0,00E+00	6,36E-03	6,56E-03	6,57E-03	1,00E-02	6,56E-03	1,00E-02	6,56E-03	6,96E-03	3,30E-03	2,00E-03	3,10E-03
Brominated resin	0,00E+00	9,54E-03	9,84E-03	9,85E-03	1,88E-02	9,84E-03	1,88E-02	9,84E-03	0,00E+00	1,60E-02	1,00E-04	5,00E-03
Antimonytrioxide	0,00E+00	1,27E-02	1,31E-02	1,31E-02	1,50E-02	1,31E-02	1,50E-02	1,31E-02	0,00E+00	0,00E+00	0,00E+00	1,54E-02
Epoxy resin	1,92E-01	1,37E-01	1,41E-01	1,41E-01	1,56E-01	1,41E-01	1,56E-01	1,41E-01	1,39E-01	9,52E-02	0,00E+00	7,76E-02
Silicon dioxide	2,88E-01	4,71E-01	4,85E-01	4,86E-01	4,25E-01	4,85E-01	4,25E-01	4,85E-01	5,50E-01	4,57E-01	4,50E-01	4,38E-01
Tin	2,04E-02	1,66E-02	1,70E-02	1,70E-02	1,50E-02	1,70E-02	1,50E-02	1,70E-02	2,37E-02	2,79E-02	2,79E-02	1,26E-02
Silver	0,00E+00	7,74E-03	1,13E-02	1,11E-02	1,21E-02	1,13E-02	1,21E-02	1,13E-02	9,53E-04	8,40E-03	8,40E-03	1,79E-02
Aluminum	2,65E-03	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,00E-04	3,00E-04	0,00E+00
Iron	1,31E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,53E-01	1,56E-01	1,56E-01	1,48E-01
Nickel	1,01E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,14E-01	1,18E-01	1,17E-01	1,12E-01
Cobalt	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,37E-03	1,40E-03	1,40E-03	2,66E-03
Manganese	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,18E-03	2,80E-03	2,80E-03	2,13E-03
Sulfur	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,00E-04	1,00E-04	0,00E+00
Formaldehyde	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	6,35E-02	1,25E-01	0,00E+00
Phenolic resin	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	5,71E-02	7,76E-02
Total	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00

Table 2
Calculated raw material acquisition inputs (in grams) of studied transistors and comparison with the data provided by EcoInvent.

Material (g)	EcoInvent	BC817#1	BC847B	BCR108	BCR533	BC847A	SMBTA06	BCX70J	FJV3110R	BC817#2	BC817-25	ZSOT23
Gold	0,00E+00	1,08E-02	8,11E-03	7,10E-03	1,17E-02	8,11E-03	1,20E-02	8,11E-03	1,05E-02	0,00E+00	9,66E-03	4,79E-02
Arsenic	0,00E+00	1,56E-05	5,83E-06	1,17E-05	2,92E-05	5,83E-06	2,72E-05	5,83E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Silicon chip	2,96E-02	1,30E-02	5,52E-03	9,45E-03	2,39E-02	5,52E-03	2,35E-02	5,52E-03	1,08E-02	2,06E-02	2,06E-02	7,20E-02
Chromium	0,00E+00	4,56E-03	4,29E-03	4,26E-03	4,58E-03	4,29E-03	4,58E-03	4,29E-03	0,00E+00	3,22E-03	3,22E-03	3,06E-03
Silicon metallurgical	0,00E+00	3,04E-04	2,85E-04	2,85E-04	3,04E-04	2,85E-04	3,04E-04	2,85E-04	3,76E-03	3,68E-03	3,68E-03	3,67E-03
Titanium	0,00E+00	1,52E-03	1,43E-03	1,42E-03	1,53E-03	1,43E-03	1,53E-03	1,43E-03	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Copper	2,11E+00	1,51E+00	1,42E+00	1,41E+00	1,52E+00	1,42E+00	1,52E+00	1,42E+00	0,00E+00	1,75E-01	1,70E-01	1,80E-01
Carbon black	0,00E+00	3,77E-02	3,89E-02	3,90E-02	5,94E-02	3,89E-02	1,95E-02	3,89E-02	1,35E-02	1,95E-02	1,17E-02	1,84E-02
Brominated resin	0,00E+00	5,66E-02	5,84E-02	5,85E-02	1,11E-01	5,84E-02	3,65E-02	5,84E-02	0,00E+00	9,48E-02	4,60E-04	2,97E-02
Antimonytrioxide	0,00E+00	7,55E-02	7,79E-02	7,79E-02	8,91E-02	7,79E-02	2,92E-02	7,79E-02	0,00E+00	0,00E+00	0,00E+00	9,15E-02
Epoxy resin	1,71E+00	8,12E-01	8,37E-01	8,38E-01	9,28E-01	8,37E-01	3,04E-01	8,37E-01	2,70E-01	5,65E-01	0,00E+00	4,60E-01
Silicon dioxide	1,14E+00	2,79E+00	2,88E+00	2,88E+00	2,52E+00	2,88E+00	8,27E-01	2,88E+00	1,07E+00	2,71E+00	2,67E+00	2,60E+00
Tin	6,97E-01	5,70E-01	5,80E-01	5,82E-01	5,14E-01	5,80E-01	5,14E-01	5,80E-01	8,10E-01	9,55E-01	9,55E-01	4,30E-01
Silver	0,00E+00	3,56E-02	5,20E-02	5,13E-02	5,56E-02	5,20E-02	5,56E-02	5,20E-02	4,38E-03	3,86E-02	3,86E-02	8,24E-02
Aluminum	1,22E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,38E-03	1,38E-03	0,00E+00
Iron	6,03E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	7,03E-01	7,19E-01	7,18E-01	6,81E-01
Nickel	4,64E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	5,26E-01	5,41E-01	5,41E-01	5,14E-01
Cobalt	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	6,29E-03	6,44E-03	6,44E-03	1,22E-02
Manganese	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,00E-02	1,29E-02	1,29E-02	9,79E-03
Sulfur	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	4,60E-04	4,60E-04	0,00E+00
Formaldehyde	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,77E-01	7,42E-01	0,00E+00
Phenolic resin	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,39E-01	4,60E-01
Total	5,80E+00	5,92E+00	5,97E+00	5,97E+00	5,84E+00	5,97E+00	3,35E+00	5,97E+00	3,44E+00	6,25E+00	6,25E+00	5,70E+00

Table 3
EcoInvent dataset selection for the main raw materials acquisition.

Material	Dataset
Gold	Gold {GLO}| market for | Alloc Def, U
Silicon chip	Silicon, electronics grade {GLO}| market for | Alloc Def, U
Chromium	Chromium {GLO}| market for | Alloc Def, U
Silicon metallurgical	Silicon, metallurgical grade {RoW}| production | Alloc Def, U
Copper	Copper {GLO}| market for | Alloc Def, U
Carbon black	Carbon black {GLO}| market for | Alloc Def, U
Epoxy resin	Epoxy resin, liquid {GLO}| market for | Alloc Def, U
Tin	Tin {GLO}| market for | Alloc Def, U
Silver	Silver {GLO}| market for | Alloc Def, U
Aluminum	Aluminum, wrought alloy {GLO}| market for | Alloc Def, U
Iron	Pig iron {GLO}| market for | Alloc Def, U
Nickel	Nickel, 99.5% {GLO}| market for | Alloc Def, U
Cobalt	Cobalt {GLO}| market for | Alloc Def, U
Manganese	Manganese {GLO}| market for | Alloc Def, U
Formaldehyde	Formaldehyde {GLO}| market for | Alloc Def, U
Phenolic resin	Phenolic resin {GLO}| market for | Alloc Def, U

4.1. Analysis of the environmental impact of all transistors

Table 4 shows the calculations of the environmental impacts of each transistor in relation to the different categories of impact. The presented results are the percentage of impact with respect to the values of the EcoInvent methodology, considering EcoInvent results as the benchmark 100%. In general, it can be said that the highest environmental impact is observed for the transistor ZSOT23. It can be seen that in all environmental categories, it creates the highest environmental impact, mainly because of its higher gold percentage in its material composition (see Tables 1 and 2). The large relevance of the use of gold is in line with the results of other studies about electronic products (Andrae and Andersen, 2011) (Nordelöf et al., 2014) (Whitehead et al., 2015). The impact of gold is mainly caused by the disposal of mine tailings containing sulfides. Gold is usually used in transistors when other materials can cause problems by current-induced ion migration (Industry, 2014). On the other hand, there is one transistor without gold content (BC817#2) that in some categories creates a lower environmental impact than the one calculated with the EcoInvent dataset.

The environmental impact created by the studied transistors in each environmental category is summarized as follows.

- The highest environmental impact for *abiotic depletion* is produced by the ZSOT23 transistor, almost 170 times higher than the EcoInvent dataset. The most significant impacts in this category are created by gold consumption; therefore the BC817#2 transistor has the lowest environmental impact investigated due to low gold consumption. In spite of that, its impact is 2.8 times higher than the EcoInvent dataset.

Table 4
Environmental impact of all studied transistors.

Impact category	Unit	EcoInvent		BC817#1	BC847B	BCR108	BCR533	BC847A	SMBTA06	BCX70J	FJV3110R	BC817#2	BC817-25	ZSOT23
Abiotic depletion	kg Sb eq	1,79E-05	100%	3910%	3060%	2720%	4310%	3060%	4400%	3060%	3690%	277%	3560%	16700%
Abiotic depletion (fossil fuels)	MJ	2,88E+00	100%	165%	149%	143%	1734%	150%	172%	149%	161%	102%	161%	403%
Global warming (GWP100y)	kg CO_2 eq	2,11E-01	100%	169%	153%	146%	177%	153%	173%	153%	162%	104%	165%	413%
Ozone layer depletion (ODP)	kg CFC-11 eq	1,28E-08	100%	160%	142%	136%	169%	142%	170%	142%	132%	73.2%	136%	389%
Human toxicity	kg 1,4-DB eq	3,10E-01	100%	1440%	1100%	974%	1560%	1100%	1590%	1100%	1340%	46.8%	1250%	6030%
Fresh water aquatic ecotox.	kg 1,4-DB eq	2,31E-01	100%	1440%	1100%	973%	1560%	1100%	1580%	1100%	1350%	53.8%	1260%	6030%
Marine aquatic ecotoxicity	kg 1,4-DB eq	7,45E+02	100%	1210%	934%	828%	1320%	934%	1340%	934%	1140%	57.3%	1060%	5040%
Terrestrial ecotoxicity	kg 1,4-DB eq	2,67E-04	100%	185%	163%	155%	195%	163%	195%	163%	192%	113%	190%	503%
Photochemical oxidation	kg C_2H_4 eq	1,04E-04	100%	123%	114%	110%	128%	114%	127%	114%	171%	148%	181%	305%
Acidification	kg SO_2 eq	2,87E-03	100%	152%	136%	129%	160%	136%	156%	136%	190%	137%	196%	428%
Eutrophication	kg PO_4− eq	1,01E-03	100%	12504%	960%	851%	1350%	960%	1380%	960%	1170%	54.9%	1090%	5190%

- *Abiotic depletion (fossil fuels) and global warming (GWP100y)* impacts are also higher in ZSOT23, followed by BCR533 and SMBTA06; all of them between 1.5 and 4.1 times higher than the EcoInvent transistor. These impacts are primarily a result of gold content and electricity consumption. Accordingly, BC817#2 has the low environmental impact in this category, similar to that of the EcoInvent dataset
- In the case of *ODP*, gold and electricity consumption generate the highest impact. The impact of transistor ZSOT23 is almost 3.9 times higher than the environmental impact provided by EcoInvent. Conversely, BC817#2 generates only 73.2% of the impact as that of the EcoInvent dataset.
- *Human toxicity* impact is mainly caused by gold, silver and electricity consumption. The ZSOT23 transistor relies heavily on all three and thus has a high environmental impact. In contrast, BC817#2 has the lowest value for this category, even lower than that of EcoInvent.
- For *fresh water aquatic ecotoxicity and marine aquatic ecotoxicity*, gold generates most of the environmental impact in both categories. As BC817#2 contains no gold, its environmental impact in these categories is the lowest of all, approximately 55% of the EcoInvent environmental impact.
- *Terrestrial ecotoxicity* once again is mainly caused by gold and electricity consumption. All of the transistors have higher values than EcoInvent in this category, from 113% for transistor BC817#2 up to 503% for transistor ZSOT23.
- *Photochemical oxidation and acidification* are mostly caused by gold, nickel and electricity consumption; in these categories, transistors BCR108 and ZSOT23 have the highest values of environmental impact.
- *Eutrophication effects* are mainly produced by the consumption of gold and nickel, and in this category BCR533 and SMBTA06 create an impact more than 13,5 times higher than EcoInvent but still lower than that of ZSOT23, which is 51,9 times higher.

After updating the EcoInvent data with manufacturers' information, Monte Carlo simulations were carried out. Although the absolute uncertainty of these results remains relatively high, due to the uncertainty in the original EcoInvent data, this relatively high uncertainty of LCA of integrated circuit packaging technologies was also shown by Andrae and Andersen (Andrae and Andersen, 2011). The people behind EcoInvent have been working on improving their uncertainty calculations and it will be updated with a refined empirical pedigree matrix in the following versions (Muller et al., 2014) (Ciroth et al., 2013).

4.2. Study of the life cycle stages of each transistor

To further analyze the environmental impact, the environmental impact of the three life cycle stages: A (Materials), B1 (Production) and D2 (End of Life) over the whole life cycle are shown in this subsection.

4.2.1. Environmental impact of raw materials acquisition

The importance of the material composition of each transistor in the environmental impact varies considerably. Table 5 presents the percentages of the environmental impacts of the input of materials (Stage A) over the whole life cycle (100%).

In the *abiotic depletion* category, the percentage of environmental impact created by materials is approximately 99.7%. However, in *abiotic depletion (fossil fuels)*, *global warming* and *terrestrial ecotoxicity*, the percentages are lower: they vary from almost 17.7% up to approximately 58.5%; remarkably, the value for transistor ZSOT23 exceeds 83.9%.

For *ODP*, *photochemical oxidation* and *acidification* the percentages of environmental impact created by the use of materials are lower than *abiotic depletion*, but higher than *abiotic depletion (fossil fuels)* or *global warming*. In *ODP* these values are between 27.2% for BC817#2 and 86.3% for ZSOT23. In *photochemical oxidation*, the percentages vary from 53.9% for the EcoInvent dataset up to 84.9% for the ZSOT23 dataset. The *acidification* category has similar values; they are between 58.3% for the EcoInvent dataset and 90.3% for the ZSOT23 dataset.

As previously mentioned, *human toxicity* is mainly caused by gold. Thus, transistors which contain gold (all the studied ones except EcoInvent and BC817#2) have high percentages, approximately 98.5% of the environmental impact of each transistor. In transistors without gold, these percentages are lower, such as that for transistor BC817#2, in which the environmental impact of materials is 54.8% of the total. Values for *fresh water aquatic ecotoxicity* and *marine ecotoxicity* categories are similar to *human toxicity*, as gold consumption generates most of the environmental impact in both categories.

Finally, the last environmental impact category *eutrophication*, also shows low percentages in BC817#2 and EcoInvent datasets due to the low consumption of gold and nickel, 44.6% and 69.6%, respectively.

4.2.2. Environmental impact of part production

Table 6 shows the results (as a percentage of the total impact) due to part production processes (Stage B1). The environmental impacts are usually lower than those due to material composition.

In *abiotic depletion*, the percentage of environmental impact created by processes are the lowest of all categories: less than 2.2% of environmental impact. The highest value comes from the EcoInvent dataset. In contrast, *abiotic depletion (fossil fuels)*, *global warming and terrestrial ecotoxicity* have higher values; they are between 16.1% in ZSOT23 and 82.0% in the EcoInvent dataset.

For *ODP*, *photochemical oxidation* and *acidification* the percentages of environmental impact are approximately 20–50% of the

Table 5
Percentage of environmental impact due to raw material acquisition.

Impact category	EcoInvent	BC817#1	BC847B	BCR108	BCR533	BC847A	SMBTA06	BCX70J	FJV3110R	BC817#2	BC817-25	ZSOT23
Abiotic depletion	97.8%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.2%	99.9%	99.9%
Abiotic depletion (fossil fuels)	18.9%	51.1%	45.7%	43.3%	53.3%	45.7%	52.8%	45.7%	49.6%	20.6%	49.8%	79.9%
Global warming (GWP100y)	17.7%	50.9%	45.5%	43.1%	53.1%	45.5%	53.7%	45.5%	50.5%	20.3%	49.6%	79.9%
Ozone layer depletion (ODP)	46.9%	66.9%	62.6%	60.8%	68.7%	62.6%	68.9%	62.6%	59.9%	27.2%	60.9%	86.3%
Human toxicity	79.0%	98.5%	98.1%	97.8%	98.6%	98.1%	98.7%	98.1%	98.5%	54.8%	98.3%	99.6%
Fresh water aquatic ecotox.	75.3%	98.3%	97.7%	97.4%	98.4%	97.7%	98.5%	97.7%	98.2%	53.5%	98.0%	99.6%
Marine aquatic ecotoxicity	66.3%	97.2%	96.4%	95.9%	97.4%	96.4%	97.5%	96.4%	97.1%	40.9%	96.8%	99.3%
Terrestrial ecotoxicity	19.0%	56.3%	50.4%	47.8%	58.5%	50.4%	58.5%	50.4%	58.0%	28.4%	57.5%	83.9%
Photochemical oxidation	53.9%	62.4%	59.5%	58.2%	64.0%	59.5%	63.7%	59.5%	73.1%	68.8%	74.5%	84.9%
Acidification	58.3%	72.6%	69.3%	67.7%	73.9%	69.3%	74.0%	69.3%	78.0%	69.4%	78.7%	90.3%
Eutrophication	69.6%	97.6%	96.8%	96.4%	97.8%	96.8%	97.8%	96.8%	97.4%	44.6%	97.2%	99.4%

Table 6
Percentage of environmental impact created due to part production.

Impact category	EcoInvent	BC817#1	BC847B	BCR108	BCR533	BC847A	SMBTA06	BCX70J	FJV3110R	BC817#2	BC817-25	ZSOT23
Abiotic depletion	2.15%	0.06%	0.07%	0.08%	0.05%	0.07%	0.05%	0.07%	0.06%	0.78%	0.060%	0.01%
Abiotic depletion (fossil fuels)	81.0%	48.9%	54.2%	56.6%	46.6%	54.2%	47.1%	54.2%	50.3%	79.2%	50.2%	20.1%
Global warming (GWP100y)	82.0%	49.0%	54.3%	56.7%	46.7%	54.3%	46.2%	54.3%	49.3%	79.5%	50.3%	20.0%
Ozone layer depletion (ODP)	52.9%	33.0%	37.3%	39.0%	31.2%	37.3%	31.0%	37.3%	39.9%	72.5%	39.0%	13.6%
Human toxicity	20.9%	1.46%	1.91%	2.16%	1.35%	1.91%	1.29%	1.91%	1.53%	45.0%	1.68%	0.35%
Fresh water aquatic ecotox.	23.9%	1.68%	2.20%	2.49%	1.55%	2.20%	1.46%	2.20%	1.72%	45.0%	1.93%	0.40%
Marine aquatic ecotoxicity	33.5%	2.77%	3.60%	4.06%	2.55%	3.60%	2.48%	3.60%	2.93%	58.7%	3.17%	0.67%
Terrestrial ecotoxicity	80.9%	43.6%	49.5%	52.1%	41.5%	49.5%	41.5%	49.5%	42.0%	71.6%	42.5%	16.1%
Photochemical oxidation	46.0%	37.5%	40.4%	41.7%	36.0%	40.4%	36.2%	40.4%	26.8%	31.1%	25.5%	15.1%
Acidification	41.6%	27.3%	30.7%	32.2%	26.0%	30.7%	26.0%	30.7%	21.9%	30.5%	21.3%	9.73%
Eutrophication	30.4%	2.44%	3.17%	3.57%	2.25%	3.17%	2.20%	3.17%	2.59%	55.4%	2.90%	0.59%

environmental impact; the values were also lower for the ZSOT23 transistor.

Human toxicity, fresh water aquatic ecotoxicity, marine ecotoxicity have low values of percentage of environmental impact from 0.4% up to 4.1% in all categories, except for the EcoInvent dataset and BC817#2, where environmental impact due to processing are higher: approximately 20% and 50%, respectively.

Eutrophication values are low. Most of the transistors have values of environmental impact lower than 3.6%. However, the EcoInvent dataset and transistor BC817#2 generate higher environmental impacts, 30.4% and 55.4%, respectively.

4.2.3. Environmental impact of end of life

The environmental impacts caused due to end of life treatments (Stage D2) are especially low, between 0% and 1.5% of the total environmental impact of all categories (data not shown). The contribution percentage of the end of life phase can be obtained subtracting to 100% the percentages of the other two LCA phases (RMA and PP). Additionally, typical values of the impacts of end of life in most categories calculated in this study are lower than 0.1%. Therefore, the EcoInvent dataset proxy used for the end of life has a low influence on the overall results.

4.3. Study of the environmental impact generation of three selected transistors

After analyzing the overall impact and the influence of each life cycle stage (A, B1 and D2), the impact generation of several transistors was analyzed and is detailed in this section. The results allow one to perform a sensitivity analysis on how material composition modifies the environmental impact.

Three different transistors have been selected: the ZSOT23, which has the highest gold content of the 12 analyzed transistors; the BC817-25, which has a material composition closest to the average material composition of all of the studied transistors; and the BC817#2, which is the transistor with an environmental impact closest to EcoInvent dataset, as it does not contain gold in its material composition.

4.3.1. Environmental impact of the ZSOT23 transistor

Table 7 shows how the environmental impact is generated for each category. Gold created between 53.8% of the impact in *photochemical oxidation* up to 98.9% in *human toxicity* thus producing most of the environmental impact of this transistor. The presence of nickel is especially relevant for *photochemical oxidation* and *acidification*. The following materials in terms of importance are tin, silver, and copper, but each has a minor (<2.7% each) influence on the overall results.

The contribution of the electricity consumption of the production processes achieves between 8,6 and 18.5% in *abiotic depletion (fossil fuels), global warming potential, ODP, terrestrial ecotoxicity, photochemical oxidation* and *acidification*. EcoInvent's assumption of an electronic component factory creates impact between 0.01% for *abiotic depletion* and up to 1.4% in *photochemical oxidation*.

4.3.2. Environmental impact of the BC817-25 transistor

The environmental impact generation for the BC817-25 transistors is shown in Table 8. In this case, gold generates between 18.3% of the impact in *photochemical oxidation* up to 96.2% in *human toxicity*. As with the previous transistor, the presence of nickel and tin is especially relevant for *photochemical oxidation* and *acidification*. Silver and copper have a minor influence on the results (<4.8% each).

The electricity consumption in the production processes creates between 18.9 and 46.1% in *abiotic depletion (fossil fuels), global warming potential, ODP, terrestrial ecotoxicity, photochemical oxidation* and *acidification*. EcoInvent's assumption of the electronic component factory generates between 0.05% *for abiotic depletion* and up to 3.0% in *ODP*.

Table 7
Detailed study of environmental impact of transistor ZSOT23.

Impact category	Gold	Electricity consumption	Nickel	Tin	Silver	Electronic component factory	Copper	Others	Total
Abiotic depletion	97.5%	0.001%	0.018%	0.273%	2.150%	0.012%	0.012%	0.001%	100%
Abiotic depletion (fossil fuels)	74.6%	18.5%	0.677%	1.090%	1.180%	0.794%	0.112%	3.08%	100%
Global warming (GWP100y)	74.8%	17.5%	0.756%	1.070%	1.43%	1.00%	0.105%	3.31%	100%
Ozone layer depletion (ODP)	80.0%	12.0%	0.565%	0.891%	1.76%	1.04%	0.832%	2.92%	100%
Human toxicity	98.9%	0.228%	0.146%	0.014%	0.259%	0.099%	0.108%	0.210%	100%
Fresh water aquatic ecotox.	98.9%	0.285%	0.203%	0.017%	0.239%	0.083%	0.102%	0.189%	100%
Marine aquatic ecotoxicity	98.6%	0.532%	0.149%	0.029%	0.259%	0.107%	0.105%	0.200%	100%
Terrestrial ecotoxicity	77.9%	14.9%	3.25%	0.82%	0.576%	0.613%	0.150%	1.76%	100%
Photochemical oxidation	53.8%	13.2%	23.3%	2.54%	2.61%	1.35%	0.919%	2.36%	100%
Acidification	69.8%	8.64%	15.2%	1.82%	2.00%	0.764%	0.750%	1.08%	100%
Eutrophication	98.7%	0.48%	0.118%	0.040%	0.273%	0.082%	0.106%	0.204%	100%

Table 8
Detailed study of the environmental impact of transistor BC817-25.

Impact category	Gold	Electricity consumption	Nickel	Tin	Silver	Electronic component factory	Copper	Others	Total
Abiotic depletion	92.2%	0.006%	0.090%	2.85%	4.73%	0.054%	0.053%	0.003%	100%
Abiotic depletion (fossil fuels)	37.6%	46.1%	1.78%	6.06%	1.38%	1.98%	0.266%	4.80%	100%
Global warming (GWP100y)	37.9%	44.0%	2.00%	5.96%	1.68%	2.52%	0.249%	5.70%	100%
Ozone layer depletion (ODP)	46.2%	34.3%	1.70%	5.70%	2.36%	2.96%	2.26%	4.62%	100%
Human toxicity	96.2%	1.10%	0.739%	0.145%	0.586%	0.48%	0.493%	0.279%	100%
Fresh water aquatic ecotox.	95.8%	1.37%	1.02%	0.181%	0.539%	0.40%	0.463%	0.238%	100%
Marine aquatic ecotoxicity	94.6%	2.53%	0.744%	0.303%	0.578%	0.51%	0.475%	0.221%	100%
Terrestrial ecotoxicity	41.5%	39.4%	9.04%	4.83%	0.713%	1.62%	0.375%	2.45%	100%
Photochemical oxidation	18.3%	22.2%	41.3%	9.54%	2.07%	2.27%	1.47%	2.74%	100%
Acidification	30.8%	18.9%	34.9%	8.83%	2.05%	1.67%	1.55%	1.35%	100%
Eutrophication	95.0%	2.3%	0.591%	0.423%	0.612%	0.391%	0.478%	0.198%	100%

Table 9
Detailed study of the environmental impact of transistor BC817#2.

Impact category	Gold	Electricity consumption	Nickel	Tin	Silver	Electronic component factory	Copper	Others	Total
Abiotic depletion	–	0.075%	1.160%	36.60%	60.73%	0.694%	0.706%	0.034%	100%
Abiotic depletion (fossil fuels)	–	72.9%	2.82%	9.57%	2.19%	3.14%	0.433%	8.94%	100%
Global warming (GWP100y)	–	69.7%	3.16%	9.44%	2.66%	3.99%	0.406%	10.7%	100%
Ozone layer depletion (ODP)	–	63.8%	3.17%	10.55%	4.40%	5.51%	4.33%	8.28%	100%
Human toxicity	–	29.4%	19.8%	3.89%	15.7%	12.80%	13.6%	4.73%	100%
Fresh water aquatic ecotox.	–	32.4%	24.3%	4.28%	12.8%	9.43%	11.3%	5.54%	100%
Marine aquatic ecotoxicity	–	47.0%	13.8%	5.63%	10.7%	9.49%	9.08%	4.24%	100%
Terrestrial ecotoxicity	–	66.4%	15.2%	8.15%	1.20%	2.73%	0.651%	5.61%	100%
Photochemical oxidation	–	27.2%	50.6%	11.7%	2.53%	2.78%	1.85%	3.41%	100%
Acidification	–	27.1%	50.1%	12.7%	2.95%	2.40%	2.30%	2.52%	100%
Eutrophication	–	45.7%	11.7%	8.38%	12.1%	7.75%	9.75%	4.61%	100%

4.3.3. Environmental impact of the BC817#2 transistor

Finally, the BC817#2 is analyzed, which is the one transistor in this study that does not contain gold in its material composition. As shown in Table 9, in this case, the electricity consumption of the production processes creates more than 60% of the environmental impact in four out of eleven categories and between 25% and 50% in the other six. As in other transistors, the consumption of nickel is relevant for *photochemical oxidation* and *acidification*; in this case creating 50% of the impact of these two categories. Silver and tin create a noteworthy impact in *abiotic depletion*, with values of 60.7% and 36.6%, respectively. The electronic component factory assumption and copper consumption also each generate nearly 10% of the total impact in *human toxicity, fresh water* and *marine aquatic ecotoxicity* and *eutrophication*.

5. Conclusions

The influence of the material composition on the environmental impact of different SMD SOT23 transistors has been analyzed. It has been found that the presence of some precious metals, especially gold, highly increases the environmental burden in most impact categories.

Using the EcoInvent SMD transistor as a reference, the overall impacts of the transistors vary from 0.48 times up to 167 times to that of the reference, primarily depending on the amount of gold content.

The consumption of gold and electricity generate most of the environmental impact in all of the studied categories. Although most transistors contain materials such as cobalt, chromium or silicon, which are considered as critical raw materials for the European Union, those do not create relevant environmental impacts for the studied transistors.

In general, RMA creates a higher impact than part production processes in most transistors and impact categories. Although this conclusion can also be obtained from the EcoInvent dataset, the relevance of RMA for the studied transistors is much higher, especially in abiotic depletion (fossil fuels), global warming (GWP100y) and terrestrial ecotoxicity environmental impact categories.

The assumed end-of-life treatments (Stage D2 according to ETSI TS 103 199 (ETSI, 2011)) create low environmental impacts (0–1.5% of the total impact) compared with the raw materials consumption (Stage A) and the production processes (Stage B1).

6. Outlook

This study has been performed with the information that is currently being made public by the manufacturers; therefore, the data that are available to analyze the impact of these electronic components. To further improve these comparisons, manufacturers should provide information about their production processes and waste generation.

To further improve the accuracy and robustness of these types of studies, the following future lines of research could be pursued.

- Recycling of raw material could be considered by the authors as a way to reduce the share of RMA, e.g., gold, in the life cycle.
- Including market data changes for materials to further improve the precision by means of the advanced attributional LCA method proposed by Andrae (Andrae, 2015). This method improves comparative LCA as real or future market changes can be taken into account and be used as a sensitivity check.

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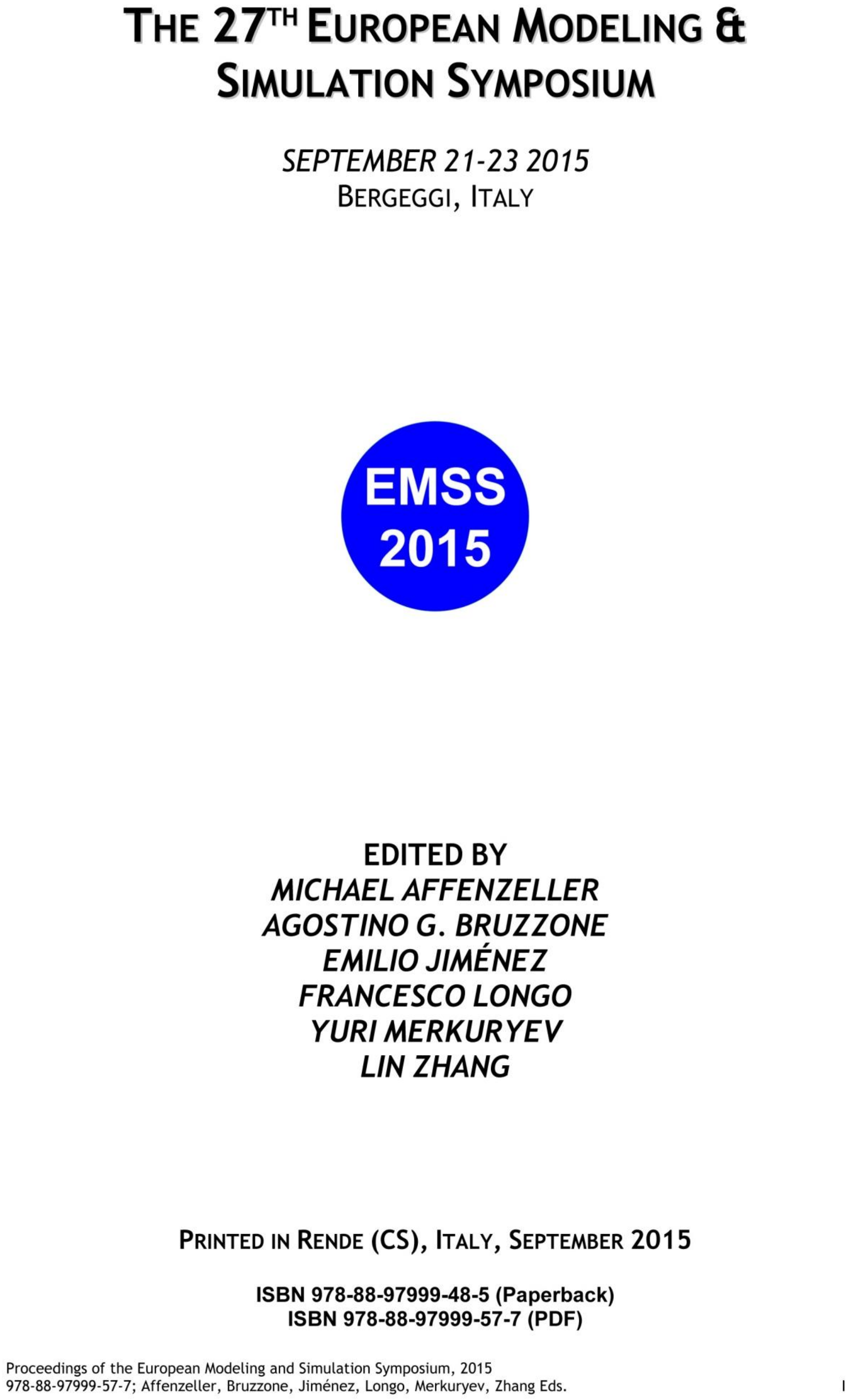

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ENVIRONMENTAL ASSESSMENT TOOL TO ANALYZE THE PRESENCE OF CRITICAL AND VALUABLE RAW MATERIALS

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ABSTRACT

The aim of this paper is to show the Software "Sustainable Electronics", developed in the University of Zaragoza as an environmental impact assessment tool, specially developed to design components taking into account the presence of critical and valuable raw materials consumption; simulating environmental impact and measuring the overall raw material consumption. It considers raw material obtaining, manufacturing processes, transports and end of life. This Software allow us to easily update and use the datasets provided by Life Cycle Inventory databases, like for example EcoInvent, developed by the Swiss Center for Life Cycle Inventories. The methodology has been tested through the software in an electronic board of a Touch Control of an induction hob, obtaining that there is a high consumption of materials such as copper, tin or aluminum.

Keywords: life cycle assessment, environmental impact simulation, methodology, critical materials.

1. INTRODUCTION

Companies and the society want to reduce the environmental impact of products and services. The concept of ecodesign began in the 1990s in order to produce more sustainable products.

In order to reducing the environmental impact of a product, methodologies and techniques such as Life Cycle Assessment (LCA) are the key, as they allow researchers to assess and reduce the impacts to the ecological environment. This tool has been used to model a wide range of products: from wind turbines (Martinez et al. 2009) (Martinez et al. 2015), electronic boards (Elduque et al. 2014) or induction hobs (Pina et al. 2015) to compost production (Leiva-Lazaro et al. 2014), food packaging (Fernández et al. 2013) or wine production (Jiménez et al. 2014).

Currently there is a large concern about the materials that affect environmental impact. Due to environmental risk, economic importance and supply risk, materials can be considered as critical (European Commission 2014). The concept of Critical Material emerged firstly in 1939 by the US Administration.

In 2010, the restriction on the exportation of neodymium in China caused a supply chain crisis, as result, prices increased by an order of magnitude (Sprecher et al. 2015)

Although nowadays, the methodology used to determine the criticality of a material is based in the combination of three main indicators (Chapman et al. 2013) (Binnemans et al. 2013) (Graedel & Nuss 2014):

- Economic vulnerability: the end of life recycling has to be taken into account and also the economic benefit that these raw materials have at the sectors in which them arise.
- Supply risk: this value arises from a combination of the stability in the production of the material in a specific country, the substitutability of the material and end-of-life recycling rates of the studied material.
- Ecological risk: this value is estimated taking into account similar criteria than supply risk, raw material country concentration, the ability to be substituted and the recyclability of the material

When calculating the criticality of a material, it is necessary to take into account that an increase in the demand of some materials, in a specific moment, involves a decrease in the demand of others, due to technological change; creating changes in risk indicators of these materials (European Commission 2010) (Achzet & Helbig 2013).

As Peck (Peck et al. 2015) points out, critical materials are "invisible", as they are normally alloyed with other materials. For this reason researchers are using LCA and Life Cycle Sustainability Assessment to systematically compile inventories of the consumption of resources (Mancini et al. 2015) (Sonnemann. et al. 2015). Environmental impact indicators for criticality are still currently being developed, as authors are developing several perspectives (Dewulf et al. 2015) (Glöser et al. 2015) (Rorbech et al. 2014) (Adibi et al. 2014)

The consumption of critical materials have been studied for products such as solar photovoltaics (Goe and

Gaustad 2014), bulbs (Lim et al. 2013) or iron alloys (Nuss et al. 2014).

Several authors have studied ways to reduce the overall consumption of critical materials, focusing specially on recycling (Rademaker et al. 2013) (Dhammika et al. 2014) (Eckelman et al. 2014), recovery (Gutierrez-Gutierrez et al. 2015) (Funari et al. 2014) (Hennebel et al. 2015) and also on reducing the consumption of raw critical materials in new products, such as permanent magnets (Mcguiness et al. 2015).

European Union laws have focused on reducing the environmental impact, by means of ecodesign (EuP 2005/32/CE) (European Parliament, 2005) (ErP 2009/125/CE) (European Parliament, 2009), chemical control and restriction of hazardous substances (REACH 1907/2006) (European Parliament, 2006) (RoHS 2002/95/CE) (European Parliament, 2003).

Applying a suitable ecodesign methodology is very interesting from an environmental point of view in electrical and electronic industry, improving all phases of electrical and electronic life cycle and analyzing the influence of material composition on the environmental impact (Gómez et al. 2015).

The aim of this paper is to show the Software "Sustainable Electronics", developed in the University of Zaragoza as an environmental impact assessment tool, specially designed to simulate environmental impact and to measure the overall raw material consumption, reducing the consumption of critical and valuable materials.

2. “SUSTAINABLE ELECTRONICS” ENVIRONMENTAL ASSESSMENT METHODOLOGY

Nowadays, most LCA models are carried out with professional databases such as EcoInvent one of the most used Life Cycle Inventory databases, developed by Swiss Centre for Life Cycle Inventories. However, these databases provide generic data that is not always adequate for specific products. Our methodology is based on a LCA model, which uses customized datasets to simulate the environmental impact and also quantifies the critical materials consumption.

2.1. General approach

The main goal of the methodology, shown in Figure 1, is to calculate the critical material consumption of an electrical or electronic component, simulating the environmental impact. For this reason, it is necessary to know all material compositions of all the parts in a component or product.

Once analyzed and compared the critical material composition of the components and also, of the products, the user decides the design of the component or the product depending on the life cycle of the component.

This methodology allows the user to compare different designs of the same component depending on the quantity of critical materials in the composition of the component. The user could choose the component with less critical or valuable raw material and also with less environmental impact.

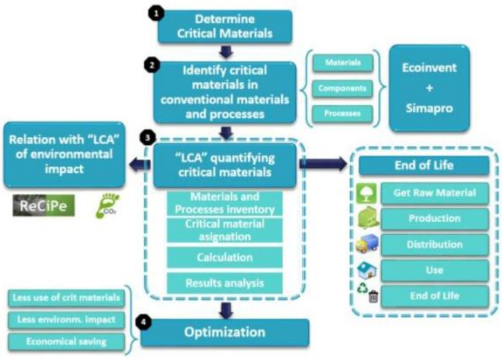


Figure 1: Methodology Diagram

2.1.1. Life Cycle stages

The software carries out environmental impact simulations by means of a LCA model that takes into account all the critical and valuable materials consumed in the life cycle. All the life cycle phases (Figure 2) of the component have to be taken into account, from getting raw materials to the end of life of the component. There will be processes that provide more critical materials consumption than others, affecting also the environmental impact simulation results.

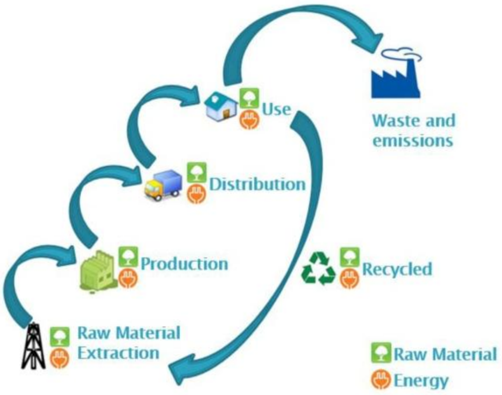


Figure 2: Life Cycle Stages

2.2. Environmental impact

The calculation methodology consist on an improved LCA adapted to critical materials, where the total amount of critical materials is obtained from the life cycle using the critical materials in raw materials of the components, critical and strategic materials in production and in distribution processes. Furthermore, the end of life phase is considered in the calculations of critical materials (Figure 3).

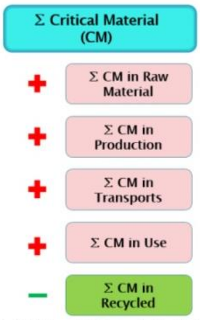


Figure 3: Critical Material Calculation

Also, the methodology considers different end of life scenarios to calculate the amount of critical materials and the environmental impact.

2.3. Results

The methodology can carry out the LCA model calculations and also take into account all the critical and valuable materials consumed in the life cycle.
Results should be clear and concise, in order to the user understand them. So that, the results would be:

- List of critical and strategic materials.
- Environmental impact simulation results.
- Summary of critical and strategic materials percentages.

In order to obtain proper results with this methodology, it is necessary to build a customized database structure that helps calculations. This methodology will be applied to the electrical and electronic field, so these are the components that should be considered for the particularization of the methodology in that field: materials, boards, components, connections and processes.

3. "SUSTAINABLE ELECTRONICS" SOFTWARE

This methodology has been implemented by means of a software tool, named "Sustainable Electronics". This tool has the aim of calculate the critical materials content and simulate the environmental impact of electrical and electronics devices.

The structure of this software is divided in three blocks, which are: New Project/ Load Project, Databases and also Results (Figure 4), where the user could evaluate quantity of critical materials and environmental impact.

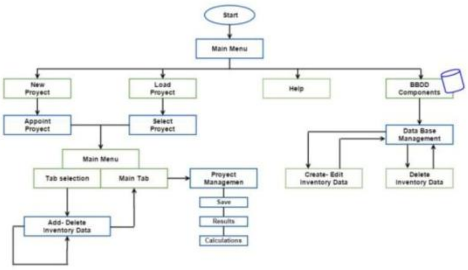


Figure 4: Software Structure

This structure of the software is represented in the main screen of the program (Figure 5).

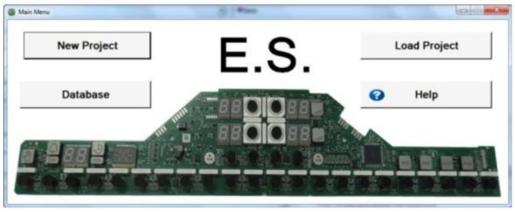
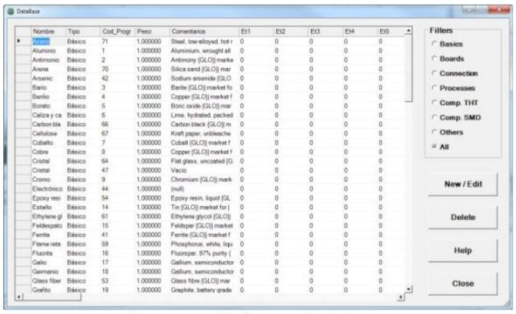


Figure 5: Main Screen of the Software

3.1. Database (LCA model inputs)

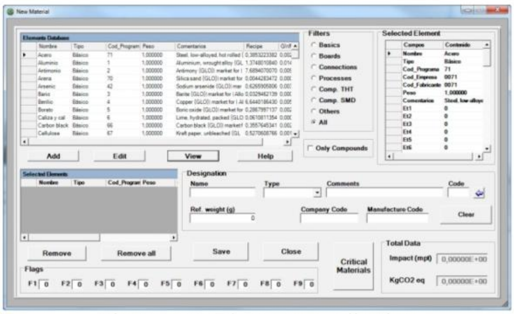
Selecting "Database" button from the main screen, the software shows the complete database (Figure 6). Navigating in this screen the user can filter and also manage the database, creating, editing and deleting inventory data.



Nombre	Tipo	Cod_Progr	Peso	Comentarios	Et1	Et2	Et3	Et4	Et5
[illegible]	Básico	71	1.000000	Steel, low-alloyed, hot r	0	0	0	0	0
Aluminio	Básico	1	1.000000	Aluminium, wrought all	0	0	0	0	0
Antimonio	Básico	2	1.000000	Antimony {GLO}| marke	0	0	0	0	0
Arena	Básico	70	1.000000	Silica sand {GLO}| mar	0	0	0	0	0
Arsenic	Básico	42	1.000000	Sodium arsenide {GLO	0	0	0	0	0
Bario	Básico	3	1.000000	Barite {GLO}| market fo	0	0	0	0	0
Berilio	Básico	4	1.000000	Copper {GLO}| market f	0	0	0	0	0
Borato	Básico	5	1.000000	Boric oxide {GLO}| mar	0	0	0	0	0
Caliza y ca	Básico	6	1.000000	Lime, hydrated, packed	0	0	0	0	0
Carbon bla	Básico	66	1.000000	Carbon black {GLO}| m	0	0	0	0	0
Cellulose	Básico	67	1.000000	Kraft paper, unbleache	0	0	0	0	0
Cobalto	Básico	7	1.000000	Cobalt {GLO}| market f	0	0	0	0	0
Cobre	Básico	8	1.000000	Copper {GLO}| market f	0	0	0	0	0
Cristal	Básico	64	1.000000	Flat glass, uncoated {G	0	0	0	0	0
Cristal	Básico	47	1.000000	Vacio	0	0	0	0	0
Cromo	Básico	9	1.000000	Chromium {GLO}| mark	0	0	0	0	0
Electrónico	Básico	44	1.000000	(null)	0	0	0	0	0
Epoxy resi	Básico	54	1.000000	Epoxy resin, liquid {GL	0	0	0	0	0
Estaño	Básico	14	1.000000	Tin {GLO}| market for |	0	0	0	0	0
Ethylene gl	Básico	61	1.000000	Ethylene glycol {GLO}|	0	0	0	0	0
Feldespato	Básico	15	1.000000	Feldspar {GLO}| market	0	0	0	0	0
Ferrita	Básico	41	1.000000	Ferrite {GLO}| market f	0	0	0	0	0
Flame reta	Básico	59	1.000000	Phosphorus, white, liqu	0	0	0	0	0
Fluorita	Básico	16	1.000000	Fluorspar, 97% purity {	0	0	0	0	0
Galio	Básico	17	1.000000	Gallium, semiconductor	0	0	0	0	0
Germanio	Básico	18	1.000000	Gallium, semiconductor	0	0	0	0	0
Glass fiber	Básico	53	1.000000	Glass fibre {GLO}| mar	0	0	0	0	0
Grafito	Básico	19	1.000000	Graphite, battery grade	0	0	0	0	0

Figure 6: Software Database

After customizing the database, the software allows to select the required components, in order to create the inventory (Figure 7). For an electronic board, the researcher can select between components, boards, production processes and also connections and other elements thanks to the previous work and research that have been performed in order to create the database.



Ref. weight (g): 0

Impact (mpt): 0,00000E+00

KgCO2 eq: 0,00000E+00

F1 0 F2 0 F3 0 F4 0 F5 0 F6 0 F7 0 F8 0 F9 0

Figure 7: Database Personalization

3.2. Software development

"Sustainable Electronics" software allows researchers and engineers to analyzing different design alternatives in order to reduce the impact to the ecological environment and diminish the use of critical raw materials, showing the overall quantity of critical and valuable raw materials in each component, process, board or connection.

Users can take design decisions taking into account critical materials and according to the environmental impact.

Figure 8 shows "New Project" and "Load Project" options, where there are several tabs such as Project, components, Processes, Boards and Connections and others, the user can navigate through them creating its own project.

Name: TOUCH.txt

Date: 05/05/2015

Description: Touch control

Impact (mpt): 2,31585E+06

KgCO2 eq: 1,65765E+04

Total weight (gr): 3,93190E+01

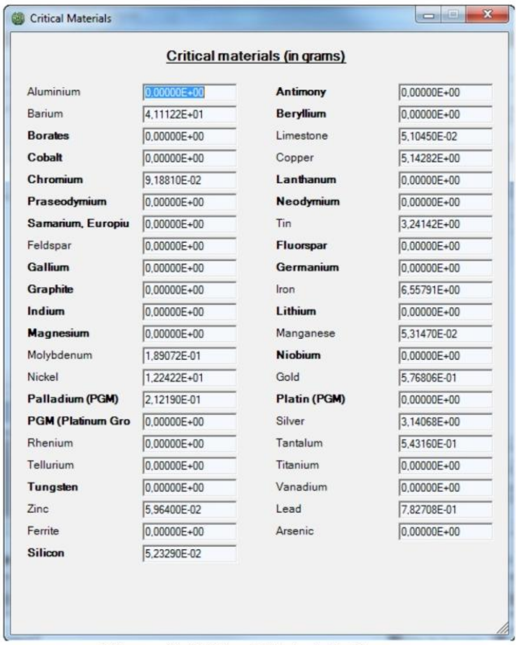
Nombre	Comentarios	Recipe	GWP	CRM1
Por peso UE	Used industrial electronic	0,01827192	0,00028284	(null)
Por pesochi	Used industrial electronic	0,03299016	0,00042266	(null)

	Impact (mpt)	KgCO2 eq
+ WO EoL	2,31585E+06	1,65765E+04
EoL	7,18434E-01	1,11212E-02
Total	2,31585E+06	1,65765E+04

Figure 8: Project Screen

All of these screens are prepared for add easily data from the inventory to the project. Once data is added, in Project screen the results could be calculated and viewed by users. In panel "Total data" appears environmental impact and also, pressing "Critical Materials" bottom, critical materials window is shown (Figure 9), where the user can see the quantities of critical and strategic materials.

These screen shows 43 critical and strategic materials, where 22, marked in bold letters, are considered by the latest EU report as critical (Commission 2014).



Critical materials (in grams)

Aluminium	0,00000E+00	**Antimony**	0,00000E+00
Barium	4,11122E+01	**Beryllium**	0,00000E+00
Borates	0,00000E+00	Limestone	5,10450E-02
Cobalt	0,00000E+00	Copper	5,14282E+00
Chromium	9,18810E-02	**Lanthanum**	0,00000E+00
Praseodymium	0,00000E+00	**Neodymium**	0,00000E+00
Samarium, Europiu	0,00000E+00	Tin	3,24142E+00
Feldspar	0,00000E+00	**Fluorspar**	0,00000E+00
Gallium	0,00000E+00	**Germanium**	0,00000E+00
Graphite	0,00000E+00	Iron	6,55791E+00
Indium	0,00000E+00	**Lithium**	0,00000E+00
Magnesium	0,00000E+00	Manganese	5,31470E-02
Molybdenum	1,89072E-01	**Niobium**	0,00000E+00
Nickel	1,22422E+01	Gold	5,76806E-01
Palladium (PGM)	2,12190E-01	**Platin (PGM)**	0,00000E+00
PGM (Platinum Gro	0,00000E+00	Silver	3,14068E+00
Rhenium	0,00000E+00	Tantalum	5,43160E-01
Tellurium	0,00000E+00	Titanium	0,00000E+00
Tungsten	0,00000E+00	Vanadium	0,00000E+00
Zinc	5,96400E-02	Lead	7,82708E-01
Ferrite	0,00000E+00	Arsenic	0,00000E+00
Silicon	5,23290E-02		

Figure 9: Critical Materials Screen

4. SOFTWARE APPLICATION

The main goal of the software application is to show the methodology and the software, and at the same time, verify the performance of the tool.

4.1. Touch Control

As previously mention, this implementation will be carried out in the field of electronics, specifically the tool is used to calculate critical materials content and simulate the environmental impact in a Touch Control device, shown in Figure 10.

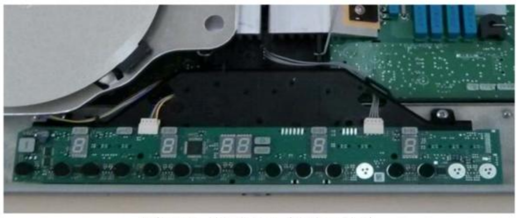


Figure 10: Touch Control

It is an electronic control board, called "Touch Control", used in induction hobs.

4.1.1. Touch Control Inventory

The inventory for this application consists on data related to electronics, such as capacitors, resistors, diodes, transistors and so on, boards and processes as welding SMD technology.

All of the inventory used in this software application, shown in table 1, has been obtained from the manufacturer of the touch control and desoldering the electronic components. Also manufacturer's datasheets of the components have been used in order to consider the exact composition of the components of the studied case, the touch control of an induction hob, following the same methodology shown in (Gómez, et al., 2015).

TOUCH CONTROL INDUCTION HOB			
Name	**Material**	**Units**	**Weight per unit (g)**
Small plastic parts	Nylon 6	7	0,199
Foam cylinders	Polyurethane, flexible foam	13	0,311
Ceramic capacitors SMD	Capacitor, for surface-mounting	52	0,0053
SMD0603 resistor	Resistor, surface-mounted	79	0,0019
Diode BAV 99	Diode, glass-, for surface-mounting	6	0,009
Tantalum capacitor	Capacitor, tantalum	1	0,237
Logical IC	Integrated circuit, logic type	5	0,102
Memory IC	Integrated circuit, memory type	2	0,057
Resonator	Resonator CPM SMD	1	0,013
7-segmentos displays	7 Segment display	6	0,75
LEDS	Light emitting diode	9	0,0015
PCB	Printed wiring board	1	37,995
Welding SMD Technology	Mounting, surface mount technology	1	0,9355

Table 1: Summarized Touch Control Inventory

Once the inventory is completed, elements that are not in the database of the software should be introduced in the tool from "New/Edit Database" option (Figure 11). Weight of each component has to be introduced in the software every time that user wants to introduce a new component in database

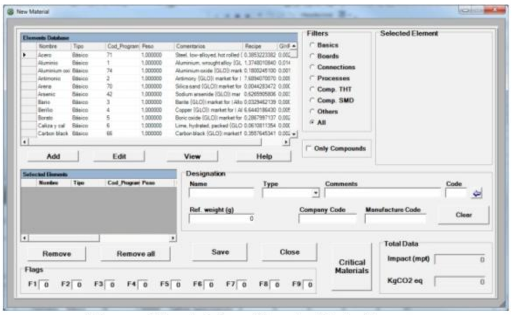
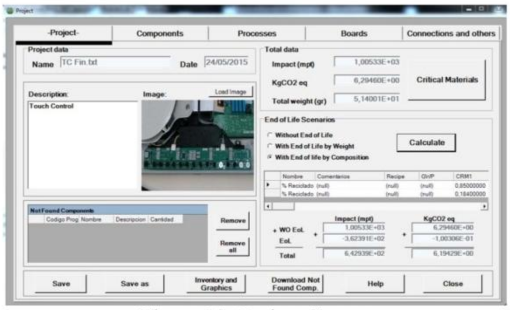


Figure 11: Add or Create Data Screen

After all the inventory of the project has been created, the next step is create the application case. For that, it is necessary to access to "New Project" (Figure 12), where appears the main menu and it is compulsory named the project.



Name: TC Fin.txt
Date: 24/05/2015
Description: Touch Control
Impact (mpt): 1,00533E+03
KgCO2 eq: 6,29460E+00
Total weight (gr): 5,14001E+01

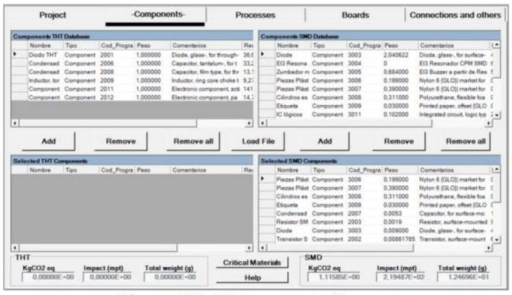
○ Without End of Life
○ With End of Life by Weight
● With End of life by Composition

Nombre	Comentarios	Recipe	GWP	CRM1
% Reciclado	(null)	(null)	(null)	0,85000000
% Reciclado	(null)	(null)	(null)	0,18400000

	Impact (mpt)	KgCO2 eq
+ WO EoL	1,00533E+03	6,29460E+00
EoL	-3,62391E+02	-1,00306E-01
Total	6,42939E+02	6,19429E+00

Figure 12: Project Screen

Browsing in tabs Project, Components, Processes, Boards, Connections and Others, data from the inventory should be introduced. Depending on the type of data it will be added in ones or in others (Figure 13).



THT: KgCO2 eq 0,00000E+00; Impact (mpt) 0,00000E+00; Total weight (g) 0,00000E+00

SMD: KgCO2 eq 1,11585E+00; Impact (mpt) 2,19487E+02; Total weight (g) 1,24696E+01

Figure 13: Components Screen

4.1.2. Touch Control Case Results

Afterwards, once the project is completed, "Project" screen gives tool's options for calculate both critical materials and environmental impact.

"Sustainable Electronics" enables apply several end of life scenarios, such as end of life by composition or by weight. The results simulated by the software show an environmental impact measurement in Recipe of 642.9 mPt and of 6.19 Kg eq. CO_2 in Carbon Footprint.

The PWB creates most of the environmental impact, followed by the SMD components. Although these components have a low overall weight, they generate a significant amount of impact and critical material consumption.

Table 2 shows the consumption of critical and strategic materials in the studied Touch Control. The quantity of copper is the highest, mostly due to its use in the Printing Wiring Board, followed by Tin, used in components soldering, and Aluminium, which is used mainly in the buzzer.

Material	Consumption (g)
Copper	34,93585
Tin	0,981889
Aluminium	0,526671
Barium	0,218226
Tantalum	0,128728
Silver	0,089304
Nickel	0,086837
Iron	0,065517
Lead	0,025029
Manganese	0,012595
Molybdenum	0,01047
Gold	0,009901
Zinc	0,005100
Feldspar	0,004296
Limestone	0,001060
Silicon	0,000934
Palladium (PGM)	0,000666
Chromium	0,000192

Table 2: Overall Material Consumption

Furthermore, there is an option in the software that allows to stand out materials with a high consumption, either global consumption or in percentage. It can be really useful for future regulations, also could be implemented to adapt the software to the legislation.

Table 3 shows critical and strategic material consumption of SMD components. These are essential because, although SMD components have slight weight, the total consumption of critical and strategic material and the environmental impact is really important.

The value of Copper consumption is the highest in SMD components, followed by Aluminium, Barium and in fourth place Tantalum.

Material	Consumption (g)
Copper	1,427462
Aluminium	0,526671
Barium	0,218226
Tantalum	0,128728
Nickel	0,077808
Iron	0,065517
Tin	0,055989
Silver	0,046820
Lead	0,025029
Manganese	0,012595
Molybdenum	0,010472
Gold	0,008097
Zinc	0,005100
Feldspar	0,004296
Limestone	0,001060
Silicon	0,000934
Palladium (PGM)	0,000666
Chromium	0,000192

Table 3: SMD Components Material Consumption

After analyzing the environmental impact and the overall critical and strategic material consumption, several conclusions can be reached. For example, there are several materials with economic importance, such as gold and silver. Gold, with a consumption of 0,0099 grams, was used mostly in integrated circuits and transistors whereas Silver, with 0,0089 grams, was used in soldering processes. On the other hand, there are also materials that present supply risk, such as Palladium and Chromium, which are used in SMD resistors.

5. CONCLUSIONS

The software SE (Sustainable Electronics), developed in Visual Basic .NET, allows the user to quantify the critical and strategic materials associated with the design of a component, also the user can simulate the environmental impact. The user interface makes easy for the user to compare between different components design, making material selection easier.

Although it has been developed for electrical and electronic components, it could be adapted to other sectors easily.

The simulation of the environmental impact of an induction hob delivers an environmental impact result of 642.9 mPt in Recipe and 6.19 Kg eq. CO_2 in Carbon Footprint. Furthermore, the consumption of Copper, Tin and Aluminium supposes a significant amount of environmental impact and material consumption.

This analysis can be used to generate new ecodesign proposals, changing critical components by others with less critical material consumption. For example, the substitution of SMD transistors for components without gold content, such as the ones offered by several electronic components suppliers, would decrease the environmental impact, and also reduce cost and supply risk.

All these results can be achieved thanks to the modeling and simulation of the environmental impact carried out in this study. This approach will allow companies to reduce supply risk, environmental impact and costs.

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9.3. International Journal of Service and Computing Oriented Manufacturing: Environmental Assessment Tool to analyze the presence of Critical and Valuable Raw Materials.

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Environmental assessment tool to analyse the presence of critical and valuable raw materials

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Abstract: The aim of this paper is show the software 'Sustainable Electronics' (SE), developed in the University of Zaragoza as an environmental impact assessment tool, specially developed to design components taking into account the presence of critical and valuable raw materials consumption; simulating environmental impact and measuring the overall raw material consumption, taking into account material composition of the electronic components. It considers raw material acquisition, manufacturing processes, transports and end of life. This software allows us to easily update and use the datasets provided by Life Cycle Inventory databases, such as, for example, EcoInvent, developed by the Swiss Centre for Life Cycle Inventories. The methodology has been tested through the software in an electronic board of a touch control used in an induction hob. As result, it has been obtained that there is a high consumption of materials such as copper, tin or aluminium.

Keywords: life cycle assessment; LCA; environmental impact simulation; methodology; critical materials; material composition.

Reference to this paper should be made as follows: Bachiller Gómez, P., Pina, C., Elduque, D., Clavería, I., Javierre, C. and Sarasa, J. (2016) 'Environmental assessment tool to analyse the presence of critical and valuable raw materials', *Int. J. Service and Computing Oriented Manufacturing*, Vol. 2, Nos. 3/4, pp.205–225.

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Judith Sarasa is a Professor of Environmental Technologies at the University of Zaragoza since 2003. She received her PhD in 1997 at the University of Zaragoza. After that, she received a Post-PhD grant of seven months in the Washington State University from the NATO Scientific Committee. Her research interests include water treatment, waste management and pollution prevention, publishing papers on the study of the degradation of chlorpyriphos in water, the control of plasticizers in drinking water, effluents and surface waters, or the study of the bio disintegration of a bioplastic material waste.

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1 Introduction

Nowadays, companies and the society are truthfully concern on reducing the environmental impact of products and services. The concept of eco design began in the 1990s in order to produce more sustainable products and also with the purpose of prevention in the design instead of correction afterwards. Focused on the design stage, material selection takes an important role on the environmental performance, as it affects the whole product life cycle, from raw material acquisition to the end of life of the product.

In order to reduce the environmental impact of a product, methodologies and techniques such as life cycle assessment (LCA) allow researchers to assess and reduce the impacts to the ecological environment. LCA is a 'cradle to grave' method to analyse the environmental impact of products or processes (Guinée, 2002; U.S. EPA, 2006); allowing to evaluate the environmental impact throughout the life cycle by means of ISO 14040 standards (International Standard Organization, 2006). This tool has been used to model a wide range of products: from wind turbines (Martínez et al., 2009, 2015), electronic boards (Elduque et al., 2014) or induction hobs (Pina et al., 2015) to compost production (Leiva-Lazaro et al., 2014), food packaging (Fernández et al., 2013) or wine production (Jiménez et al., 2014).

Currently, in the electronic industry there is a large concern about the materials that affect environmental impact and it is considered important to measure the environmental impact of a component considering the influence of the material composition. The composition of an electronic component must be analysed taking also into account the presence of critical raw materials.

The criticality of a material is determined by means of the environmental risk, economic importance and supply risk (European Commission, 2014). Firstly, the concept of critical material emerged in 1939 by the US Administration. But when determining the criticality of a material is necessary to consider that the demand of materials is volatile in time.

With technological change, an increase in the demand of some materials in a specific moment supposes the decrease of others, creating changes in risk indicators of these materials (European Commission, 2010; Achzet and Helbig, 2013). For example, in 2010, the restrictions on the exportation of neodymium in China caused a global supply chain crisis, as a result, prices increased by one order of magnitude (Sprecher et al., 2015).

Nowadays the methodology used to determine the criticality of a material is based in the combination of three main indicators (Chapman et al., 2013; Binnemans et al., 2013; Graedel and Nuss, 2014):

- economic vulnerability: the end of life recycling has to be taken into account and also the economic benefit that these raw materials have at the sectors in which them arise
- supply risk: this value arises from a combination of the stability in the production of the material in a specific country, the substitutability of the material and end-of-life recycling rates of the studied material
- ecological risk: this value is estimated taking into account similar criteria than supply risk, raw material country concentration, the ability to be substituted and the recyclability of the material.

As Peck points out (Peck et al., 2015), critical materials are 'invisible' as they are normally alloyed with other materials. For this reason, researchers are using LCA and life cycle sustainability assessment to systematically compile inventories of the consumption of resources (Mancini et al., 2015; Sonnemann et al., 2015). Environmental impact indicators for criticality are still currently being developed, as authors are developing several perspectives (Dewulf et al., 2015; Glöser et al., 2015; Rorbech et al., 2014; Adibi et al., 2014). The consumption of critical materials has been studied for products such as solar photovoltaics (Goe and Gaustad, 2014), bulbs (Lim et al., 2013) or iron alloys (Nuss et al., 2014).

Currently, there is a huge increase in the demand of electronic devices, due to their cheap prices and high efficiency. This demand supposes the generation of huge quantities of waste of electrical and electronic equipment (WEEE) and consequently, the European Union has introduced several laws as the WEEE Directive (European Parliament, 2012) with the purpose of reduce waste production, or energy-using products (EuP 2005/32/CE) (European Parliament, 2005) and energy-related products laws (ErP2009/125/CE) (European Parliament, 2009) to protect the environment by means of eco design. Furthermore, European Union laws have focused on reducing the environmental impact, by means of chemical control and restriction of hazardous substances (REACH 1907/2006) (European Parliament, 2006) (RoHS 2002/95/CE) (European Parliament, 2003).

Several authors have studied ways to reduce the overall consumption of critical materials, focusing specially on recycling (Rademaker et al., 2013; Dhammika Bandara et al., 2014; Eckelman et al., 2014), recovery (Gutierrez-Gutierrez et al., 2015; Funari et al., 2014; Hennebel et al., 2015) and also on reducing the consumption of raw critical materials in new products, such as permanent magnets (Mcguiness et al., 2015).

From an environmental point of view, the application of a suitable eco design methodology is very interesting in the electrical and electronic industry, improving all phases of the product's life cycle and analysing the influence of material composition on the environmental impact (Gómez et al., 2015).

The aim of this paper is to show the software 'Sustainable Electronics', developed in the University of Zaragoza as an environmental impact assessment tool, specially designed to simulate environmental impact and to measure the overall raw material consumption, allowing researchers to reduce the consumption of critical and valuable materials.

2 'Sustainable Electronics' environmental assessment methodology

Nowadays, most LCA models are carried out with professional databases such as EcoInvent, which is one of the most used Life Cycle Inventory databases, developed by Swiss Centre for Life Cycle Inventories. However, these databases provide generic data that are not always adequate for specific products. Our methodology is based on a LCA model, which uses customised datasets to simulate the environmental impact and also quantify the critical materials consumption.

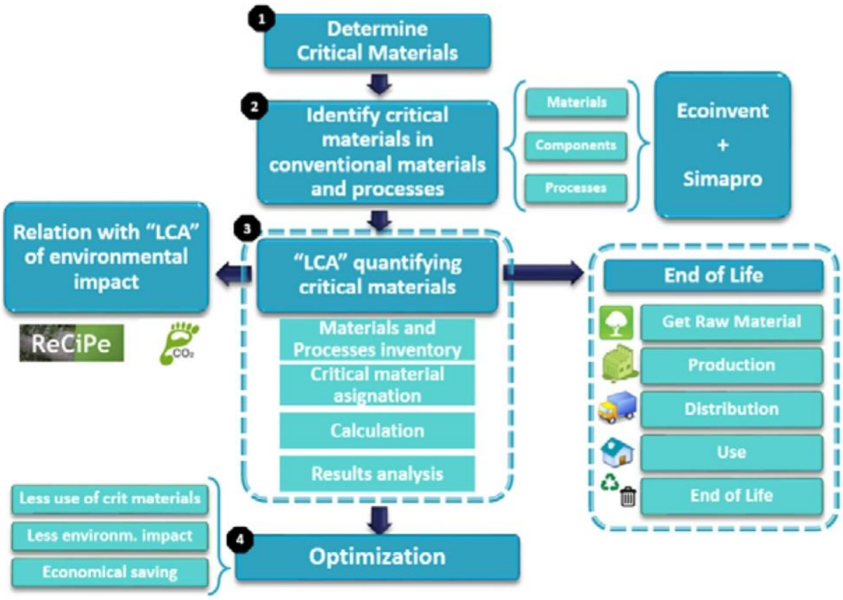
2.1 General approach

The main goal of the methodology, shown in Figure 1, is to calculate the critical material consumption of an electrical or electronic component, simulating the environmental impact. For this reason, it is necessary to know all material compositions of all the parts in a component or product.

Once analysed and compared the critical material composition of the components and also, of the products, the user decides the design of the component or the product depending on the life cycle of the component.

This methodology allows the user to compare different designs of the same component depending on the quantity of critical materials in the composition of the component. The user could choose the component with less critical or valuable raw material and also with less environmental impact.

Figure 1 Methodology diagram (see online version for colours)



2.2 *Life cycle stages*

The software carries out environmental impact simulations by means of a LCA model that takes into account all the critical and valuable materials consumed in the life cycle. All the life cycle phases (Figure 2) of the component have to be taken into account, from getting raw materials to the end of life of the component.

Figure 2 Life cycle stages (see online version for colours)

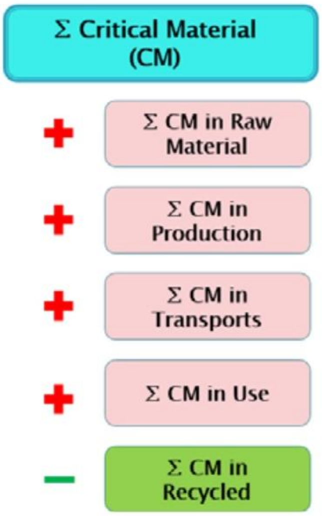
Raw material extraction, directly associated with material composition and also with the presence of critical materials, is the beginning of the life cycle of a product, followed by production process and distribution stage, where must be considered all energetic consumption and raw materials. Finally, use phase and the end of life of the component, where in the last one, it has been considered two treatments, recycling and land filling. By mean of recycling treatment, the component is transformed into raw material after the end uses.

There will be processes that have more critical materials consumption than others, affecting also the environmental impact simulation results, so all of the processes must be taken into account.

2.3 *Environmental impact*

The calculation methodology consists of an improved LCA adjusted to critical materials, where the total amount of critical materials is obtained from the life cycle using the critical materials in raw materials of the components, critical and strategic materials in production and in distribution processes. Furthermore, the end of life phase is considered in the calculations of critical materials (Figure 3).

Figure 3 Critical material calculation (see online version for colours)



The methodology considers different end of life scenarios to calculate the amount of critical materials and the environmental impact.

Also, the LCA has been calculated with ReCiPe Endpoint methodology and IPCC 2013 method. The first one, ReCiPe has been developed as an endpoint attempt to align the CML 2002 midpoint and Eco-indicator99 systems, while IPCC 2013 is an update of the method that lists the climate change with a timeframe of 20, 100 and 500 years (Goedkoop et al., 2013).

2.4 Results

The methodology can carry out the LCA model calculations, taking into account all the critical and valuable materials consumed in the life cycle.

Results should be clear and concise, in order to help the user to understand them. So that, the results would be:

- list of critical and strategic materials
- environmental impact simulation results
- summary of critical and strategic materials percentages.

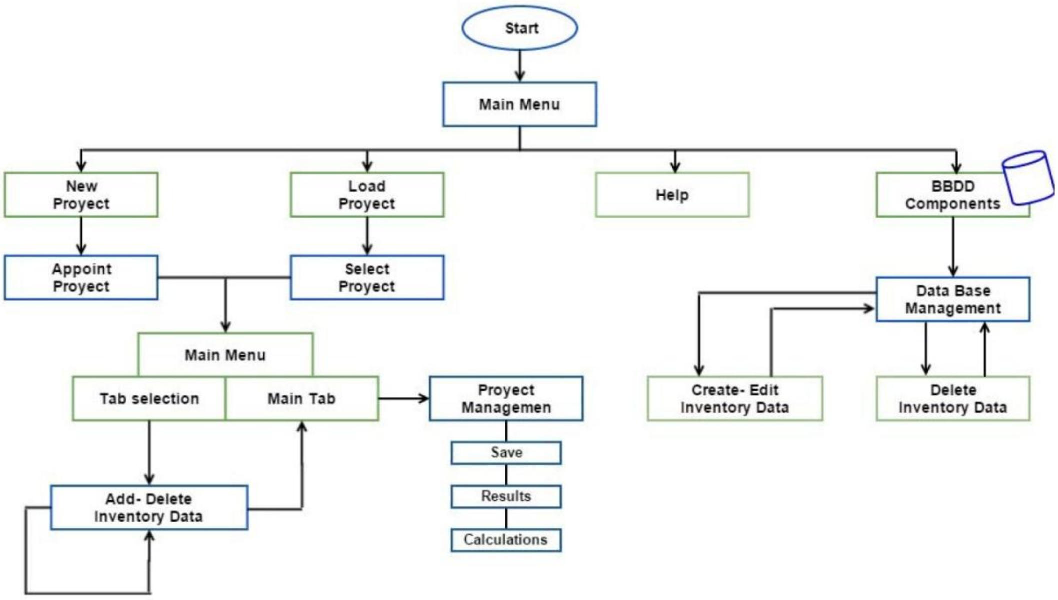
In order to obtain appropriate results with this methodology, it is necessary to build a customised database structure that helps calculations. As this methodology will be applied to the electrical and electronic field, these are the components that should be considered for the particularisation of the methodology in that field: materials, boards, components, connections and processes.

3 ‘Sustainable Electronics’ software

This methodology has been implemented by means of a software tool, named ‘Sustainable Electronics’. This tool has the aim of calculate the critical materials content and simulate the environmental impact of electrical and electronics devices.

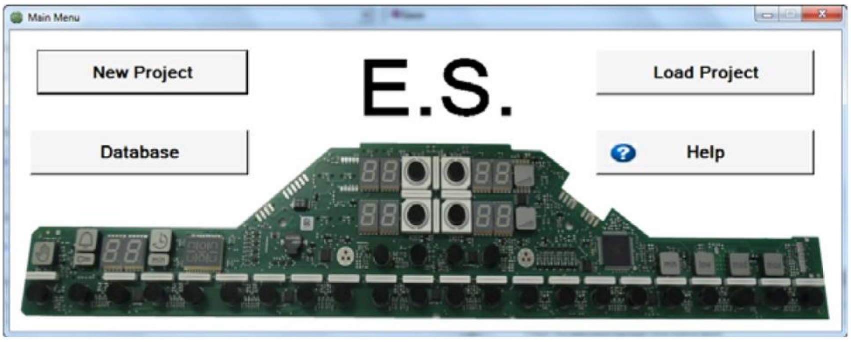
The structure of this software is divided in three main blocks, which are: new project/load project, databases and also results (Figure 4), where the user could evaluate quantity of critical materials and environmental impact. In the figure is shown the program flow, which gives a general view about the program tools. From 'new project', the user could named a project, while in block 'load project' it could be selected an existing project. The block 'database' shows the completed database that is available in the tool, it is allowed to create filters and manage the database.

Figure 4 Software structure (see online version for colours)



This structure of the software is represented in the main screen of the program (Figure 5).

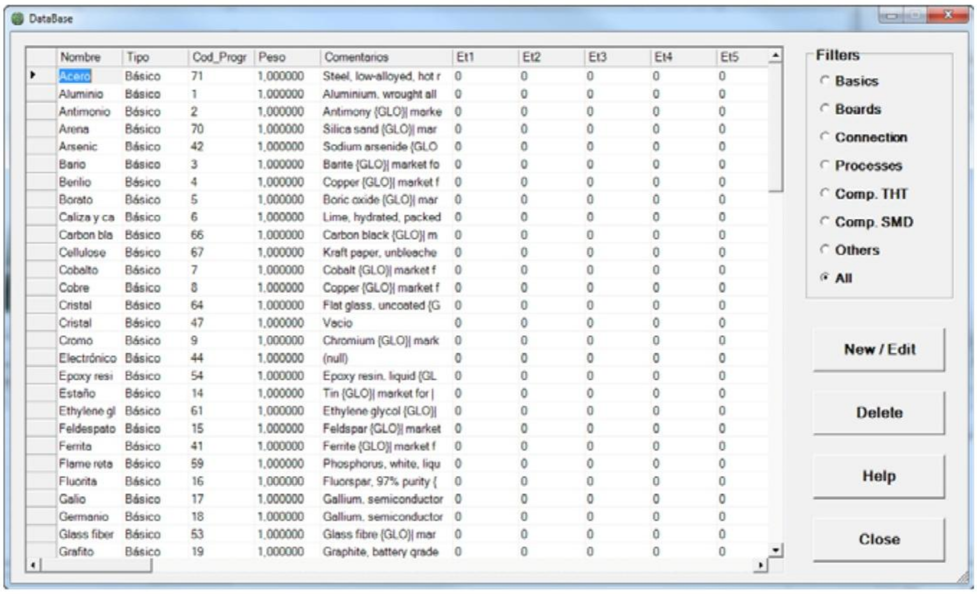
Figure 5 Main screen of the software (see online version for colours)



3.1 *Database (LCA model inputs)*

Selecting 'database' button from the main screen, the software shows the complete database (Figure 6). As mentioned before, navigating in this screen the user can filter and also manage the database, creating, editing and deleting inventory data.

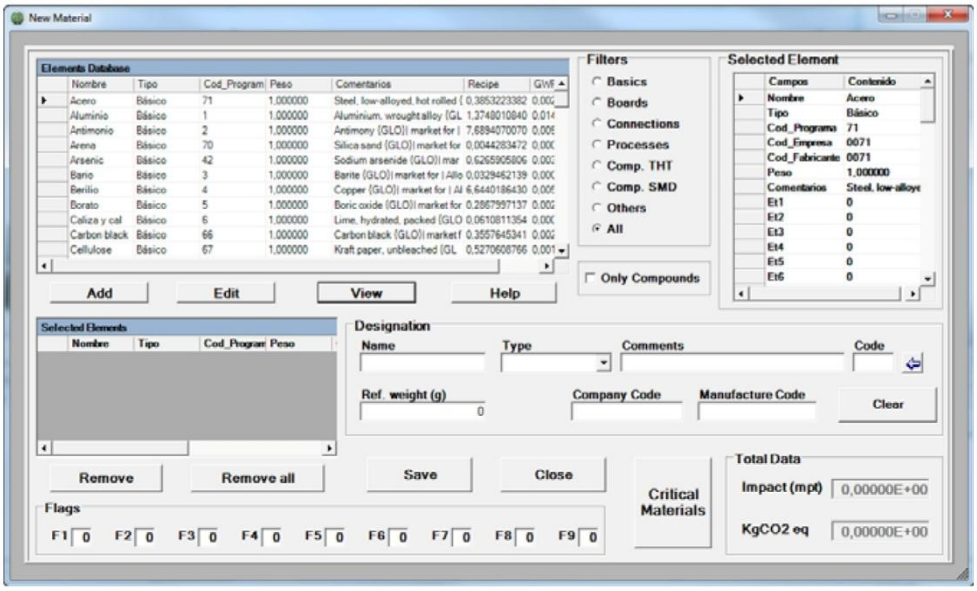
Figure 6 Software database (see online version for colours)



Nombre	Tipo	Cod_Progr	Peso	Comentarios	Et1	Et2	Et3	Et4	Et5
Acero	Básico	71	1,000000	Steel, low-alloyed, hot r	0	0	0	0	0
Aluminio	Básico	1	1,000000	Aluminium, wrought all	0	0	0	0	0
Antimonio	Básico	2	1,000000	Antimony {GLO}| marke	0	0	0	0	0
Arena	Básico	70	1,000000	Silica sand {GLO}| mar	0	0	0	0	0
Arsenic	Básico	42	1,000000	Sodium arsenide {GLO	0	0	0	0	0
Bario	Básico	3	1,000000	Barite {GLO}| market fo	0	0	0	0	0
Berilio	Básico	4	1,000000	Copper {GLO}| market f	0	0	0	0	0
Borato	Básico	5	1,000000	Boric oxide {GLO}| mar	0	0	0	0	0
Caliza y ca	Básico	6	1,000000	Lime, hydrated, packed	0	0	0	0	0
Carbon bla	Básico	66	1,000000	Carbon black {GLO}| m	0	0	0	0	0
Cellulose	Básico	67	1,000000	Kraft paper, unbleache	0	0	0	0	0
Cobalto	Básico	7	1,000000	Cobalt {GLO}| market f	0	0	0	0	0
Cobre	Básico	8	1,000000	Copper {GLO}| market f	0	0	0	0	0
Cristal	Básico	64	1,000000	Flat glass, uncoated {G	0	0	0	0	0
Cristal	Básico	47	1,000000	Vacio	0	0	0	0	0
Cromo	Básico	9	1,000000	Chromium {GLO}| mark	0	0	0	0	0
Electrónico	Básico	44	1,000000	(null)	0	0	0	0	0
Epoxy resi	Básico	54	1,000000	Epoxy resin, liquid {GL	0	0	0	0	0
Estaño	Básico	14	1,000000	Tin {GLO}| market for |	0	0	0	0	0
Ethylene gl	Básico	61	1,000000	Ethylene glycol {GLO}|	0	0	0	0	0
Feldespato	Básico	15	1,000000	Feldspar {GLO}| market	0	0	0	0	0
Ferrita	Básico	41	1,000000	Ferrite {GLO}| market f	0	0	0	0	0
Flame reta	Básico	59	1,000000	Phosphorus, white, liqu	0	0	0	0	0
Fluorita	Básico	16	1,000000	Fluorspar, 97% purity {	0	0	0	0	0
Galio	Básico	17	1,000000	Gallium, semiconductor	0	0	0	0	0
Germanio	Básico	18	1,000000	Gallium, semiconductor	0	0	0	0	0
Glass fiber	Básico	53	1,000000	Glass fibre {GLO}| mar	0	0	0	0	0
Grafito	Básico	19	1,000000	Graphite, battery grade	0	0	0	0	0

After customising the database, the software allows to select the required components, in order to create the inventory (Figure 7). For an electronic board, the researcher can select between components, boards, production processes and also connections and other elements thanks to the previous work and research that have been performed in order to create the database.

Figure 7 Database personalisation's (see online version for colours)



Elements Database

Nombre	Tipo	Cod_Program	Peso	Comentarios	Recipe	GWF
Acero	Básico	71	1,000000	Steel, low-alloyed, hot rolled {	0,3853223382	0,00
Aluminio	Básico	1	1,000000	Aluminium, wrought alloy {GL	1,3748010840	0,01
Antimonio	Básico	2	1,000000	Antimony {GLO}| market for |	7,6894070070	0,00
Arena	Básico	70	1,000000	Silica sand {GLO}| market for	0,0044283472	0,00
Arsenic	Básico	42	1,000000	Sodium arsenide {GLO}| mar	0,6265905806	0,00
Bario	Básico	3	1,000000	Barite {GLO}| market for | Allo	0,0329462139	0,00
Berilio	Básico	4	1,000000	Copper {GLO}| market for | Al	6,6440186430	0,00
Borato	Básico	5	1,000000	Boric oxide {GLO}| market for	0,2867997137	0,00
Caliza y cal	Básico	6	1,000000	Lime, hydrated, packed {GLO	0,0610811354	0,00
Carbon black	Básico	66	1,000000	Carbon black {GLO}| market f	0,3557645341	0,00
Cellulose	Básico	67	1,000000	Kraft paper, unbleached {GL	0,5270608766	0,001

Selected Element

Campos	Contenido
Nombre	Acero
Tipo	Básico
Cod_Programa	71
Cod_Empresa	0071
Cod_Fabricante	0071
Peso	1,000000
Comentarios	Steel, low-alloye
Et1	0
Et2	0
Et3	0
Et4	0
Et5	0
Et6	0

Selected Elements

Nombre	Tipo	Cod_Program	Peso

Name:
Type:
Comments:
Code:
Ref. weight (g): 0
Company Code:
Manufacture Code:

F1 0 F2 0 F3 0 F4 0 F5 0 F6 0 F7 0 F8 0 F9 0

Impact (mpt): 0,00000E+00
KgCO2 eq: 0,00000E+00

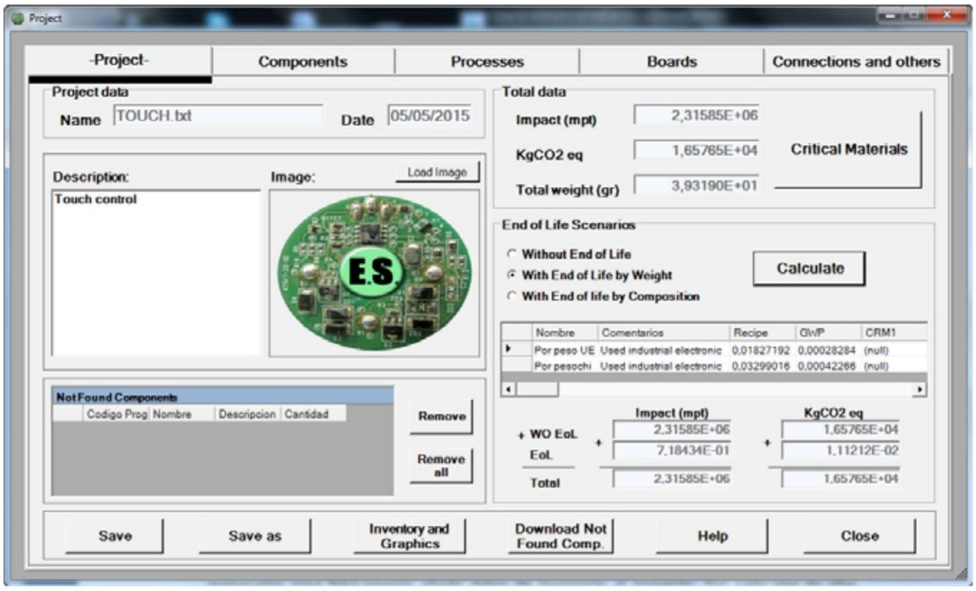
The most complex option in this screen is block 'new/edit' where the inventory could be created, filling the required fields, and also editing those that already exist.

3.2 Software development

‘Sustainable Electronics’ software allows researchers and engineers to analyse different design alternatives in order to reduce the impact to the ecological environment and diminish the use of critical raw materials, showing the overall quantity of critical and valuable raw materials in each component, process, board or connection.

Users can take design decisions taking into account critical materials and according to the environmental impact.

Figure 8 Project screen (see online version for colours)



Project data

Name: TOUCH.txt

Date: 05/05/2015

Description: Touch control

Image:

Total data

Impact (mpt): 2,31585E+06

KgCO2 eq: 1,65765E+04

Total weight (gr): 3,93190E+01

End of Life Scenarios

○ Without End of Life

● With End of Life by Weight

○ With End of life by Composition

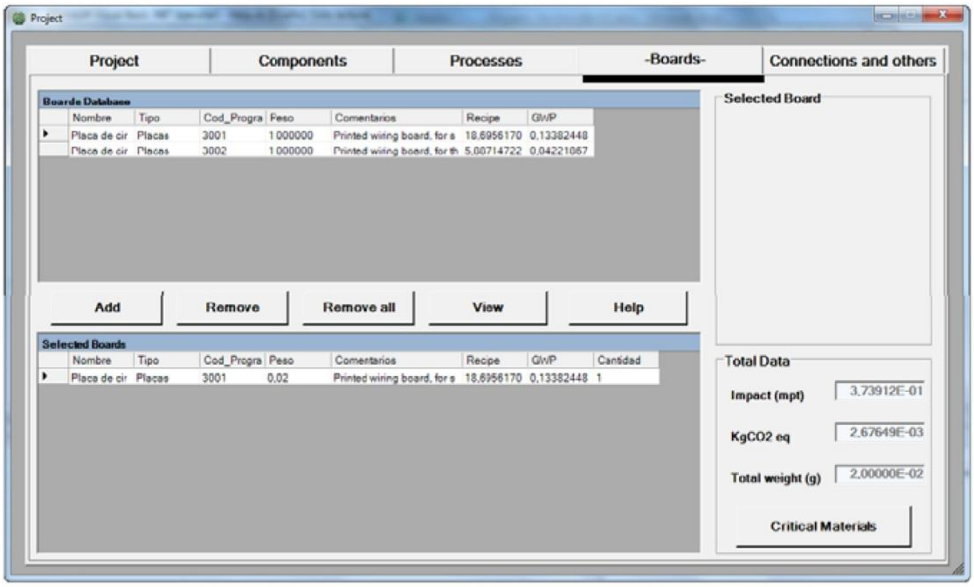
	Nombre	Comentarios	Recipe	GWP	CRM1
▸	Por peso UE	Used industrial electronic	0,01827192	0,00028284	(null)
	Por pesochi	Used industrial electronic	0,03299016	0,00042266	(null)

		Impact (mpt)		KgCO2 eq
+ WO EoL	+	2,31585E+06	+	1,65765E+04
EoL		7,18434E-01		1,11212E-02
Total		2,31585E+06		1,65765E+04

Not Found Components

	Codigo Prog	Nombre	Descripcion	Cantidad

Figure 9 Boards screen (see online version for colours)



Boards Database

	Nombre	Tipo	Cod_Progra	Peso	Comentarios	Recipe	GWP
▸	Placa de cir	Placas	3001	1.000000	Printed wiring board, for s	18,6956170	0,13382448
	Placa de cir	Placas	3002	1.000000	Printed wiring board, for th	5,00714722	0,04221067

Selected Boards

	Nombre	Tipo	Cod_Progra	Peso	Comentarios	Recipe	GWP	Cantidad
▸	Placa de cir	Placas	3001	0,02	Printed wiring board, for s	18,6956170	0,13382448	1

Total Data

Impact (mpt): 3,73912E-01

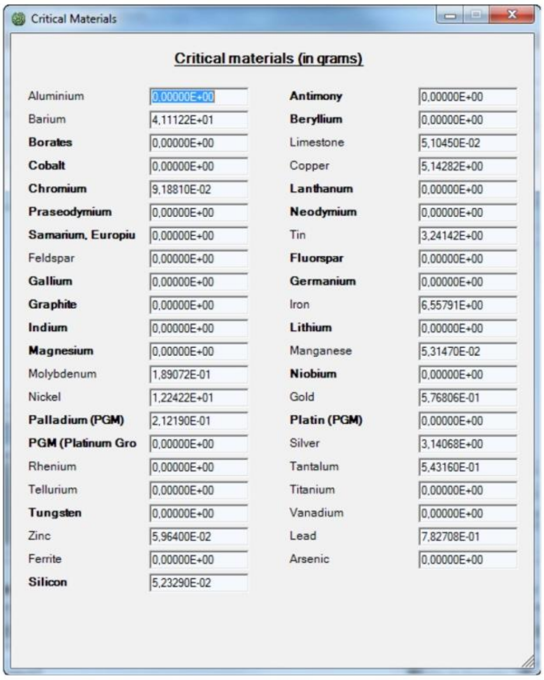
KgCO2 eq: 2,67649E-03

Total weight (g): 2,00000E-02

Figure 8 shows 'new project' and 'load project' options, where there are several tabs such as project, components, processes, boards and connections and others, the user can navigate through them creating its own project. The main screen is 'project', where it is shown a summary of the project with data such as the name, the creation date or an image of the project, among others.

All of these screens are prepared for easily adding data from the inventory to the project and in each screen the inventory data of each type are available. Thereby, in 'board' screen appears inventory data regarding that field (Figure 9).

Figure 10 Critical materials screen (see online version for colours)



Critical materials (in grams)

Aluminium	0,00000E+00	**Antimony**	0,00000E+00
Barium	4,11122E+01	**Beryllium**	0,00000E+00
Borates	0,00000E+00	Limestone	5,10450E-02
Cobalt	0,00000E+00	Copper	5,14282E+00
Chromium	9,18810E-02	**Lanthanum**	0,00000E+00
Praseodymium	0,00000E+00	**Neodymium**	0,00000E+00
Samarium, Europiu	0,00000E+00	Tin	3,24142E+00
Feldspar	0,00000E+00	**Fluorspar**	0,00000E+00
Gallium	0,00000E+00	**Germanium**	0,00000E+00
Graphite	0,00000E+00	Iron	6,55791E+00
Indium	0,00000E+00	**Lithium**	0,00000E+00
Magnesium	0,00000E+00	Manganese	5,31470E-02
Molybdenum	1,89072E-01	**Niobium**	0,00000E+00
Nickel	1,22422E+01	Gold	5,76806E-01
Palladium (PGM)	2,12190E-01	**Platin (PGM)**	0,00000E+00
PGM (Platinum Gro	0,00000E+00	Silver	3,14068E+00
Rhenium	0,00000E+00	Tantalum	5,43160E-01
Tellurium	0,00000E+00	Titanium	0,00000E+00
Tungsten	0,00000E+00	Vanadium	0,00000E+00
Zinc	5,96400E-02	Lead	7,82708E-01
Ferrite	0,00000E+00	Arsenic	0,00000E+00
Silicon	5,23290E-02		

Once data are added, in project screen the results could be calculated and viewed by users. In panel 'total data' appears environmental impact and also, pressing 'critical materials' button, critical materials window is shown (Figure 10), where the user can see the quantities of critical and strategic materials.

These screen shows 43 critical and strategic materials, where 22, marked in bold letters, are considered by the latest EU report as critical (European Commission 2014).

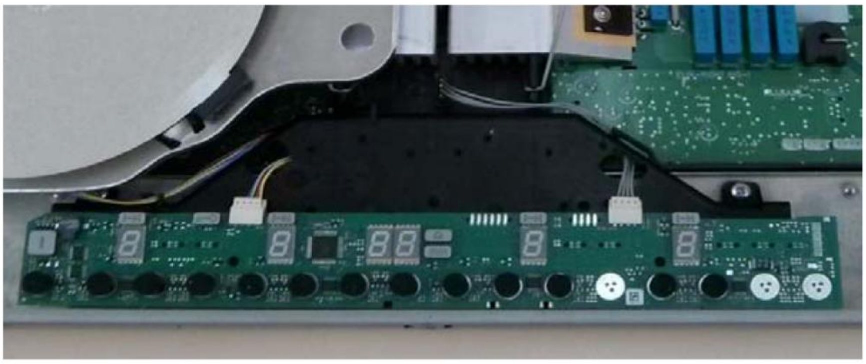
4 Software application

The main goal of the software application is to show the methodology and the software, and at the same time, show the performance of the tool.

4.1 Touch control

As previously mentioned, this implementation will be carried out in the field of electronics, specifically the tool is used to calculate critical materials content and simulate the environmental impact in a touch control device, shown in Figure 11.

Figure 11 Touch control (see online version for colours)



It is an electronic control board, called 'touch control', used in induction hobs.

4.2 Touch control inventory

The inventory for this application consists on data related to electronics, such as capacitors, resistors, diodes, transistors and so on, boards and processes as welding SMD technology.

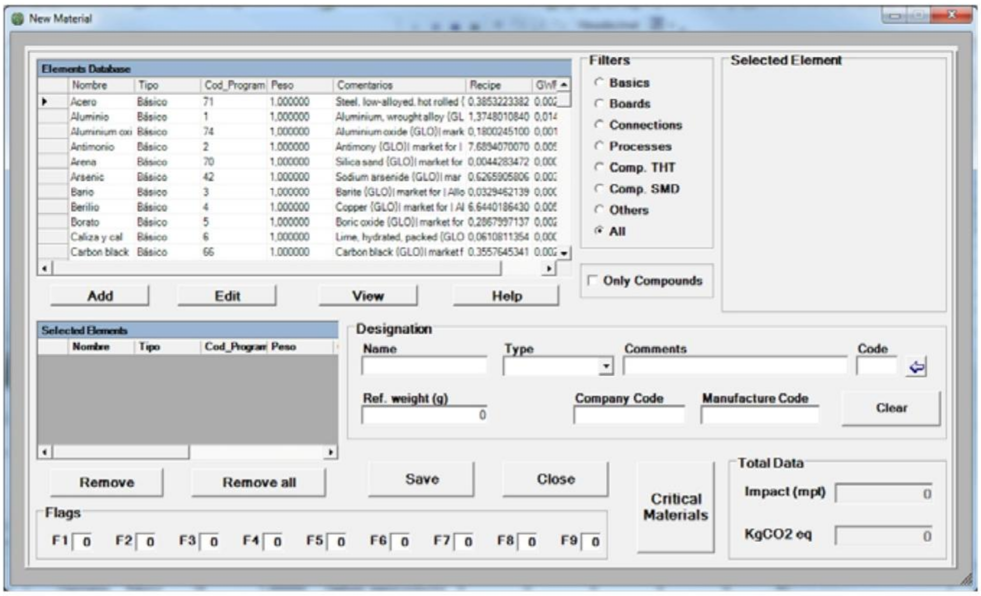
The entire inventory used in this software application, shown in Table 1, has been obtained from the manufacturer of the touch control and desoldering the electronic components. Also manufacturer's datasheets of the components have been used in order to consider the exact composition of the components of the studied case, the touch control of an induction hob, following the same methodology shown in Gómez et al. (2015).

Table 1 Summarised touch control inventory (see online version for colours)

Touch control induction hob			
Name	*Material*	*Units*	*Weight per unit (g)*
Small plastic parts	Nylon 6	7	0.199
Foam cylinders	Polyurethane, flexible foam	13	0.311
Ceramic capacitors SMD	Capacitor, for surface-mounting	52	0.0053
SMD0603 resistor	Resistor, surface-mounted	79	0.0019
Diode BAV 99	Diode, glass-, for surface-mounting	6	0.009
Tantalum capacitor	Capacitor, tantalum	1	0.237
Logical IC	Integrated circuit, logic type	5	0.102
Memory IC	Integrated circuit, memory type	2	0.057
Resonator	Resonator CPM SMD	1	0.013
7-segment displays	7 Segment display	6	0.75
LEDS	Light emitting diode	9	0.0015
PCB	Printed wiring board	1	37.995
Welding SMD technology	Mounting, surface mount technology	1	0.9355

Once the inventory is completed, elements that are not in the database of the software should be introduced in the tool from ‘new/edit database’ option (Figure 12).

Figure 12 Add or create data screen (see online version for colours)



Elements Database

Nombre	Tipo	Cod_Program	Peso	Comentarios	Recipe	GWP
Acero	Básico	71	1.000000	Steel, low-alloyed, hot rolled (	0.3853223382	0.00
Aluminio	Básico	1	1,000000	Aluminium, wrought alloy (GL	1,3748010840	0,014
Aluminium oxi	Básico	74	1,000000	Aluminium oxide (GLO)| mark	0,1800245100	0,001
Antimonio	Básico	2	1.000000	Antimony (GLO)| market for |	7.6894070070	0.00
Arena	Básico	70	1,000000	Silica sand (GLO)| market for	0,0044283472	0,00
Arsenic	Básico	42	1.000000	Sodium arsenide (GLO)| mar	0.6265905806	0.00
Bario	Básico	3	1,000000	Barite (GLO)| market for | Allo	0,0329462139	0,00
Berilio	Básico	4	1.000000	Copper (GLO)| market for | Al	6.6440186430	0.00
Borato	Básico	5	1,000000	Boric oxide (GLO)| market for	0,2867997137	0,00
Caliza y cal	Básico	6	1,000000	Lime, hydrated, packed (GLO	0,0610811354	0,00
Carbon black	Básico	66	1.000000	Carbon black (GLO)| market f	0.3557645341	0.00

Filters: ● All

Ref. weight (g): 0

Total Data

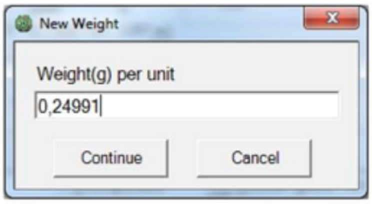
Impact (mpt): 0

KgCO2 eq: 0

Flags: F1 0, F2 0, F3 0, F4 0, F5 0, F6 0, F7 0, F8 0, F9 0

Weight of each component has to be introduced in the software every time that user wants to introduce a new component in database (Figure 13).

Figure 13 Weight introductions (see online version for colours)

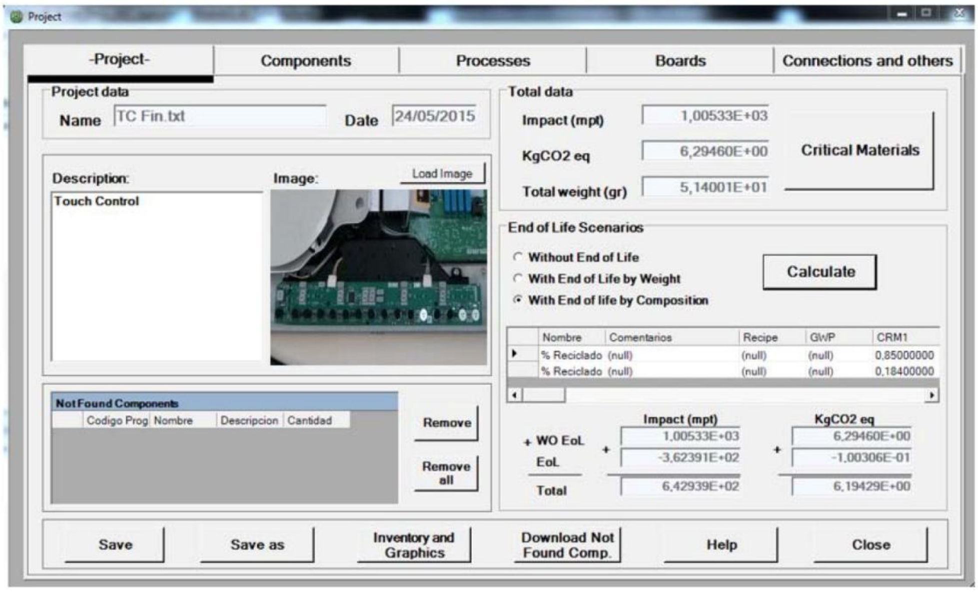


Weight(g) per unit: 0,24991

After all the inventory of the project has been created, the next step is creating the application case. For that, it is necessary to access to ‘new project’ (Figure 14), where appears the main menu and it is compulsory named the project.

Browsing in tabs project, components, processes, boards, connections and others, data from the inventory should be introduced. Depending on the type of data it will be added in ones or in others (Figure 15).

Figure 14 Project screen (see online version for colours)



Project data

Name: TC Fin.txt

Date: 24/05/2015

Description: Touch Control

Image:

Total data

Impact (mpt): 1,00533E+03

KgCO2 eq: 6,29460E+00

Total weight (gr): 5,14001E+01

End of Life Scenarios

○ Without End of Life
○ With End of Life by Weight
● With End of life by Composition

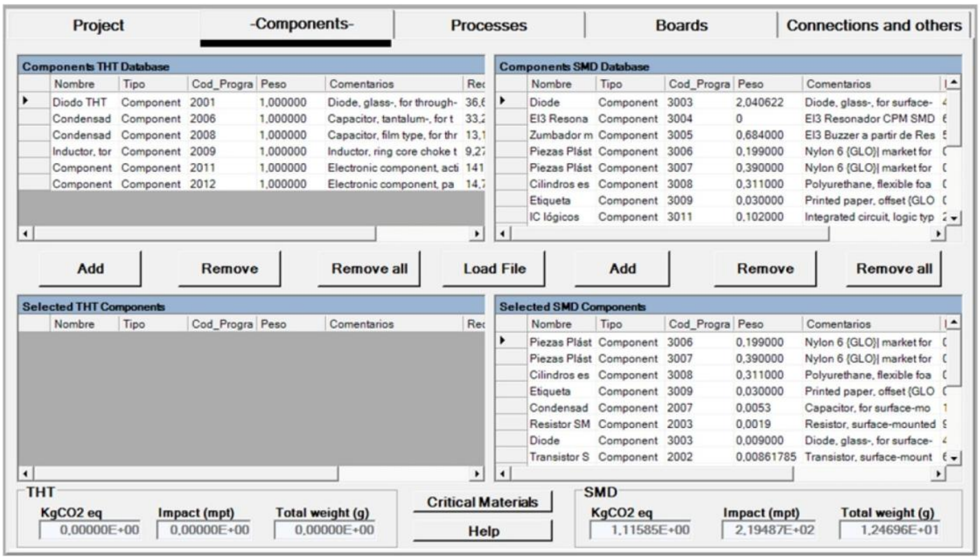
	Nombre	Comentarios	Recipe	GWP	CRM1
▸	% Reciclado	(null)	(null)	(null)	0,85000000
	% Reciclado	(null)	(null)	(null)	0,18400000

	Impact (mpt)		KgCO2 eq
+ WO EoL	1,00533E+03	+	6,29460E+00
EoL	-3,62391E+02	+	-1,00306E-01
Total	6,42939E+02		6,19429E+00

Not Found Components

	Codigo Prog	Nombre	Descripcion	Cantidad

Figure 15 Components screen (see online version for colours)



Components THT Database

	Nombre	Tipo	Cod_Progra	Peso	Comentarios	Rec
▸	Diodo THT	Component	2001	1,000000	Diode, glass-, for through-	36,
	Condensad	Component	2006	1,000000	Capacitor, tantalum-, for t	33,
	Condensad	Component	2008	1,000000	Capacitor, film type, for thr	13,1
	Inductor, tor	Component	2009	1,000000	Inductor, ring core choke t	9,2
	Component	Component	2011	1,000000	Electronic component, acti	141
	Component	Component	2012	1,000000	Electronic component, pa	14,

Components SMD Database

	Nombre	Tipo	Cod_Progra	Peso	Comentarios
▸	Diode	Component	3003	2,040622	Diode, glass-, for surface-
	EI3 Resona	Component	3004	0	EI3 Resonador CPM SMD
	Zumbador m	Component	3005	0,684000	EI3 Buzzer a partir de Res
	Piezas Plást	Component	3006	0,199000	Nylon 6 {GLO}| market for
	Piezas Plást	Component	3007	0,390000	Nylon 6 {GLO}| market for
	Cilindros es	Component	3008	0,311000	Polyurethane, flexible foa
	Etiqueta	Component	3009	0,030000	Printed paper, offset {GLO
	IC lógicos	Component	3011	0,102000	Integrated circuit, logic typ

Selected THT Components

	Nombre	Tipo	Cod_Progra	Peso	Comentarios	Rec

Selected SMD Components

	Nombre	Tipo	Cod_Progra	Peso	Comentarios
▸	Piezas Plást	Component	3006	0,199000	Nylon 6 {GLO}| market for
	Piezas Plást	Component	3007	0,390000	Nylon 6 {GLO}| market for
	Cilindros es	Component	3008	0,311000	Polyurethane, flexible foa
	Etiqueta	Component	3009	0,030000	Printed paper, offset {GLO
	Condensad	Component	2007	0,0053	Capacitor, for surface-mo
	Resistor SM	Component	2003	0,0019	Resistor, surface-mounted
	Diode	Component	3003	0,009000	Diode, glass-, for surface-
	Transistor S	Component	2002	0,00861785	Transistor, surface-mount

THT

KgCO2 eq	Impact (mpt)	Total weight (g)
0,00000E+00	0,00000E+00	0,00000E+00

SMD

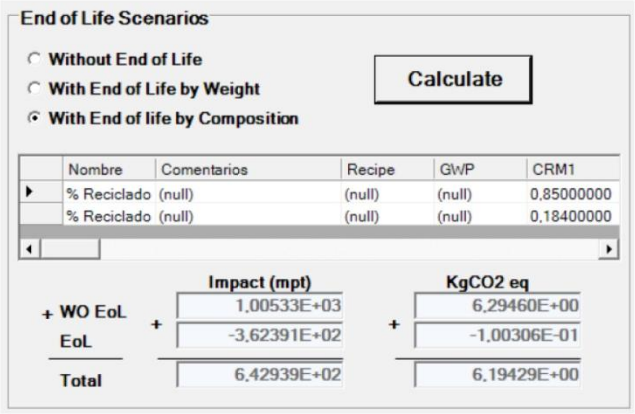
KgCO2 eq	Impact (mpt)	Total weight (g)
1,11585E+00	2,19487E+02	1,24696E+01

4.3 Touch control case results

Afterwards, once the project is completed, 'project' screen gives tool's options for calculating both critical materials and environmental impact.

'Sustainable Electronics' enables applying several ends of life scenarios, such as end of life by composition or by weight (Figure 16). The results simulated by the software show an environmental impact measurement in recipe of 642.9 mPt and of 6.19 Kg eq. CO_2 in carbon footprint.

Figure 16 End of life by composition scenario



End of Life Scenarios

○ Without End of Life
○ With End of Life by Weight
● With End of life by Composition

Nombre	Comentarios	Recipe	GWP	CRM1
% Reciclado	(null)	(null)	(null)	0,85000000
% Reciclado	(null)	(null)	(null)	0,18400000

	Impact (mpt)	KgCO2 eq
+ WO EoL	1,00533E+03	6,29460E+00
EoL	-3,62391E+02	-1,00306E-01
Total	6,42939E+02	6,19429E+00

In order to get more information regarding environmental impact or critical material composition, the results can be exported in an Excel file by means of button ‘inventory and graphics’.

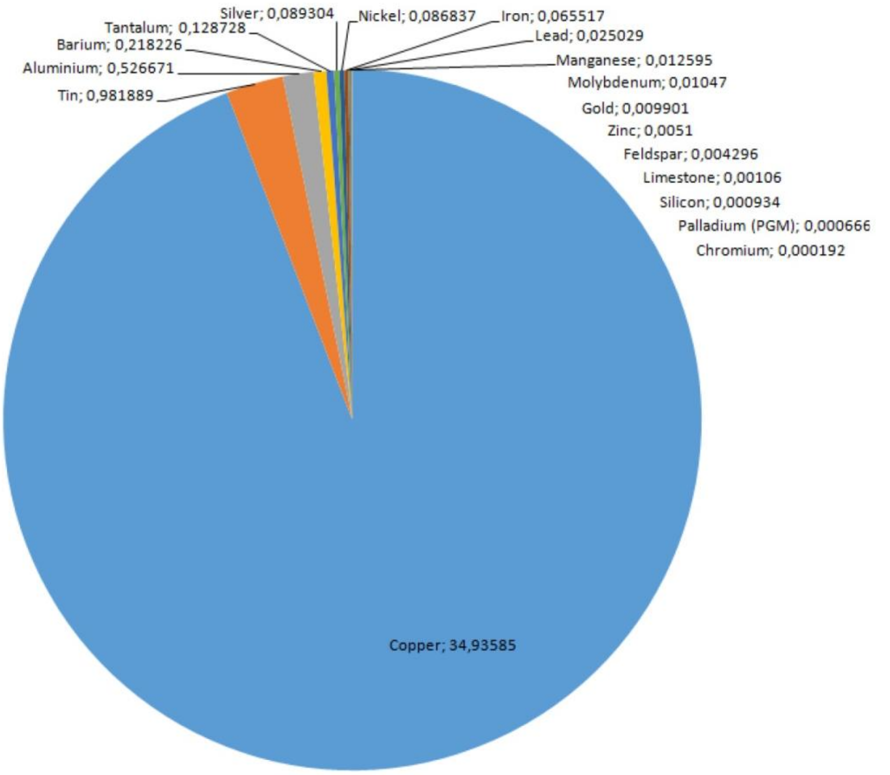
The PWB creates most of the environmental impact, followed by the SMD components. Although these components have a low overall weight, they generate a significant amount of impact and critical material consumption.

Table 2 Overall material consumption

Material	*Consumption (g)*
Copper	34.93585
Tin	0.981889
Aluminium	0.526671
Barium	0.218226
Tantalum	0.128728
Silver	0.089304
Nickel	0.086837
Iron	0.065517
Lead	0.025029
Manganese	0.012595
Molybdenum	0.01047
Gold	0.009901
Zinc	0.005100
Feldspar	0.004296
Limestone	0.001060
Silicon	0.000934
Palladium (PGM)	0.000666
Chromium	0.000192

Table 2 and Figure 17 show the consumption of critical and strategic materials in the studied touch control. The quantity of copper is the highest, mostly due to its use in the printing wiring board, followed by tin, used in components soldering, and aluminium, which is used mainly in the buzzer.

Figure 17 Overall material consumption (see online version for colours)



Furthermore, there is an option in the software that allows highlighting materials with a high consumption, either global consumption or in percentage. It can be really useful for future regulations, also could be implemented to adapt the software to the legislation.

Table 3 and Figure 18 show critical and strategic material consumption of SMD components. These are essential because, although SMD components have a low weight, the total consumption of critical and strategic material and the environmental impact is important.

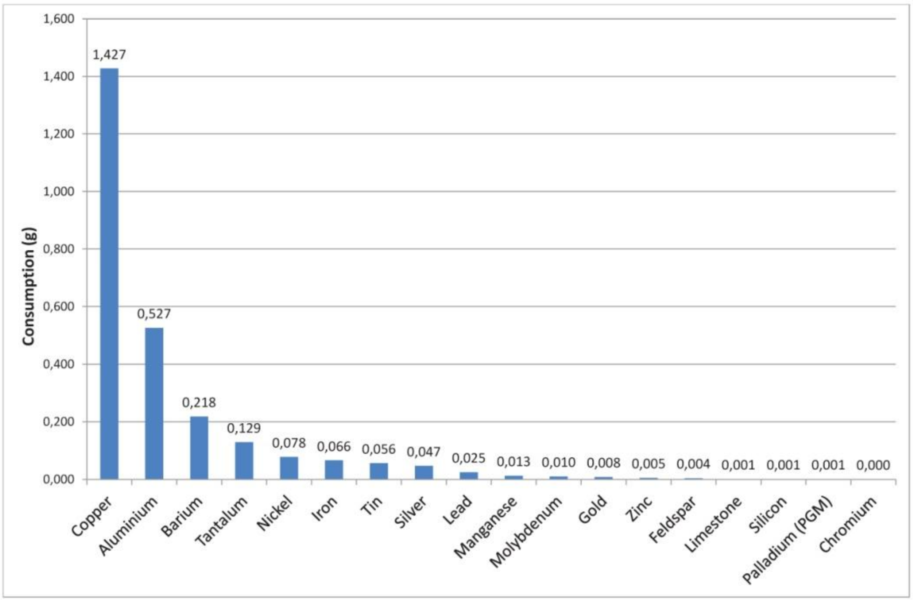
Table 3 SMD components material consumption

Material	*Consumption (g)*
Copper	1.427462
Aluminium	0.526671
Barium	0.218226
Tantalum	0.128728
Nickel	0.077808
Iron	0.065517
Tin	0.055989

Table 3 SMD components material consumption (continued)

Material	*Consumption (g)*
Silver	0.046820
Lead	0.025029
Manganese	0.012595
Molybdenum	0.010472
Gold	0.008097
Zinc	0.005100
Feldspar	0.004296
Limestone	0.001060
Silicon	0.000934
Palladium (PGM)	0.000666
Chromium	0.000192

Figure 18 SMD components material consumption (see online version for colours)



The value of copper consumption is the highest in SMD components, followed by aluminium, barium and in fourth place tantalum.

Once analysed the environmental impact and the overall critical and strategic material consumption, several conclusions can be reached. For example, there are several materials with economic importance, such as gold and silver. The first one, gold, with a consumption of 0.0099 grams, was used mostly in integrated circuits and transistors whereas silver, with 0.0089 grams, was used in soldering processes. On the other hand, there are also materials that present supply risk, such as palladium and chromium, which are used in SMD resistors.

5 Conclusions

The software ‘Sustainable Electronics’, developed in Visual Basic .NET, allows the user to quantify the critical and strategic materials associated with the design of a component; also the user can simulate the environmental impact.

The user interface makes easy for the user to compare between different components design, making material selection easier. It consists on an improved LCA adjusted to take into account the composition and the presence of critical materials, which has been calculated with ReCiPe and IPCC 2013 methodology.

Furthermore, the influence of material composition has been taken into account analysing the presence of critical raw material and although it has been developed for electrical and electronic components, it could be adapted to other sectors easily.

The simulation of the environmental impact of an induction hob delivers an environmental impact result of 642.9 mPt in Recipe and 6.19 Kg eq. CO_2 in carbon footprint. Furthermore, the consumption of copper, tin and aluminium supposes a significant amount of environmental impact and material consumption.

This analysis can be used to generate new eco design proposals, changing critical components by others with less critical material consumption. For example, the substitution of SMD transistors for components without gold content, such as the ones offered by several electronic components suppliers, would decrease the environmental impact, and also reduce cost and supply risk.

All these results can be achieved thanks to the modelling and simulation of the environmental impact carried out in this study. This approach will allow companies to reduce supply risk, environmental impact and costs.

Acknowledgements

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9.4. Materials: Influence of the composition on the environmental impact of cast aluminum alloy.

materials

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Influence of Composition on the Environmental Impact of a Cast Aluminum Alloy

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Abstract: The influence of alloy composition on the environmental impact of the production of six aluminum casting alloys (Al Si12Cu1(Fe), Al Si5Mg, Al Si9Cu3Zn3Fe, Al Si10Mg(Fe), Al Si9Cu3(Fe)(Zn) and Al Si9) has been analyzed. In order to perform a more precise environmental impact calculation, Life Cycle Assessment (LCA) with ReCiPe Endpoint methodology has been used, with the EcoInvent v3 AlMg3 aluminum alloy dataset as a reference. This dataset has been updated with the material composition ranges of the mentioned alloys. The balanced, maximum and minimum environmental impact values have been obtained. In general, the overall impact of the studied aluminum alloys varies from 5.98×10^{-1} pts to 1.09 pts per kg, depending on the alloy composition. In the analysis of maximum and minimum environmental impact, the alloy that has the highest uncertainty is AlSi9Cu3(Fe)(Zn), with a range of ±9%. The elements that contribute the most to increase its impact are Copper and Tin. The environmental impact of a specific case, an LED luminaire housing made out of an Al Si12Cu1(Fe) cast alloy, has been studied, showing the importance of considering the composition. Significant differences with the standard datasets that are currently available in EcoInvent v3 have been found.

Keywords: life cycle assessment; material composition; environmental impact; aluminum alloy; luminaire housing

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1. Introduction

Nowadays there is great social concern about the protection of the environment. Problems like climate change, the greenhouse effect or acid rain are consequences of environmental issues that affect our daily life. In that regard, enterprises have made great efforts to design their products over the last few years to produce goods that preserve environmental resources and reduce the amount of waste and environmental impact.

The ecodesign concept originated with the aim of prevention in the design stage, instead of correction, as most of the environmental impacts are defined when the product idea is conceived and the product is designed [1,2]. At the design stage, material selection takes an important role on the environmental performance, as its affects the whole product life cycle: raw material acquisition, manufacturing process, transportation, and also end of life [3,4].

Many examples of ecodesigned products illustrate this process [5], in areas such as automobiles, bicycles or lighting [6,7], increasing their market competitiveness [8].

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Several European policies have been devoted to promoting ecodesign (EuP, 2005/32/CE [9] and ErP, 2009/125/CE [10]) and reducing the use of toxic substances (RoHS, 2002/95/CE [11] and REACH, 1907/2006 [12]). Also, several standards have been created with the aim of introducing the criteria of minimum environmental impact on the development of products (ISO 14006) [13].

An adequate methodology to analyze the environmental impacts is Life Cycle Assessment (LCA), which evaluates the environmental impact of a material, product, process or service, identifying the main types of environmental impact throughout the life cycle [14,15]. LCA has been applied to a wide range of different products and materials such as commercial biodegradable polymers [16], concrete [17,18], luminaires [19], lubricants [20] or cars based on aluminum, steel, magnesium and plastic [21].

This article is focused on evaluating the environmental impact of the production of aluminum alloys, currently used in a wide range of applications [22]. Aluminum has high strength, high electrical and thermal conductivity, low density, good ductility and high hardness [23]. Although there are many techniques and manufacturing processes for aluminum such as extrusion, rolling, stamping or bending, this study is focused on aluminum casting [24,25].

Many authors and experts have used the LCA to analyze the environmental impact of several aluminum products such as beverage cans [26], the use of aluminum in the automotive sector [27], or its use in buildings [28]. Furthermore, in the last few decades aluminum alloys have been widely used in the industry, due to their enhanced properties such as a lower melting point, strength or hardness [29,30]. A great variety of properties can be obtained depending on the elements added to the alloy. For example, silicon improves the fluidity of the alloy and at the same time reduces its melting temperature, while tin increases the machinability of the alloys [29]. However, the alloying elements should be chosen carefully. Although these elements generally improve the properties of the material, they also have an influence on the environmental impact of the alloy.

LCA can be used as a potential tool to help businesses or governments to assess their supply chains and to analyze the environmental impact of materials or components. It also provides information about the presence of critical raw materials, thanks to the development of a detailed Life Cycle Inventory [31,32]. A critical material is defined for several reasons: shortage or supply risk, economic vulnerability or ecological risk [33–37]. For all these reasons, the composition of an alloy must be studied while taking into consideration the presence of critical raw materials and how they can affect the total environmental impact. This research came up when LCA was applied to a real case of an LED luminaire housing made of an aluminum casting alloy. The compositions of aluminum alloys are defined by standards that include elements intentionally added to improve properties, and also those impurities that cannot be removed during alloy production. There are a wide range of LCA studies which use datasets from databases such as EcoInvent to evaluate the environmental impact of metals alloys like aluminum, steel, copper or titanium [38–40]. However, it was found that the composition of aluminum casting alloys did not correspond to the ones available in the EcoInvent database. This fact could influence the calculated environmental impact.

Therefore, the main objective of this work is to assess the environmental impact of several aluminum alloys and evaluate the influence that their composition has on the environment. To this end, the differences between several alloys have been analyzed using EcoInvent v3 data [24]. A real case study of an LED luminaire housing is presented to show those differences.

2. Materials and Methods

2.1. Composition and Properties of Aluminum Casting Alloys

This work is based on the EcoInvent methodology, using EcoInvent v3 datasets customized with different alloying elements, in order to achieve a more precise environmental impact assessment calculation. In this work, six different alloys that are commonly used for casting have been selected (Table 1). The composition of aluminum casting alloys is defined by standards, such as the European

EN 1706:2011 [41], the Japanese H5302 [42], the British BS 1490 [43], the French NF EN 755-3-2008 [44], or the American AA ASTM B179-14 [45,46]. The corresponding equivalences of the selected alloys under different standards are shown in Table 1. The differences in the alloy compositions influence their properties, which are shown in Table 2.

Table 1. Designation and nomenclature of the studied alloys.

Alloy	EN AC 1760 Symbolic	EN AC 1706 Numeric	JIS H5302	BS 1490	NF 755-3	ASTM B179	UNS
#1	Al Si12Cu1(Fe)	47,100	ADC1	LM 20	A-S12U	–	–
#2	Al Si5Mg	–	–	LM 8	A-SAG-Y	–	–
#3	Al Si9Cu3Zn3Fe	–	ADC10	LM 24	AS9U3	380	A90380
#4	Al Si10Mg(Fe)	43,400	ADC3	–	–	–	–
#5	Al Si9Cu3(Fe)(Zn)	46,500	ADC10Z	LM 24	A-S9U3X	–	–
#6	Al Si9	44,400	–	–	AS-9	–	–

Table 2. Main properties of the studied alloys.

Mechanical Characteristics	Alloy #1	Alloy #2	Alloy #3	Alloy #4	Alloy #5	Alloy #6
Expansion coefficient (10^{-6}/k)	20.0	23.0	21.5	21.0	21.0	21.0
Thermal conductivity (w/mK)	120–150	146–180	109	130–150	110–120	130–150
Electrical conductivity (MS/m)	15–20	4.5–5.3	7.5	16–21	13–17	16–22
Tensile strength, Rm (MPa)	240	140	170	240	240	220
Elastic limit, Rp0.2% (MPa)	140	100	100	140	140	120
Elongation (%)	1	1	1	1	<1	2
Brinell hardness (HBW)	70	60	75	70	80	55

2.2. Dataset Improvement Methodology for Aluminum Casting Alloys

The production processes of each aluminum alloy have been analyzed, taking into account the composition of each studied alloy. The methodology used by EcoInvent for the dataset "Aluminium alloy, AlMg3 {RER} | production" has been applied in this research. This dataset, which can be used as a proxy for this type of aluminum casting alloy, has a 3% content of magnesium and small amounts of other metals [24]. These data allows an analysis of the total material consumption. The overall amount of raw materials needed for the production processes corresponds to the materials that appear in the final alloy and also the overall material consumption considering auxiliary raw material consumption. The compositions ranges of all the selected alloys are shown in Section 3.

The EcoInvent v3 AlMg3 dataset has been updated with the material composition of the mentioned alloys. As the composition of an alloy is defined by ranges, a balanced composition has been calculated in order to obtain a defined representative composition of that alloy. This balanced composition calculation method consists of the following phases:

- Firstly, the alloying elements that have a range are identified for each alloy.
- Secondly, for each alloy and for each of these alloying elements defined with a range, the average value between the minimum and the maximum values of each range is calculated. This leads to a balanced composition that is representative of an alloy whose alloying elements percentages are in the middle of the allowed range.
- Finally, the average percentage values for each alloying element of the composition are considered. For the analyzed alloys, it has been checked that the sum of the alloying element percentages in each alloy adds up 100%.

All the information of the alloys is processed while taking into account EcoInvent system characterization introducing it into EcoInvent v3 dataset and updating it.

In this way, the LCA of aluminum casting alloys was performed and compared with EcoInvent's original dataset, in order to evaluate the influence of the composition on the environmental impact.

2.3. LCA Methodology

2.3.1. Goal and Scope Definition

The aim of this LCA is to quantify the impact of several aluminum casting alloys, analyzing the influence of the composition on the environmental impact. ISO 14040 standards of LCA have been applied [47].

2.3.2. Functional Unit

The definition of a functional unit is essential in life cycle assessment. In this paper, the functional unit has been defined as the production of 1 kg of aluminum alloy, taking into consideration the composition of the alloying, energy consumption and the end of life of the waste produced in the production processes.

2.3.3. System Boundaries

The scope of this research is to focus on the study of the environmental impact of the production of an aluminum cast alloy and to investigate the influence of the variation of the composition.

The LCA has been developed to evaluate the environmental impact of each aluminum alloy considering the composition of alloying elements and also impurities, focusing on the stages shown in Figure 1. Following EcoInvent's methodology, a material loss of 1.48% during production is assumed. Following these methodology, market (GLO) datasets have been used to consider transportation of the raw material from the average providers to the alloy manufacturing plant.

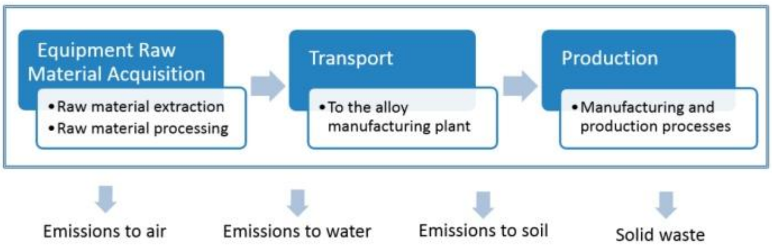

Figure 1. System boundaries.

2.3.4. Inventory Data and Assumptions

The life cycle inventory has been developed by means of EcoInvent v3, one of the most important databases implemented by the Swiss Centre for Life Cycle Inventories [48], using the attributional modeling approach "Allocation, ecoinvent default", where market datasets are considered a mix between primary and secondary sources.

The LCA has been modeled with SimaPro 8.0.3.14, developed by Pré Consultants [49]. Furthermore, the LCA was developed with ReCiPe methodology. This methodology is useful for designers because of its ease of interpretation. ReCiPe methodology was developed as an endpoint attempt to align the CML 2002 midpoint and the Eco-indicator 99 systems [50].

3. Life Cycle Inventory

In order to compare each alloy with EcoInvent's dataset, the life cycle inventories of all the selected aluminum alloys have been developed. Table 3 shows a detailed inventory of the composition of each aluminum alloy, including the one that corresponds to EcoInvent's v3 dataset. The composition of the studied alloys is given with respect to 1 kg of aluminum alloy. It can be seen that the quantity of some elements varies considerably from some alloys to others. This is the case with nickel, titanium, lead or tin. These materials are not considered in EcoInvent's AlMg3 aluminum alloy dataset; however, they are used in all of the other studied alloys. Chromium is only included in EcoInvent and alloy #5 (Al Si9Cu3(Fe)(Zn)) datasets, but none of the other alloys have this element in their composition.

Table 3. Material composition for 1 kg of aluminum alloy.

Material (kg)	EcoInvent	Alloy #1		Alloy #2		Alloy #3		Alloy #4		Alloy #5		Alloy #6	
Silicon	4.00×10^{-3}	1.10×10^{-1}	1.35×10^{-1}	4.00×10^{-2}	5.50×10^{-2}	8.00×10^{-2}	1.10×10^{-1}	9.00×10^{-2}	1.10×10^{-1}	8.00×10^{-2}	1.10×10^{-1}	8.00×10^{-2}	1.10×10^{-1}
Iron	4.00×10^{-3}	1.30×10^{-2}		6.00×10^{-3}		1.30×10^{-2}		1.00×10^{-2}		6.00×10^{-3}	1.20×10^{-2}	5.50×10^{-3}	
Copper	1.01×10^{-3}	1.00×10^{-2}		1.00×10^{-3}		2.00×10^{-2}	4.00×10^{-2}	1.00×10^{-3}		2.00×10^{-2}	4.00×10^{-2}	8.00×10^{-4}	
Manganese	5.01×10^{-3}	5.00×10^{-3}		6.00×10^{-3}		5.50×10^{-3}		5.50×10^{-3}		5.50×10^{-3}		5.00×10^{-3}	
Magnesium	3.01×10^{-2}	2.00×10^{-3}		5.00×10^{-3}	8.00×10^{-3}	5.00×10^{-4}	5.50×10^{-3}	2.00×10^{-3}	5.00×10^{-3}	1.50×10^{-3}	5.50×10^{-3}	1.00×10^{-3}	
Nickel	0.00	5.00×10^{-3}		1.00×10^{-3}		5.50×10^{-3}		1.50×10^{-3}		5.50×10^{-3}		5.00×10^{-4}	
Zinc	2.00×10^{-3}	5.00×10^{-3}		1.00×10^{-3}		3.00×10^{-2}		1.50×10^{-3}		3.00×10^{-2}		1.50×10^{-3}	
Titanium	0.00	2.00×10^{-3}		2.00×10^{-3}		2.50×10^{-3}		2.00×10^{-3}		2.00×10^{-3}		1.50×10^{-3}	
Lead	0.00	1.50×10^{-3}		1.00×10^{-3}		3.50×10^{-3}		1.50×10^{-3}		3.50×10^{-3}		5.00×10^{-4}	
Tin	0.00	1.00×10^{-3}		5.00×10^{-4}		2.50×10^{-3}		5.00×10^{-4}		1.50×10^{-3}		5.00×10^{-4}	
Chromium	3.01×10^{-3}	0.00		0.00		0.00		0.00		1.50×10^{-3}		0.00	
Aluminum	9.51×10^{-1}	8.21×10^{-1}	8.46×10^{-1}	9.19×10^{-1}	9.37×10^{-1}	7.82×10^{-1}	8.37×10^{-1}	8.85×10^{-1}	8.62×10^{-1}	7.83×10^{-1}	8.43×10^{-1}	8.73×10^{-1}	9.03×10^{-1}
Total	1.00	1.00		1.00		1.00		1.00		1.00		1.00	

On the other hand, the main material, aluminum, and some elements like silicon, copper and magnesium are present in a range of quantities for each alloy. The ranges in the composition will be considered to obtain not only a balanced value of the environmental impact, as explained in Section 2, but also the minimum and the maximum environmental impact of the range of each alloy. Table 4 shows the balanced composition present in 1 kg of each aluminum alloy.

Table 4. Balanced material composition for 1 kg of aluminum alloy.

Material (kg)	EcoInvent	Alloy #1	Alloy #2	Alloy #3	Alloy #4	Alloy #5	Alloy #6
Silicon	0.0040	0.1225	0.0475	0.0950	0.1000	0.0950	0.0950
Iron	0.0040	0.0130	0.0060	0.0130	0.0100	0.0090	0.0055
Copper	0.0010	0.0100	0.0010	0.0300	0.0010	0.0300	0.0008
Manganese	0.0050	0.0050	0.0060	0.0055	0.0055	0.0055	0.0050
Magnesium	0.0301	0.0020	0.0065	0.0030	0.0035	0.0035	0.0010
Nickel	0.0000	0.0050	0.0010	0.0055	0.0015	0.0055	0.0005
Zinc	0.0020	0.0050	0.0010	0.0300	0.0015	0.0300	0.0015
Titanium	0.0000	0.0020	0.0020	0.0025	0.0020	0.0020	0.0015
Lead	0.0000	0.0015	0.0010	0.0035	0.0015	0.0035	0.0005
Tin	0.0000	0.0010	0.0005	0.0025	0.0005	0.0015	0.0005
Chromium	0.0030	0.0000	0.0000	0.0000	0.0000	0.0015	0.0000
Aluminum	0.9509	0.8330	0.9275	0.8095	0.8730	0.8130	0.8882
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 5 shows the studied aluminum alloys and the material inputs needed to manufacture 1 kg of each alloy. These data are used to calculate the amount of aluminum alloy raw input used, considering not only 1 kg of input but also all the raw materials inputs to obtain the functional unit. An input of raw material acquisition of 1.0148 kg for each kilogram of manufactured aluminum alloy, as established by EcoInvent's methodology, has been considered to develop the LCA, as explained in Section 2.3.3.

Table 5. Balanced material composition inputs for 1 kg of aluminum alloy.

Material (kg)	EcoInvent	Alloy #1	Alloy #2	Alloy #3	Alloy #4	Alloy #5	Alloy #6
Silicon	0.0041	0.1243	0.0482	0.0964	0.1015	0.0964	0.0964
Iron	0.0041	0.0132	0.0061	0.0132	0.0101	0.0091	0.0056
Copper	0.0010	0.0101	0.0010	0.0304	0.0010	0.0304	0.0008
Manganese	0.0051	0.0051	0.0061	0.0056	0.0056	0.0056	0.0051
Magnesium	0.0305	0.0020	0.0066	0.0030	0.0036	0.0036	0.0010
Nickel	0.0000	0.0051	0.0010	0.0056	0.0015	0.0056	0.0005
Zinc	0.0020	0.0051	0.0010	0.0304	0.0015	0.0304	0.0015
Titanium	0.0000	0.0020	0.0020	0.0025	0.0020	0.0020	0.0015
Lead	0.0000	0.0015	0.0010	0.0036	0.0015	0.0036	0.0005
Tin	0.0000	0.0010	0.0005	0.0025	0.0005	0.0015	0.0005
Chromium	0.0031	0.0000	0.0000	0.0000	0.0000	0.0015	0.0000
Aluminum	0.9650	0.8453	0.9412	0.8215	0.8859	0.8250	0.9013
Total	1.0148	1.0148	1.0148	1.0148	1.0148	1.0148	1.0148

The most relevant EcoInvent datasets that have been used to characterize the inputs of the aluminum alloys are shown in Table 6. All of them have been selected following EcoInvent's guidelines [24].

Table 6. EcoInvent dataset selection.

Material	Dataset
Copper	Copper {GLO}| market for | Alloc Def, U
Magnesium	Magnesium {GLO}| market for | Alloc Def, U
Aluminum	Aluminium, cast alloy {GLO}| market for | Alloc Def, U
Silicon	Silicon, metallurgical grade {GLO}| market for | Alloc Def, U
Manganese	Manganese {GLO}| market for | Alloc Def, U
Zinc	Zinc {GLO}| market for | Alloc Def, U
Chromium	Chromium {GLO}| market for | Alloc Def, U
Nickel	Nickel, 99.5% {GLO}| market for | Alloc Def, U
Lead	Lead {GLO}| market for | Alloc Def, U
Tin	Tin {GLO}| market for | Alloc Def, U

4. Results

Once the life cycle inventories were introduced in SimaPro, the balanced, minimum and maximum environmental impacts were obtained for the alloys. These results have been analyzed in order to study the influence of the material composition. Finally, the results of environmental impact of a LED luminaire aluminum housing are shown to demonstrate the composition influence with a real example.

4.1. Analysis of the Balanced Environmental Impact of the Aluminum Alloys

Table 7 shows the environmental impact calculations of each alloy in ReCiPe points by kilogram, considering the balanced value of the materials that are given as a range in Table 3. In general, it can be said that the highest environmental impact is produced by alloy #3 (Al Si9Cu3Zn3Fe) with 1.01 pts, followed by alloy #5 (Al Si9Cu3(Fe)(Zn)) with 9.44×10^{-1} pts. The minimum environmental impact is produced by alloy #6 (Al Si9) with an environmental impact of 6.09×10^{-1} pts; Furthermore, it can be observed that the alloying elements that create the highest environmental impact are copper, silicon and tin, elements commonly used in aluminum alloys [29]. The alloys which have the highest environmental impact are those with the highest copper and tin percentage values. In contrast, the EcoInvent original dataset produces only 6.36×10^{-1} points of environmental impact, a low value, because EcoInvent's composition does not include tin and its quantity of silicon is the lowest of the studied alloys.

Table 7. Environmental impact of 1 kg of the studied aluminum alloys.

Material	EcoInvent	Alloy #1	Alloy #2	Alloy #3	Alloy #4	Alloy #5	Alloy #6
Total (pts)	6.36×10^{-1}	7.62×10^{-1}	6.12×10^{-1}	1.01	6.36×10^{-1}	9.44×10^{-1}	6.09×10^{-1}
Silicon	4.26×10^{-3}	1.32×10^{-1}	5.13×10^{-2}	1.03×10^{-1}	1.08×10^{-1}	1.03×10^{-1}	1.03×10^{-1}
Iron	1.03×10^{-3}	3.40×10^{-3}	1.57×10^{-3}	3.40×10^{-3}	2.61×10^{-3}	2.35×10^{-3}	1.44×10^{-3}
Copper	6.68×10^{-3}	6.74×10^{-2}	6.74×10^{-3}	2.02×10^{-1}	6.74×10^{-3}	2.02×10^{-1}	5.39×10^{-3}
Manganese	4.37×10^{-2}	4.43×10^{-2}	5.32×10^{-2}	4.88×10^{-2}	4.88×10^{-2}	4.88×10^{-2}	4.43×10^{-2}
Magnesium	1.40×10^{-1}	9.49×10^{-3}	3.08×10^{-2}	1.42×10^{-2}	1.66×10^{-2}	1.66×10^{-2}	4.74×10^{-3}
Nickel	0.00	3.66×10^{-2}	7.32×10^{-3}	4.02×10^{-2}	1.10×10^{-2}	4.02×10^{-2}	3.66×10^{-3}
Zinc	2.01×10^{-3}	5.10×10^{-3}	1.02×10^{-3}	3.06×10^{-2}	1.53×10^{-3}	3.06×10^{-2}	1.53×10^{-3}
Titanium	0.00	1.26×10^{-3}	1.26×10^{-3}	1.58×10^{-3}	1.26×10^{-3}	1.26×10^{-3}	9.47×10^{-4}
Lead	0.00	9.34×10^{-5}	6.23×10^{-5}	2.18×10^{-4}	9.34×10^{-5}	2.18×10^{-4}	3.11×10^{-5}
Tin	0.00	7.34×10^{-2}	3.67×10^{-2}	1.84×10^{-1}	3.67×10^{-2}	1.10×10^{-1}	3.67×10^{-2}
Chromium	1.30×10^{-2}	0.00	0.00	0.00	0.00	6.60×10^{-3}	0.00
Aluminum	3.24×10^{-1}	2.88×10^{-1}	3.21×10^{-1}	2.80×10^{-1}	3.02×10^{-1}	2.81×10^{-1}	3.07×10^{-1}

As mentioned before, alloy #3 (Al Si9Cu3Zn3Fe) creates the highest environmental impact in points by kilogram, where Copper and Tin composition percentages contribute in a significant way to this impact, with values of 2.02×10^{-1} and 1.84×10^{-1} points per kilogram of alloy, respectively. Also in this alloy, aluminum represents 80.95% of the composition and its environmental impact corresponds to 27.74% of the total environmental impact of the alloy. This alloy contains 3% copper, which has a significant effect on the strength and hardness of the alloy and generates 20.06% of the total environmental impact of the alloy. Similarly, although tin in the alloy is only 0.25% of the composition, it accounts for 18.21% of the environmental impact of the alloy. Tin is used to reduce friction when it is a requirement in some applications [29].

Chromium, magnesium and silicon, which are used in several alloys, show a high environmental impact. EU studies carried out in 2013 include these elements in the EU critical material list, regarding economic vulnerability, shortage and ecological risk. [33,51]. They therefore have a high importance to the EU, and a high risk associated with their supply risk and economic importance. On the other hand, lead and iron contribute to reducing impact values, owing to their low environmental impact values in the studied alloys. Both materials contribute positively to the characteristics of the alloys. Lead improves the machinability of the alloy and iron increases the mechanical strength [52,53].

All the studied alloys present an uncertainty owing to the range values in some components. The maximum and the minimum possible environmental impacts of all the analyzed aluminum alloys are calculated in Subsection 4.2 and Subsection 4.3.

4.2. Analysis of the Maximum Environmental Impact of the Aluminum Alloys

Table 8 shows the maximum environmental impact produced by the studied aluminum alloys in points by kilogram. This maximum impact is calculated taking into account all the possible combinations of the compositions ranges for each alloy (Table 3). The compositions that create this maximum impact are shown as Supplementary Materials (Table S1).

Table 8. Maximum environmental impact of 1 kg of the studied aluminum alloys.

Material	Alloy #1	Alloy #2	Alloy #3	Alloy #4	Alloy #5	Alloy #6
Total (pts)	7.72×10^{-1}	6.24×10^{-1}	1.09	6.50×10^{-1}	1.03	6.21×10^{-1}
Silicon	1.46×10^{-1}	5.94×10^{-2}	1.19×10^{-1}	1.19×10^{-1}	1.19×10^{-1}	1.19×10^{-1}
Iron	3.40×10^{-3}	1.57×10^{-3}	3.40×10^{-3}	2.61×10^{-3}	3.14×10^{-3}	1.44×10^{-3}
Copper	6.74×10^{-2}	6.74×10^{-3}	2.70×10^{-1}	6.74×10^{-3}	2.70×10^{-1}	5.39×10^{-3}
Manganese	4.43×10^{-2}	5.32×10^{-2}	4.88×10^{-2}	4.88×10^{-2}	4.88×10^{-2}	4.43×10^{-2}
Magnesium	9.49×10^{-3}	3.79×10^{-2}	2.61×10^{-2}	2.37×10^{-2}	2.61×10^{-2}	4.74×10^{-3}
Nickel	3.66×10^{-2}	7.32×10^{-3}	4.02×10^{-2}	1.10×10^{-2}	4.02×10^{-2}	3.66×10^{-3}
Zinc	5.10×10^{-3}	1.02×10^{-3}	3.06×10^{-2}	1.53×10^{-3}	3.06×10^{-2}	1.53×10^{-3}
Titanium	1.26×10^{-3}	1.26×10^{-3}	1.58×10^{-3}	1.26×10^{-3}	1.26×10^{-3}	9.47×10^{-4}
Lead	9.34×10^{-5}	6.23×10^{-5}	2.18×10^{-4}	9.34×10^{-5}	2.18×10^{-4}	3.11×10^{-5}
Tin	7.34×10^{-2}	3.67×10^{-2}	1.84×10^{-1}	3.67×10^{-2}	1.10×10^{-1}	3.67×10^{-2}
Chromium	0.00	0.00	0.00	0.00	6.60×10^{-3}	0.00
Aluminum	2.84×10^{-1}	3.17×10^{-1}	2.70×10^{-1}	2.98×10^{-1}	2.71×10^{-1}	3.02×10^{-1}

When the maximum environmental impact of each alloy is compared with the balanced value, it can be seen that, in general, it increases between 1% and 8.9%. The highest difference is observed for alloy #5 (Al Si9Cu3(Fe)(Zn)), as there is an increment of 8.35×10^{-2} pts (8.9%), from 9.44×10^{-1} to 1.03 pts. Copper and silicon are the components with the highest absolute increase. The maximum environmental impact due to copper has increased 6.74×10^{-2} pts from the balanced value, which was 2.02×10^{-1} pts. The contribution of environmental impact caused by silicon is lower but 1.62×10^{-2} pts higher than the balanced value.

Alloy #3 (Al Si9Cu3Zn3Fe) also shows an increment of environmental impact of 8.5% from balanced to maximum values. This impact is mainly caused by copper, which has increased 6.74×10^{-2} pts from the balanced composition value. By contrast, the alloy that shows the lowest increase is alloy #1(Al Si12Cu1(Fe)) with only a 1% increase.

4.3. Analysis of the Minimum Environmental Impact of the Aluminum Alloys

The minimum environmental impact produced by the studied aluminum alloys in points by kilogram is shown in Table 9. As in the previous subsection, this minimum impact is calculated by combinations of the composition ranges for each alloy (Table 3). The compositions that create this minimum impact are shown as Supplementary Materials (Table S2).

Table 9. Minimum environmental impact of 1 kg of the studied aluminum alloys.

Material (pts)	Alloy #1	Alloy #2	Alloy #3	Alloy #4	Alloy #5	Alloy #6
Total (pts)	7.53×10^{-1}	6.00×10^{-1}	9.22×10^{-1}	6.22×10^{-1}	8.60×10^{-1}	5.98×10^{-1}
Silicon	1.19×10^{-1}	4.32×10^{-2}	8.64×10^{-2}	9.72×10^{-2}	8.64×10^{-2}	8.64×10^{-2}
Iron	3.40×10^{-3}	1.57×10^{-3}	3.40×10^{-3}	2.61×10^{-3}	1.57×10^{-3}	1.44×10^{-3}
Copper	6.74×10^{-2}	6.74×10^{-3}	1.35×10^{-1}	6.74×10^{-3}	1.35×10^{-1}	5.39×10^{-3}
Manganese	4.43×10^{-2}	5.32×10^{-2}	4.88×10^{-2}	4.88×10^{-2}	4.88×10^{-2}	4.43×10^{-2}
Magnesium	9.49×10^{-3}	2.37×10^{-2}	2.37×10^{-3}	9.49×10^{-3}	7.11×10^{-3}	4.74×10^{-3}
Nickel	3.66×10^{-2}	7.32×10^{-3}	4.02×10^{-2}	1.10×10^{-2}	4.02×10^{-2}	3.66×10^{-3}
Zinc	5.10×10^{-3}	1.02×10^{-3}	3.06×10^{-2}	1.53×10^{-3}	3.06×10^{-2}	1.53×10^{-3}
Titanium	1.26×10^{-3}	1.26×10^{-3}	1.58×10^{-3}	1.26×10^{-3}	1.26×10^{-3}	9.47×10^{-4}
Lead	9.34×10^{-5}	6.23×10^{-5}	2.18×10^{-4}	9.34×10^{-5}	2.18×10^{-4}	3.11×10^{-5}
Tin	7.34×10^{-2}	3.67×10^{-2}	1.84×10^{-1}	3.67×10^{-2}	1.10×10^{-1}	3.67×10^{-2}
Chromium	0.00	0.00	0.00	0.00	6.60×10^{-3}	0.00
Aluminum	2.92×10^{-1}	3.24×10^{-1}	2.89×10^{-1}	3.06×10^{-1}	2.91×10^{-1}	3.12×10^{-1}

As in the study of the maximum environmental impact, alloy #5 (Al Si9Cu3(Fe)(Zn)) contributes to the highest percentage decrease of environmental impact from balanced to minimum values, with a decrease of 8.9%, from 9.44×10^{-1} to 8.60×10^{-1} pts. This impact is mainly decreased by magnesium, which decreases 9.49×10^{-3} pts from the balanced composition value. By contrast, the alloys that show the lowest decrease are alloy #2 (Al Si5Mg) and alloy #4 (Al Si10Mg(Fe)), whereas in alloy #5 the environmental impact is mainly decreased by magnesium in both alloy #2 and #4.

Finally, once the balanced, maximum and minimum environmental impacts of all aluminum alloys were analyzed, it can be seen that those alloys with the highest environmental impact (alloy #3 and alloy #5) are the ones that show the highest difference between maximum and minimum environmental impact, with values of 1.72×10^{-1} and 1.67×10^{-1} pts, respectively.

4.4. Study of the Environmental Impact of an LED Luminaire Housing

One of the applications of these alloys is to manufacture LED luminaire housings. LED luminaires generate a significant amount of heat that has to be dissipated away from the electronic components to ensure proper performance and avoid failure. That is achieved in weatherproof luminaires using a 1.4 kg aluminum housing. This housing is manufactured out of an aluminum alloy into a mold using a die casting machine with a locking force of 12,000 kN. Of all the studied alloys, the luminaire under study is made out of alloy #1 (Al Si12Cu1(Fe)) which offers good manufacturability and machinability for the component. It has an excellent fluidity that makes it suitable for thin-wall casting (Figure 2), thanks to a high silicon content. Other relevant alloying elements are nickel, which is used to increase the strength, and tin, which increases machinability. Focusing on the alloy properties, and taking into account the use for an LED luminaire housing, the selected alloy offers the lowest expansion coefficient and the highest elastic limit of all the six analyzed alloys. It also provides an adequate range of thermal conductivity, which is useful to enhance the thermal behaviour of the LED system.

Figure 2. LED luminaire.

Due to its specific composition, the environmental impact of this component, should not be calculated with standard datasets such as "Aluminium, cast alloy {GLO}" or "Aluminium alloy, AlMg3 {RER}", available in EcoInvent, as it has been demonstrated that the differences in environmental impact are relevant. Table 10 compares the impact with EcoInvent's proxy and the selected alloy. There is an increase of between 0.158 and 0.179 pts per housing if compared with the AlMg3 alloy; moreover, the environmental impact is up to 127% higher than the standard aluminum cast alloy described by EcoInvent. This is a clear example of the influence of the alloy composition on the environmental impact results.

Table 10. Environmental impact of the material of a LED luminaire housing.

Material Dataset	LED Luminaire Housing Material ReCiPe Impact (pts)	LED Luminaire Housing Material CO_2 IPCC 2013 GWP (100 y) (kg CO_2 eq.)
Aluminium, cast alloy {GLO}	4.778×10^{-1}	4.472
Aluminium alloy, AlMg3 {RER}	9.037×10^{-1}	9.748
Minimum impact alloy #1 Al Si12Cu1(Fe)	1.056	6.182
Balanced alloy #1 Al Si12Cu1(Fe)	1.070	6.328
Maximum impact alloy #1 Al Si12Cu1(Fe)	1.083	6.473

In order to show the magnitude of the environmental impact of this case study, the Global Warming Potential (GWP) expressed in kg CO_2 eq., is also given in the tables of this subsection. Under this impact category, the calculated carbon footprint decreases between 3.28 and 3.57 kg CO_2 eq. per housing when compared with the AlMg3 alloy. For GWP, the impact of the analyzed alloy decreases, as some of the alloying elements, such as copper or tin, have a significant impact on ReCiPe endpoint methodology, and a relatively lower one in this category.

To show broader analysis of this case study, the system boundaries for this case study have been expanded to include the manufacturing process in of this LED luminaire housing in a die casting machine. Table 11 shows the same information as Table 10, but considering the environmental impact of the produced part (materials plus production processes).

From these results it can be said that on the one hand, as previously shown in Table 10, using balanced alloy #1 allowed us to obtain a more precise environmental impact, which in this case is lower in GWP than the value obtained with the AlMg3 EcoInvent dataset, but higher under ReCiPe endpoint methodology. On the other hand, analyzing the environmental impact considering the production process shows the great relevance of material production, and therefore its composition, on the overall environmental impact. Focusing on alloy #1, the material production generates between 83.8% and 84.1% of the total impact under the ReCiPe methodology, and between 73% and 73.9% under Global Warming Potential.

Table 11. Environmental impact of the material plus manufacturing process of an LED luminaire housing.

Material Dataset	Produced LED Luminaire Housing (Material + Manufacturing) ReCiPe Impact (pts)	Produced LED Luminaire Housing (Material + Manufacturing) CO_2 IPCC 2013 GWP (100 y) (kg CO_2 eq.)
Aluminium, cast alloy {GLO}	6.826×10^{-1}	6.759
Aluminium alloy, AlMg3 {RER}	1.109	1.204×10
Minimum impact alloy #1 Al Si12Cu1(Fe)	1.261	8.469
Balanced alloy #1 Al Si12Cu1(Fe)	1.275	8.615
Maximum impact alloy #1 Al Si12Cu1(Fe)	1.288	8.760

5. Conclusions

This article highlights the importance of considering the material composition in order to properly assess the environmental impact of aluminum casting alloys, allowing engineers not only to compare these alloys based on cost or mechanical properties, but also to determine a more precise environmental impact. The influence of the alloy composition has been analyzed by means of Life Cycle Assessment, using the EcoInvent AlMg3 aluminum alloy dataset as a reference.

As standards define aluminum casting alloys with composition ranges, once the EcoInvent v3 dataset was updated with the material composition of the mentioned alloys, the balanced, maximum and minimum environmental impact values have been obtained using these ranges.

In general, the overall impact of the studied balanced aluminum alloys (Al Si12Cu1(Fe), Al Si5Mg, Al Si9Cu3Zn3Fe, Al Si10Mg(Fe), Al Si9Cu3(Fe)(Zn) and Al Si9), using the ReCiPe endpoint methodology, varies from 6.09×10^{-1} pts to 1.01 pts per kg, depending on the alloy composition. These results are significantly different from the EcoInvent AlMg3 dataset, in which the impact is 6.36×10^{-1} pts per kg. Some of the alloying elements that contribute to increased environmental impact are copper and tin. Furthermore, most of the studied alloys have raw materials such as magnesium, chromium and silicon, which are considered critical raw materials by the European Union due to their supply risk and economic importance.

When analyzing the maximum and minimum environmental impact of the aluminum alloys, the impact varies from 5.98×10^{-1} pts to 1.09 pts per kg. The alloy that has the highest uncertainty is alloy #5 (Al Si9Cu3(Fe)(Zn)), with a range of $\pm 9\%$, due to copper and silicon.

The LED luminaire Al Si12Cu1(Fe) housing case study has shown the relevance of taking the composition into account, with average differences from EcoInvent's proxy of 0.17 pts in ReCiPe and 3.4 kg CO_2 eq. per housing in GWP. Also, the importance of the material impact on the production process has been shown.

Supplementary Materials: The following are available online at www.mdpi.com/1996-1944/9/6/412/s1.

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9.5. MATERIALS: INFLUENCE OF THE COMPOSITION ON THE ENVIRONMENTAL IMPACT OF SOFT FERRITES.

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Influence of the Composition on the Environmental Impact of Soft Ferrites

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Abstract: The aim of this paper is to better understand the influence of the composition on the environmental impact of soft ferrite magnetic materials. Magnetically soft ferrites are ceramic homogeneous materials that have a cubic crystal structure. Soft ferrites have low coercitivity with a high resistivity, low losses and high permeability, and are commonly used in high frequency applications. A life cycle assessment (LCA) has been carried out analyzing EcoInvent average ferrite dataset and updating it with material compositions of manganese-zinc (MnZn) ferrites, one of the major categories of soft ferrites. MnZn ferrites use iron oxide as their main component adding manganese oxide (17%-24.5% in weight) and zinc oxide (6.5%-14% in weight). Depending on their composition, their magnetical properties change (such as permeability, losses, Curie temperature…). The influence of the material composition has been assessed, obtaining more knowledge of their environmental impact. The main environmental problem that generates the use of soft ferrites, under ReCiPe methodology, is in the metal depletion category. Ferrites use in their composition metals that are scarce, such as Manganese. Manganese is included in the 2017 EU strategic materials list due to its high economic importance in the EU industry, and also its supply risk. The software used to develop the LCA model was SimaPro 8.4, with EcoInvent v3.4 life cycle inventory database. Both are currently the most used tools to evaluate environmental impact in the LCA scientific community. By means of the performed LCA, environmental impact values under ReCiPe methodology will be obtained to assess the influence of the composition on the overall impact. This analysis shows the large influence of material composition on the environmental impact of ferrites, allowing engineers and material scientist to choose between different ones taking also into account its sustainability.

Keywords: Soft ferrites; magnetic materials; MnZn; material composition; environmental impact; critical raw materials.

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1. Introduction

Ferrites started to be used in the industry in the middle of the 20th century [1]. The main uses of ferrites in its origins were mainly in electronic devices: transformers, anti-electromagnetic filters or magnetic recording media [2-7]. Apart from previous applications, nowadays, the use of ferrites is increasing in other types of electronic devices such as televisions and radios, thanks to their low cost and their mechanical resistance [8]. Although the use of ferrites has mainly been focused on electronic components, they are also used in different applications, like in wastewater treatments [9-11], as a catalyst to increase the reaction rate of chemical reactions [12], or as an indicator in magnetic resonances [13] or in hyperthermia treatments [14].

Ferrites are mainly classified according to their chemical formula and they can be spinel, garnet, hexaferrites and orthoferrites. The most used are spinel type which have the next chemical formula

MFeO where M are metallic cations like the cobalt [15-17], manganese-zinc alloy [18] [19] or other metals like iron [20], and FeO are iron oxides.

The chemical formula and the structure give these compounds different properties that change depending on the cation used and the sites occupied by the both types of atoms due to the magnetic moments [21]. These properties can be high magnetic permeability, high resistivity and high Curie temperature [22].

Also, depending on the composition the environmental impact changes. Although iron oxides are usually in higher proportion than metallic cations, most of the impact of these compounds are caused by the cations, as many of these materials have high environmental impact and some are classified as critical. Critical materials are defined by different criteria such as ecological risk, supply risk or economy vulnerability [23-26].

Because of these reasons, it is important to obtain the environmental impact value taking into account the composition. One of the main methodologies to measure environmental impact is the Life Cycle Assessment (LCA). LCA evaluates the environmental impact of a product, material, service, process or the whole life cycle [27-29]. There are many examples of LCA applied to different products such as induction hobs [30] or luminaires [31].

LCA helps companies to evaluate how the environmental impact is generated, and modify the product to reduce the environmental impact in the design phase, instead of correcting it later. This process is called ecodesign [32-34].

LCA relies on large Life Cycle Inventory (LCI) databases, as EcoInvent, which help to assign each material, process or transport an environmental impact. The problem of these databases is that only have got a limited amount of compositions, therefore reducing the accuracy of the environmental impact results [35] [36].

The aim of this paper is to better understand the influence of the composition on the environmental impact of soft ferrite magnetic materials. A LCA has been carried out analyzing EcoInvent average ferrite dataset and updating it with material compositions of manganese-zinc (MnZn) ferrites, one of the major categories of soft ferrites. These soft ferrites (Figure 1) have low coercitivity with a high resistivity, low losses and high permeability, and are commonly used in high frequency applications.

Figure 1. MnZn soft ferrite.

2. Methods

This research is based on EcoInvent ferrite, but focusing on MnZn soft ferrites, which have a wide range of composition depending on the amount of Zinc and Manganese Oxides.

Table 1 shows the minimum and maximum molar percentages of MnZn [37]. These percentages have to be transformed to mass percentages (Table 2) in order to quantify the environmental impact of 1 Kg of soft ferrite material.

Table 1. Material molar composition percentage of soft ferrites.

Molar Percentage	Fe_2O_3	ZnO	MnO
Minimum (%)	50	10	30
Maximum (%)	60	30	40

Table 2. Material mass composition percentage of soft ferrites.

Mass Percentage	Fe_2O_3	ZnO	MnO
Minimum (%)	68,0	6,5	17,0
Maximum (%)	76,5	14,0	24,5

The percentages composition ranges shown in Table 2 establish all the possible composition combinations for soft ferrites, based on the molar composition shown in Table. Figure 2 shows the composition diagram for MnZn ferrites.

Figure 2. MnZn soft ferrite composition diagram.

The aim of this LCA is to analyze the influence of the composition on the environmental impact of MnZn soft ferrites. So, ISO 14040 and 14044 standards have been followed. EcoInvent dataset "Ferrite production {GLO}" has been used as a base, to make the same assumptions that EcoInvent, but it has been updated to include the composition of MnZn soft ferrites.

2.1. Functional Unit and System Boundaries

In order to carry out a proper LCA, the functional unit has to be defined. In this research, the functional unit is the production of 1 kg of MnZn soft ferrite.

The LCA has been carried out to assess the environmental impact of a wide range of ferrite compositions (Table 2) but also considering raw material acquisition, energy consumption (electricity, natural gas) and the infrastructure efforts. Following EcoInvent methodology, market datasets have been used to consider the transportation processes of raw materials from average providers to a ferrite manufacturing plant.

2.2. Inventory Data and Assumptions

The software used to develop the LCA model was SimaPro 8.4, with EcoInvent v3.4 LCI database. Both are currently the most used tools to evaluate environmental impact in the LCA scientific community. Table 3 shows the selected EcoInvent datasets for the main materials. In order to evaluate the environmental impact, ReCiPe endpoint methodology was used. ReCiPe is makes the results easy to analyze from an engineering point of view, making it easier to select between different materials [36].

Table 3. EcoInvent dataset selection.

Material	Dataset
Iron Oxide	market for portafer - GLO
Zinc Oxide	market for zinc oxide - GLO
Manganese Oxide	market for manganese - GLO

3. Results and Discussion

In this section, the results of the LCA study are shown. Using the composition ranges of Table 2, a MonteCarlo analysis is carried out to assess the environmental impact of samples that comply with the composition range. For this study, 68 different MnZn soft ferrites were calculated. The main results are shown in Table 4.

Table 4. Minimum, maximum and average environmental impact in ReCiPe methodology.

-	Fe_2O_3 (%)	ZnO (%)	MnO (%)	Environmental Impact (mPt/Kg)
Minimum	76,5	6,5	17,0	1571,6
Average	70	10	20	1833,3
Maximum	68	7,5	24,5	2223,9

Table 4 shows that, under ReCiPe methodology, a ferrite with 6.5% ZnO and 17% MnO has the lowest environmental impact, whereas the ferrite with 7.5% ZnO and 24.5% creates the highest environmental impact. These differences are created by the percentage of Manganese, as this material has a high environmental impact per Kg. In all cases, the environmental impact of soft ferrites, under ReCiPe methodology, is mainly cause in the metal depletion category due to the use of scarce metals such as Manganese. Manganese is also included in the 2017 EU strategic materials list due to its high economic importance in the EU industry, and its supply risk.

Figure 3 allows us to analyze these results in depth. The composition that creates the lower environmental impact is the one with a lowest Manganese and Zinc oxides composition percentages. This means that it has the highest Iron oxide percentage. Focusing on the environmental impact under ReCiPe methodology, the presence of Manganese oxide generates almost 95% of the overall environmental impact. Iron oxide creates 3.63% of the impact whereas production process only account to 1.1%. The presence of Zinc oxide is the one that produces the lower environmental impact percentage.

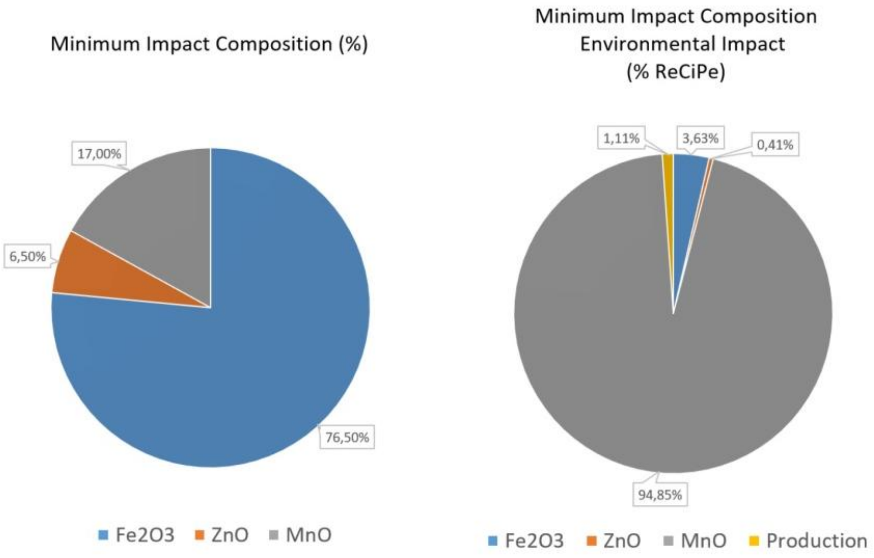

Figure 3. MnZn soft ferrite with minimum environmental impact.

Figure 4 shows the composition and environmental impact for the average soft ferrite. The composition has average values for all the used materials. Analyzing how the environmental impact is created under ReCiPe methodology allow us to obtain that the presence of Manganese oxide causes 95.7% of the impact. Iron oxide generates 2.8% of the impact while the production process of this ferrite are below 1%. In addition, the use of Zinc oxide is the one that produces the lower environmental impact percentage.

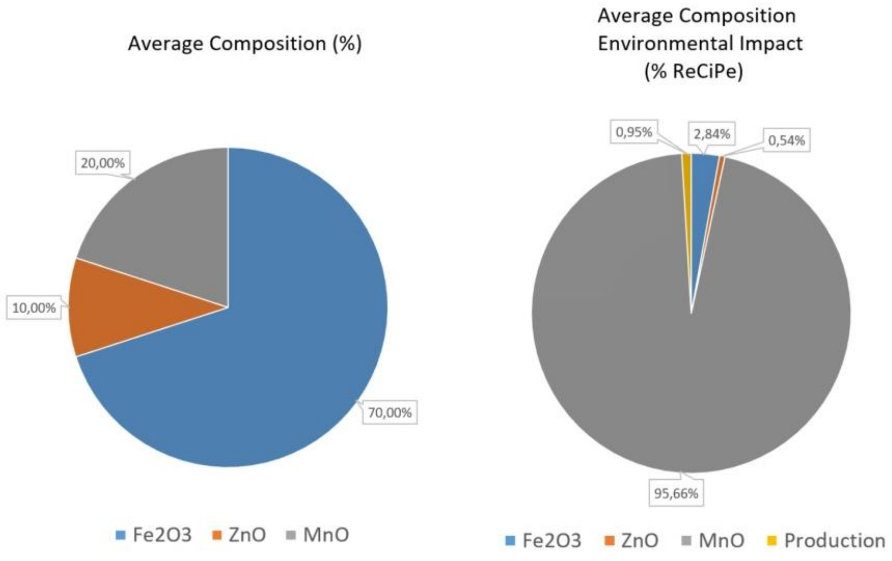

Figure 4. MnZn soft ferrite with average environmental impact.

On the other hand, Figure 5 represents the ferrite with the maximum environmental impact. The composition is the one with the highest Manganese oxide percentage, all almost the lowest percentages for Iron and Zinc Oxides. From an environmental impact point of view, the use of Manganese oxide produces 96.6% of the impact, while Iron oxide only creates 2.28% of the impact and production process only account to 0.78%. The presence of Zinc oxide also creates for this ferrite the lowest environmental impact percentage.

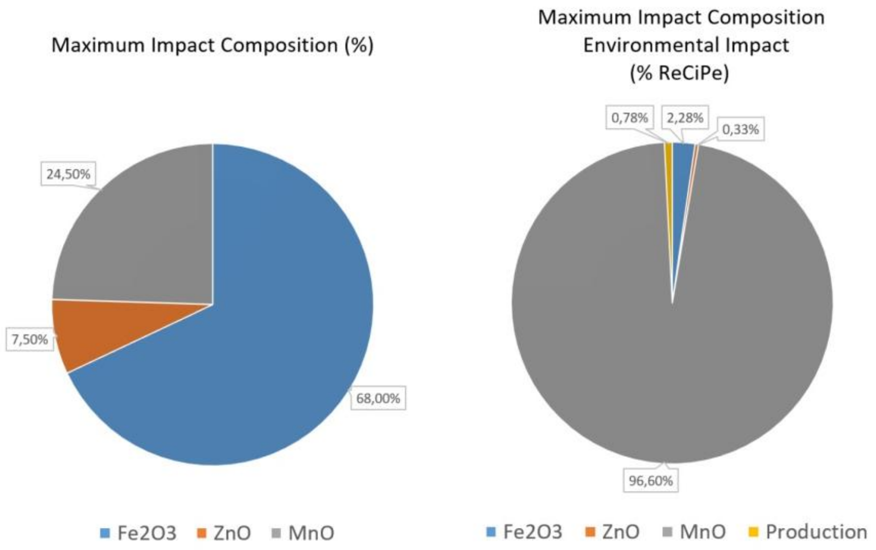

Figure 5. MnZn soft ferrite with maximum environmental impact.

Figure 6 represents all the analyzed ferrites composition. These values have been arranged from lower to higher environmental impact, showing that the presence of Manganese Oxide supposes the highest influence on the environmental impact.

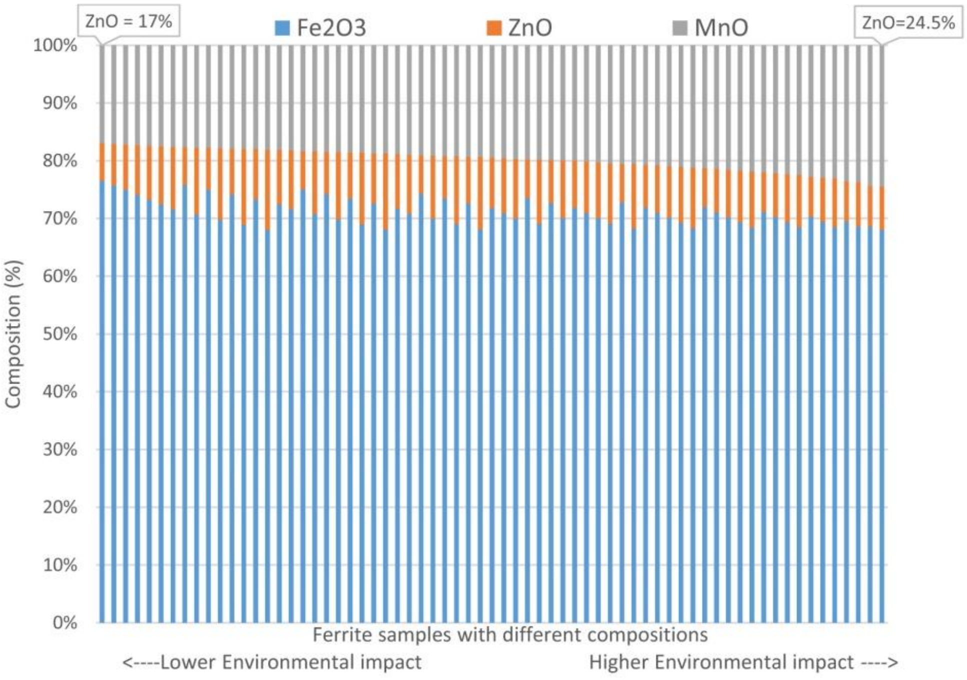

Figure 6. Range of the analyzed MnZn soft ferrite compositions.

Figure 7 shows all the calculated environmental impact for all the ferrites composition. These values have also been arranged from lower to higher environmental impact, showing that the distribution is homogeneous.

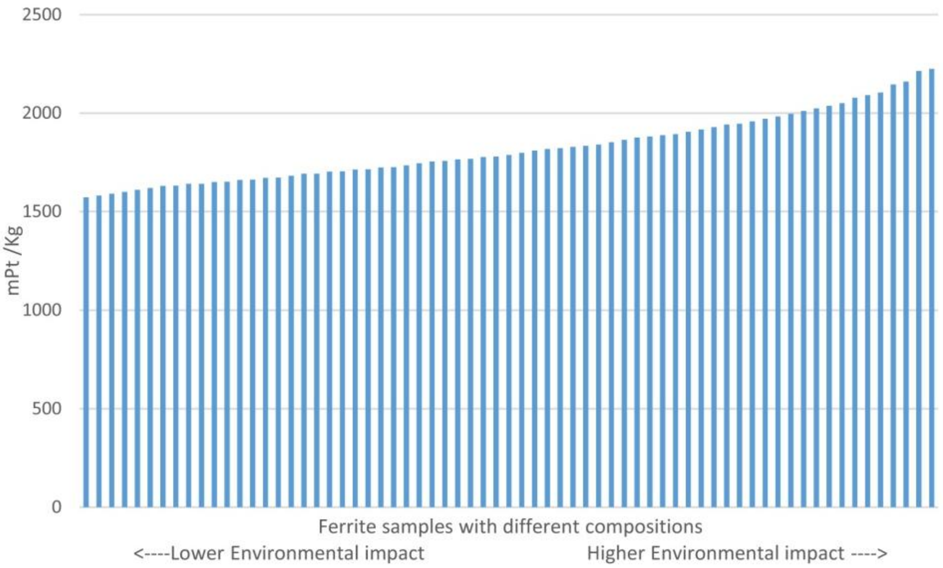

Figure 7. Range of environmental impact of 1Kg of MnZn soft ferrite depending on the composition.

When comparing all the results of Figure 7, almost a 42% difference can be found between the lowest and highest environmental impact. This difference is more important when comparing these results with EcoInvent´s “Ferrite production {GLO}”, which is shown in Table 5.

Table 5. EcoInvent ferrite dataset environmental impact in ReCiPe methodology.

Fe_2O_3 (%)	ZnO (%)	MnO (%)	Environmental Impact (mPt/Kg)
55,0	15,0	30,0	2704,0

As we can see analyzing Table 5, EcoInvent ferrite composition has a higher Manganese content than the MnZn soft ferrites that are analyzed in this article. As previously explained, this manganese presence generates a high environmental impact, which can be up to 72% higher than the minimum environmental impact ferrite that has been calculated in this article with 6.5% ZnO and 17% MnO. Analyzing Figure 8, it shows us that as EcoInvent ferrite composition has a higher Manganese Oxide content, this presence also creates the highest environmental impact, almost 97.3%. The second contribution is caused by Iron Oxides, with 1.5%, which is a lower percentage of all the analyze ferrites. Production processes generate 0.64% while Zinc oxides produce 0.55%, the highest impact of all the studied ferrites.

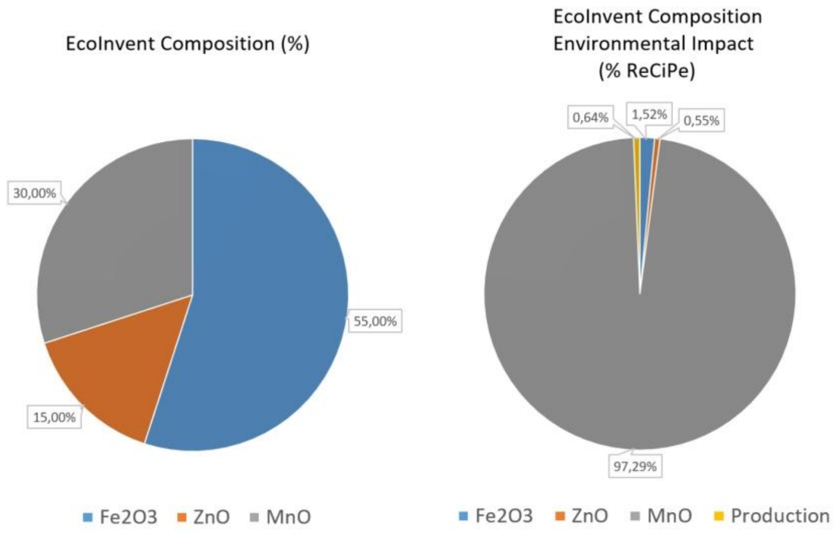

Figure 8. MnZn soft ferrite.

4. Conclusions

This article shows the importance of considering the material composition in order to accurately assess the environmental impact of MnZn soft ferrites. This will allow engineers to compare these ferrites based on cost, properties, but also environmental impact. To do that, EcoInvent "Ferrite production {GLO}" has been used as a reference, but customizing the composition ranges of MnZn soft ferrites.

The impact per Kg of the studied ferrites, using the ReCiPe endpoint methodology, varies from 1571,6 mPt to 2223,9 mPt, depending on the ferrite composition. These values are significantly different from the one from EcoInvent: 2704 mPt per Kg. This difference is mainly caused by the higher content of Manganese in EcoInvent's ferrite, as Manganese material has the highest environmental impact per Kg in a ferrite. This analysis shows the large influence of material composition, especially due to the presence of Manganese, allowing material scientist and engineers to be able to choose between different soft ferrites taking also into account its sustainability.

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Author Contributions: Patricia Gómez is responsible of customizing the analyzed datasets, processing the data and making the calculations using the environmental impact assessment software SimaPro; all mentioned in collaboration with Daniel Elduque. Carlos Javierre performed the first draft of the article, taking an active part in the entire manuscript and its conclusions. Carmelo Pina helped with the analysis of the results also to the final state of the article and its conclusions. All of the authors participated in the writing and correction of this article and they all agree to its final version.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LCA: Life Cycle Assessment
LCI: Life Cycle Inventory

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9.6. MATERIALS: INFLUENCE OF THE COMPOSITION ON THE ENVIRONMENTAL IMPACT OF SOFT FERRITES.

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Influence of the Composition on the Environmental Impact of Soft Ferrites

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Abstract: The aim of this paper is to analyze the influence of the composition on the environmental impact of the two main types of soft ferrites, allowing scientists and engineers to compare them based not only on cost and properties, but also on an environmental point of view. Iron oxides are the basis of soft ferrites, but these ferrites have a wide range of compositions, using materials such as manganese or nickel, which affect their magnetic properties, but also modify the environmental impact. A Life Cycle Assessment has been carried out for manganese-zinc (MnZn) and nickel-zinc (NiZn) soft ferrites, with a Monte Carlo approach to assess multiple compositions. The LCA model was developed with SimaPro 8.4, using the EcoInvent v3.4 life cycle inventory database. Environmental impact values were calculated under the ReCiPe and Carbon Footprint methodologies, obtaining a broad variety of results depending on the composition. The results were also significantly different from the standard EcoInvent ferrite. For the analyzed soft ferrites, the presence of manganese or nickel is a key factor from an environmental perspective, as these materials involve high environmental impacts, and their supply risk has increased during recent years, making them a concern for European manufacturers.

Keywords: LCA; soft ferrites; magnetic materials; MnZn; NiZn; material composition; environmental impact; critical raw materials

1. Introduction

Issues such as pollution and climate change have caused people's concern about environmental impacts to increase exponentially. At the end of the 20th century, the concept of Ecodesign started, with the aim of prevention during the design stage, instead of correction afterward [1]. Following these ecological trends, enterprises are making efforts to reduce the environmental impact of their products, processes, and waste [2,3]. Standards such as ISO 14006 promote minimal environmental impact on product development [4], and several policies, such as EuP 2005/32/CE and ErP 2009/125/CE, contribute to a green economy and Ecodesign in the European Union [5–8].

For all these reasons, during the design of a new product, material selection is considered one of the main influences on the entire life cycle, and therefore it is essential to assess the environmental impact of materials accurately, taking into account their actual composition [9–11].

One of the primary methodologies to measure environmental impact is Life Cycle Assessment (LCA). LCA evaluates the environmental impact of a product, material, service, or process [12–14]. There are many examples of LCA applied to specific materials such as asphalt or concrete road pavement materials [15], wood [16], plastics [17]; or metallic materials such as lead [18], steel [19]

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a and aluminum [20]. Other authors have focused their studies on methods to reduce the overall consumption of raw materials, especially, of critical raw materials [21].

LCA helps companies evaluate how environmental impact is generated, enabling them to modify and reduce the environmental impact of their products in the design phase, instead of correcting it later [11,22,23]. LCA relies on large Life Cycle Inventory (LCI) databases, such as EcoInvent, which helps to assign each material, process, or transport an environmental impact. The problem with these databases is that they only have a limited amount of datasets, therefore reducing the accuracy of the environmental impact results [9,24]. To properly assess the environmental impact, it is key to consider the exact material composition. Industries, enterprises, and governments are currently using LCA to analyze the environmental impact, and also to assess their material consumption and supply risk [25]. During recent years, the European Union and other governments and associations have developed a list of materials that are considered strategic due to their economic importance and supply risk. Those materials with both high risk and high importance are called critical raw materials [26].

This paper aims to examine and better understand the influence of the composition on the environmental impact of soft ferrite magnetic materials. Ferrites use materials such as manganese or nickel, which are included on those lists.

Ferrites started to be used in the industry in the middle of the 20th century, after they were discovered by Dr. Kato and Dr. Takei in 1930 [27]. The main applications of ferrites were in electronic devices: transformers, anti-electromagnetic filters, or magnetic recording media [28–33]. Apart from those applications, nowadays the consumption of ferrites is increasing in other types of electronic devices, such as televisions and radios, thanks to their low cost and mechanical resistance [34]. Although the use of ferrites has mainly been focused on electronic components, they are also used in different applications, for example, in wastewater treatments [35–37], as a catalyst to increase the reaction rate of chemical reactions [38], as indicators in magnetic resonance [39], or in hyperthermia treatments [40].

Ferrites are mainly classified according to their chemical formula in: spinel, garnet, hexaferrites, and orthoferrites. Spinel is the most used type, and its chemical formula is MFeO, where M are metallic cations like cobalt [41–43], manganese-zinc alloy [44,45], nickel-zinc or other metals like iron [46]; and FeO are iron oxides [47]. Their chemical formula and structure gives these compounds different properties, such as high magnetic permeability, high resistivity, or high Curie temperature [48,49]. They are also classified into hard and soft ferrites depending on their resistance to being demagnetized [47]. Hard ferrites are considered excellent magnetic materials or even permanent magnets due to their high resistance to being demagnetized. The second type, soft ferrites, have low coercivity, changing their magnetization easily; therefore, they are excellent magnetic cores for induction fields.

In the case of soft ferrites, the two main types are manganese-zinc (MnZn) and nickel-zinc (NiZn). Both have similar properties: low coercivity with high resistivity, low losses, and high permeability. They are commonly used in high-frequency applications, and both types share a common working area for frequencies between 10^{-2} and 1 MHz frequency, as well as an initial permeability of around 10^3 [47]. This study focuses on comparing these two types of soft ferrites from an environmental point of view, as composition changes involve modifications of the environmental impact. Although iron oxides are usually in higher proportion than metallic cations, the latter generate most of the environmental impact of these compounds, as many of these metallic cation materials (such as manganese or nickel) have an important environmental impact.

Since 2011, every three years the European Union assesses how critical raw materials are for their economy, following a specific methodology that considers criteria such as supply risk and economic importance [50–53]. In the last report, 27 materials were defined as critical by the EU out of the 78 strategic materials analyzed [54,55]. Manganese, nickel, and zinc, included in the analyzed soft ferrites, were considered as strategic materials in the last 2017 EU report. According to it, manganese has a high supply risk, given that 90% of the EU supply comes from only three countries, and it is of significant economic importance as it is related to the production of steel and other non-steel alloys. Nickel also has high economic importance as it is used in stainless steel and other steel alloys, but its supply is more diversified, therefore presenting lower risk. Finally, zinc is characterized with similar economic importance and supply risk as nickel. It is mainly used for steel and zinc alloys [54].

In this paper, a LCA has been carried out analyzing the EcoInvent ferrite dataset and customizing it with material compositions of manganese-zinc (MnZn) and nickel-zinc (NiZn) ferrites, the two major categories of soft ferrites.

2. Methods

This research is based on the EcoInvent ferrite dataset, but customized to MnZn and NiZn soft ferrites, which have an extensive range of compositions depending on their amount of zinc, nickel, and manganese oxides.

2.1. Functional Unit and System Boundaries

In order to carry out an LCA, the functional unit is defined as the production of 1 kg of soft ferrite. Therefore, all the results are shown on a kilogram basis.

The LCA has been carried out to assess the environmental impact of a wide range of MnZn and NiZn ferrite compositions. Considering the selected functional unit, a cradle to gate approach has been followed, including raw materials and ferrite production. The first stage includes Raw Material Acquisition (RMA) and its transportation to the factory, whereas the manufacturing stage considers all the related inputs: energy consumption (electricity, natural gas, coal, etc.), and the infrastructure efforts. Distribution to the customer, use phase, and end of life are outside of the boundaries of our consideration, as the aim of this study is to investigate the influence of the variation of the composition. The system boundaries are shown in Figure 1.

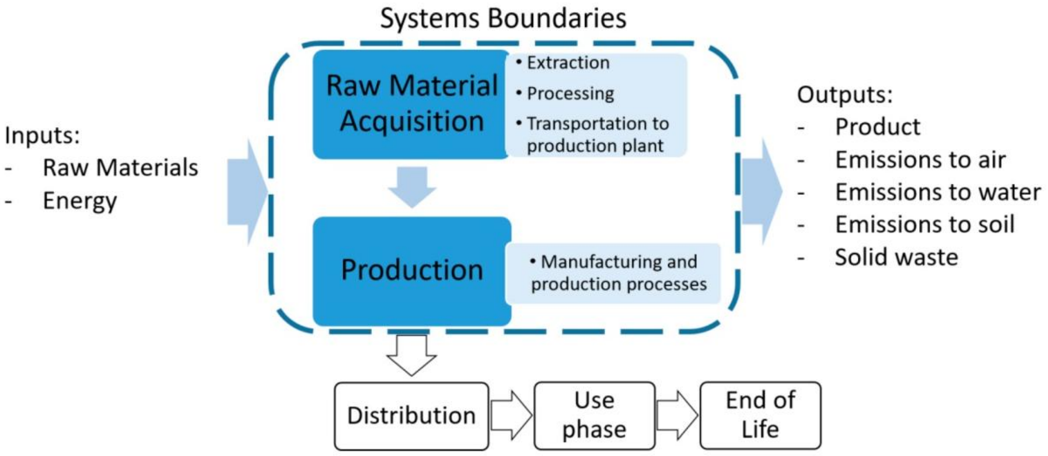

Figure 1. System boundaries.

Following the EcoInvent methodology, market datasets have been used to consider the transportation processes of raw materials from average providers to a ferrite manufacturing plant [56]. To consider these life cycle stages, the ISO 14040 and 14044 standards have been followed [57,58].

2.2. Inventory Data and Assumptions

The software used to develop the LCA model was SimaPro 8.4 [59], with the EcoInvent v3.4 LCI database, one of the most well-known databases, which is developed by the Swiss Center for Life Cycle Inventories [56]. Both are currently the most used tools to evaluate environmental impact in the LCA scientific community.

This LCA aims to analyze the influence of the composition on the environmental impact of soft ferrites. The EcoInvent dataset "Ferrite production {GLO}" has been used as a reference, following the EcoInvent methodology and assumptions, but customizing it to include compositions of MnZn and NiZn soft ferrites. Table 1 shows the selected EcoInvent datasets for the ferrite materials.

Table 1. EcoInvent dataset selection.

Material	Dataset
Iron Oxides	market for portafer—GLO
Zinc Oxide	market for zinc oxide—GLO
Manganese Oxide	market for manganese—GLO
Nickel Oxide	market for nickel—GLO

In order to evaluate the environmental impact, the ReCiPe EndPoint (H/A) and IPCC 2013 Carbon footprint GWP100a methodologies were used [59]. ReCiPe considers a wide range of environmental impact categories, and its EndPoint approach makes the results easier to analyze from an engineering point of view, allowing us to perform easier comparisons between different materials. On the other hand, the IPCC 2013 Carbon footprint GWP100a establishes the emissions generated by a product expressed as Carbon Dioxide equivalents, focusing only on one environmental impact category, that is, Climate Change, which has special social relevance.

2.3. Life Cycle Inventory

After establishing the LCA framework, the Life Cycle Inventories have to be defined for both MnZn and NiZn soft ferrites.

Table 2 shows the minimum and maximum molar percentages of MnZn [60]. These percentages have to be transformed into mass percentages (Table 3) in order to quantify the environmental impact of 1 kg of soft ferrite material.

Table 2. Material molar composition percentage of MnZn soft ferrites.

Molar Percentage	Fe_2O_3	ZnO	MnO
Minimum (%)	50	10	30
Maximum (%)	60	30	40

Table 3. Material mass composition percentage of MnZn soft ferrites.

Mass Percentage	Fe_2O_3	ZnO	MnO
Minimum (%)	68.0	6.5	17.0
Maximum (%)	76.5	14.0	24.5

Table 4 shows the minimum and maximum molar percentages of NiZn [60]. As in the previous ones, these percentages have been transformed into mass percentages (Table 5).

Table 4. Material molar composition percentage of NiZn soft ferrites.

Molar Percentage	Fe_2O_4	ZnO	NiO
Minimum (%)	50	10	5
Maximum (%)	50	90	45

The percentages composition range shown in Tables 3 and 5 establish all the possible composition combinations for soft ferrites, based on the molar composition shown in Tables 2 and 4.

Table 5. Material mass composition percentage of NiZn soft ferrites.

Mass Percentage	Fe_2O_4	ZnO	NiO
Minimum (%)	68.5	3.2	2.9
Maximum (%)	70.0	28.6	28.8

Table 6 shows the inventory for the production processes of 1 kg of soft ferrite. These values are obtained from the EcoInvent data.

Table 6. Production processes from the EcoInvent inventory for soft ferrites.

Input	Quantity per kg
Production processes electricity consumption	0.01 kWh
Production processes heat (natural gas)	0.0363 MJ
Production processes heat (anthracite)	1.0064 MJ
Production processes heat (other sources)	0.4236 MJ
Infrastructure efforts	2.5×10^{-11} factories

As previously explained, market datasets have been used to consider the transportation processes of raw materials from average providers to a ferrite manufacturing plant. Table 7 shows the used EcoInvent data.

Table 7. EcoInvent distances and mode of transportation from suppliers to the manufacturing plant.

Material	Mode of Transport	Kilometers
Iron Oxides	Truck	86
	Train	191
	Freight ship	5851
Nickel Oxide	Truck	361
	Train	345
	Freight ship	400
Zinc Oxide	Truck	209
	Train	309
	Freight ship	624
Manganese Oxide	Truck	361
	Train	345
	Freight ship	400

Figure 2 shows the composition diagram for MnZn ferrites, and Figure 3 for NiZn ferrites. As there are multiple composition combinations, for each ferrite a wide variety of compositions are going to be calculated. For this research, a Monte Carlo analysis is carried out in order to analyze the environmental impact of an extensive range of soft ferrites compositions. In order to do that, the input values to obtain 1 kg of soft ferrite have been modified for each of the materials, considering a uniform distribution. This means that any value within the composition ranges (Tables 3 and 5) is as probable as the others. The rest of the inventory values of this study have been considered constant in this Monte Carlo approach.

The Monte Carlo analysis first provides the calculated material inputs, and then, the environmental impact results are calculated. These input values have to be normalized to 1 kg of soft ferrite, which is the functional unit, and checked to make sure that they comply with the composition ranges (e.g., 765 g of Fe_2O_3 + 245 g of MnO + 140 g of ZnO can be provided by the Monte Carlo analysis; but when normalized to 1000 g of ferrite, the Fe_2O_3 content is 648.3 g, 64.8%, and therefore outside of the defined range).

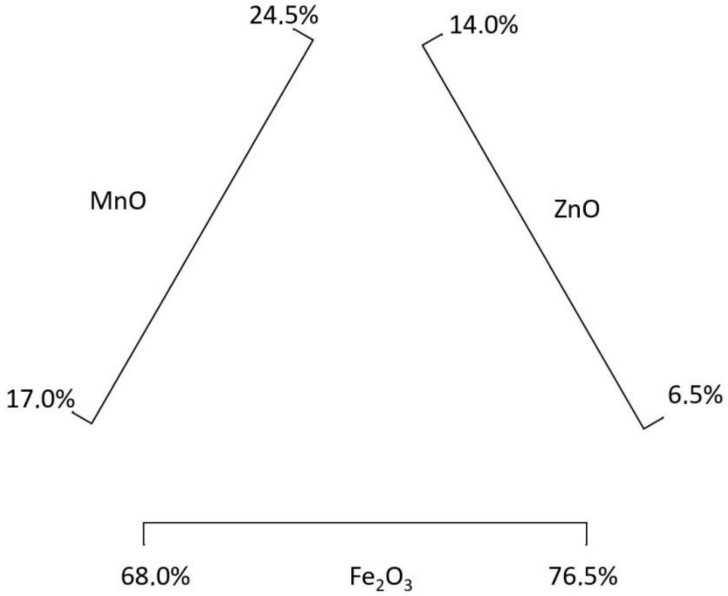

Figure 2. MnZn soft ferrite composition diagram.

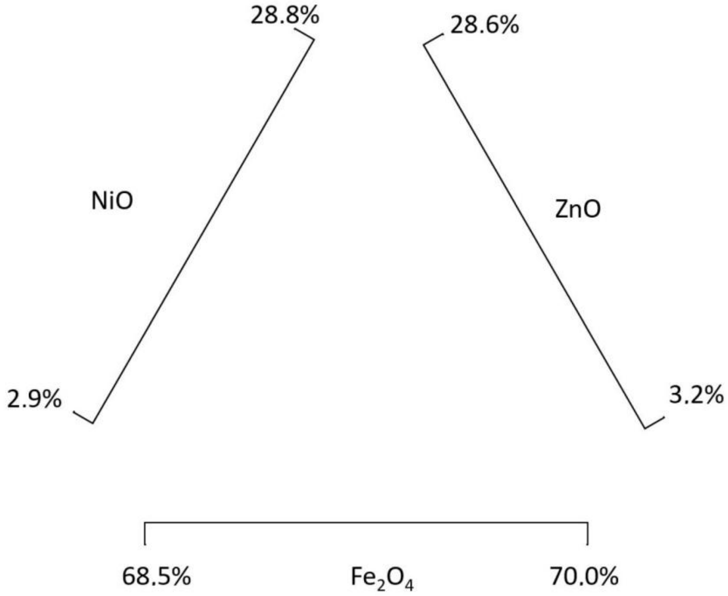

Figure 3. NiZn soft ferrite composition diagram.

3. Results and Discussion

In this section, the results of the LCA study are given. Using the composition ranges of Tables 3 and 5, a Monte Carlo analysis was carried out to assess the environmental impacts of soft ferrites that complied with the respective composition range. In total, 67 MnZn and 67 NiZn soft ferrites were analyzed. Table 8 shows the main environmental impact results of MnZn ferrites, indicating maximum, average, and minimum environmental impact combinations in Figure 4, whereas the results for NiZn are shown in Table 9 and represented in Figure 5. These results consider all the stages within the system boundaries.

Table 8. Minimum, maximum, and average environmental impact of 1 kg MnZn soft ferrite (RMA + Production).

	Fe_2O_3 (%)	ZnO (%)	MnO (%)	ReCiPe (mPt/kg)	IPCC 2013 (kg CO_2 eq.)
Minimum	76.5	6.5	17.0	1571.6	1.026
Average	70	10	20	1833.3	1.156
Maximum	68	7.5	24.5	2223.9	1.292

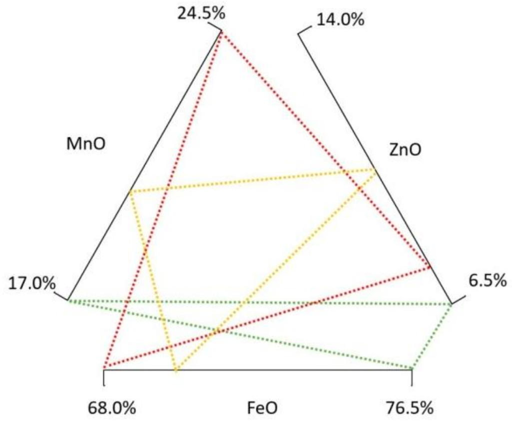

Figure 4. MnZn soft ferrite environmental impact diagram.

For MnZn ferrites, impacts range from 1572 mPt/kg up to 2224 mPt/kg. Whereas, using the Carbon Footprint methodology, MnZn ferrites range from 1.02 up to 1.29 Kg CO_2 eq.

Table 8 and Figure 4 show that, under the ReCiPe and Carbon Footprint methodologies, the MnZn ferrite, with 6.5% ZnO and 17% MnO, has the lowest environmental impact (green lines in Figure 4). The composition with 7.5% ZnO and 24.5% MnO (red lines in Figure 4) creates the highest environmental impact. Finally, the yellow lines show the average composition. These differences are largely created by the content of manganese, as this material involves high environmental impact values (8769 mPt/kg in the ReCiPe, and 3.59 kg CO_2 eq. per kg in the Carbon Footprint methodology).

Manganese is also included in the 2017 EU strategic materials list due to its high economic importance in the EU industry, and its supply risk, but it is not currently considered among the 27 materials from the critical list. Analyzing the European Union data on Critical Raw Materials, we can see that the economic importance of manganese has decreased in the last three years, whereas the supply risk indicator has doubled, making it an import issue for EU manufacturers.

The same analysis approach has been followed for NiZn ferrites. Figure 5 and Table 9 show the results using the ReCiPe and Carbon Footprint methodologies. These impacts range from 272 mPt/kg up to 1682 mPt/kg. Using the Carbon Footprint methodology, NiZn ferrites vary from 0.94 up to 3.46 kg CO_2 eq. per kg.

Table 9. Minimum, maximum, and average environmental impact of 1 kg NiZn soft ferrite (RMA + Production).

	Fe_2O_4 (%)	ZnO (%)	NiO (%)	ReCiPe (mPt/kg)	IPCC 2013 (kg CO_2 eq.)
Minimum	68.5	28.6	2.9	271.0	0.934
Average	69	16	15	985.7	2.213
Maximum	70	3.2	26.8	1681.8	3.455

The NiZn ferrite that creates the lowest environmental impact (green lines in Figure 5) has 2.9% of NiO and 28.6% of ZnO. In contrast, a content of 26.8% NiO and 3.2% ZnO, generates the highest environmental impact per kg (red lines in Figure 5). These data show that the main differences are created by the use of nickel in the composition. Nickel has a high environmental impact (6006 mPt/kg in the ReCiPe, and 11.5 kg CO_2 eq. per kg in the Carbon Footprint methodology), and is also considered a strategic material, but, currently, it is not in the critical list. Analyzing the European Union data on Critical Raw Materials, although the economic importance has slightly decreased in the last three years, its supply risk has increased.

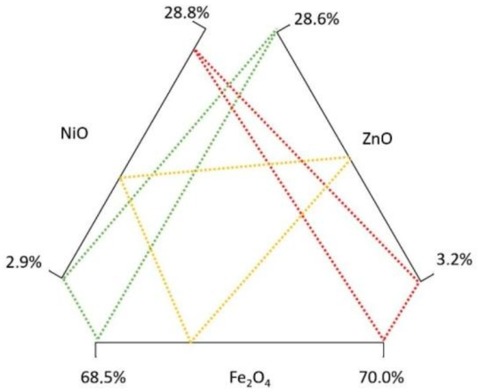

Figure 5. NiZn soft ferrite environmental impact diagram.

In order to further analyze the environmental impact of soft ferrites, the following figure allows us to quantify the percentages of the environmental impact, both in ReCiPe and Carbon Footprint, that are caused by the RMA of each material, and which are related to the production processes at the manufacturing plant. This analysis is going to be performed for the average compositions of MnZn and NiZn, as they are the most representative for each ferrite type and, finally, for the EcoInvent ferrite dataset, which is used as a benchmark.

Focusing on MnZn ferrites, the average composition in MnZn ferrite is the one with 70% of Fe_2O_3, 20% MnO, and 10% of ZnO (Figure 6). When analyzing the environmental impact under the ReCiPe methodology, the presence of manganese oxide generates almost 95.7% of the overall environmental impact. Iron oxide creates 2.84% of the impact, whereas production processes only account for 0.95%. Under the Carbon Footprint methodology, the content of MnO generates more than 62.1% of the total environmental impact, followed by production processes, which create 21.9% of the environmental impact. In both methodologies, the presence of zinc oxide produces the lowest environmental impact due to its low composition percentages, and also its low environmental impacts, with 99 mPt/kg in the ReCiPe and, almost 0.89 kg CO_2 eq. per kg, with the Carbon Footprint methodology.

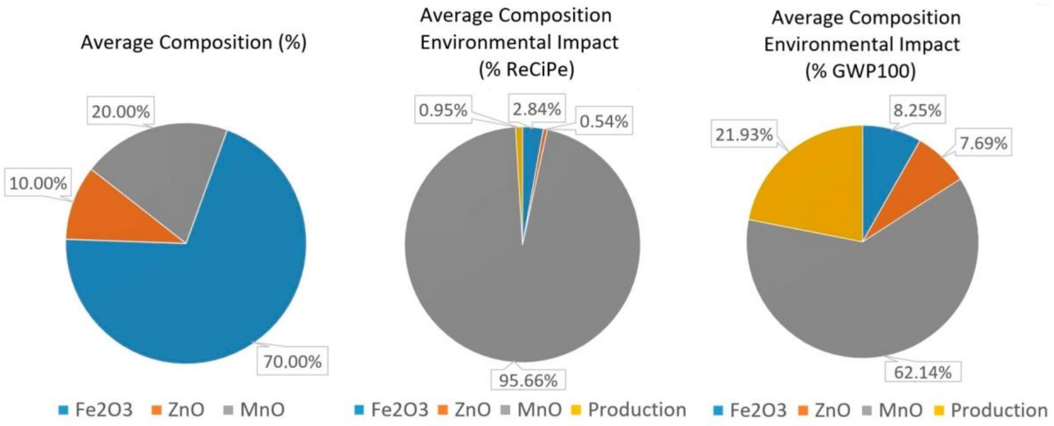

Figure 6. MnZn soft ferrite with average composition environmental impact in the ReCiPe and Carbon Footprint methodologies.

Figures 7 and 8 represent all the analyzed MnZn ferrite compositions, under the ReCiPe and Carbon Footprint methodologies. The 67 ferrites analyzed with the Monte Carlo analysis have been arranged from lowest to highest environmental impacts under ReCiPe, showing that the presence of manganese oxide represents the highest influence on the environmental impact. As shown in Table 8, environmental impact increases 652.3 mPt/kg and 0.267 kg CO_2 eq. per kg when MnO content changes from 17% to 24.5% of the total. All the detailed data (composition, ReCiPe, and Carbon Footprint environmental impact, and the percentages of each material and the production processes for both methodologies) are shown in Table S1.

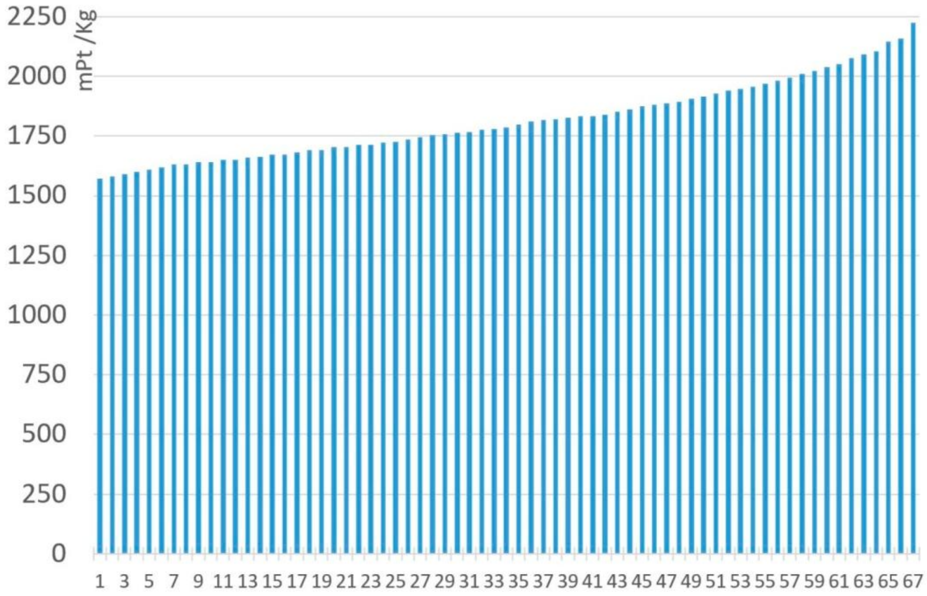

Figure 7. Environmental impact (RMA + Production). of 1 kg MnZn for the 67 ferrites, under the ReCiPe methodology.

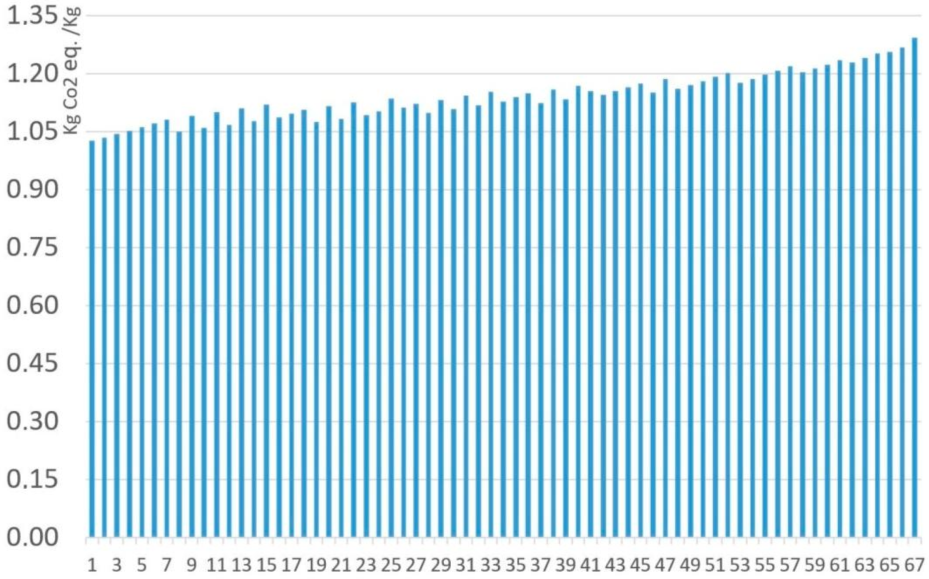

Figure 8. Environmental impact (RMA + Production) of 1 kg MnZn for the 67 ferrites, under the Carbon Footprint methodology.

The results provided in Table S1 also allow us to analyze the relevance of the two considered LCA stages: Raw Material Acquisition and Production. Table 10 shows the percentages for both environmental impact methodologies.

Table 10. RMA and production percentages for minimum, maximum, and average MnZn soft ferrites.

	Fe_2O_3 (%)	ZnO (%)	MnO (%)	ReCiPe RMA (%)	ReCiPe Production (%)	IPCC 2013 RMA (%)	IPCC 2013 Production (%)
Minimum	76.5	6.5	17.0	98.89	1.11	75.29	24.71
Average	70	10	20	99.05	0.95	78.07	21.93
Maximum	68	7.5	24.5	99.22	0.78	80.39	19.61

As can be seen in the previous table, RMA environmental impact percentages have the highest contribution to the environmental impact, and increase as the overall impact does for both the ReCiPe and Carbon Footprint methodologies. Production processes represent between 0.78% and 1.11% percent under the ReCiPe methodology, showing the essential relevance of raw material consumption, especially of manganese, with a higher environmental impact. These production processes are more relevant under the Carbon Footprint methodology (19.61–24.71%), as it is highly influenced by the use of fossil fuels to generate electricity and heat. For both the analyzed methodologies, Raw Material Acquisition generates most of the impact; therefore, the composition is the key to determining the impact of MnZn ferrites.

Figure 9 shows the composition and environmental impacts for the average NiZn soft ferrite. Analyzing how the environmental impact is created under the ReCiPe methodology allows us to conclude that the presence of nickel oxide causes almost 91.4% of the impact. Iron oxide generates 5.3% of it, while the production processes of this ferrite are below 1.8%. The use of zinc oxide produces the lowest environmental impact. Focusing on the environmental impact under the Carbon Footprint methodology, the content of NiO also generates the highest environmental impact: 77.7% of the total. In contrast, Fe_2O_4 with only 4.3% of the total environmental impact creates the lowest contribution to the environmental impact of the average composition. Finally, production processes account for 11.6%.

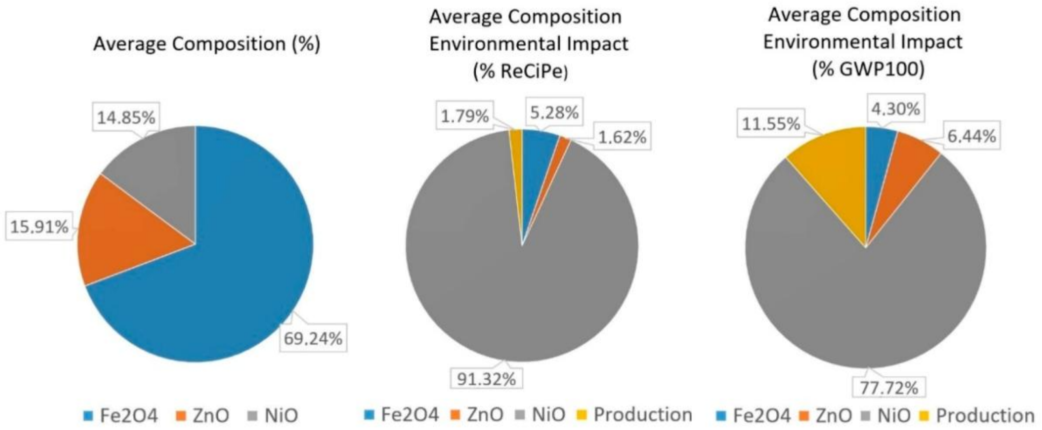

Figure 9. NiZn soft ferrite with average composition environmental impact in the ReCiPe and Carbon Footprint methodologies.

Figures 10 and 11 represent all the analyzed NiZn ferrite compositions, under the ReCiPe and Carbon Footprint methodologies. The 67 ferrites analyzed with the Monte Carlo analysis have also been arranged from lowest to highest environmental impacts under ReCiPe, showing that the presence of nickel oxide has the greatest influence on the environmental impact. Focusing on NiO content, an increase to the maximum composition value represents a rise of almost 1410 mPt/kg in the ReCiPe methodology, and a rise of 2.52 kg CO_2 eq. per kg in the Carbon Footprint methodology. All the specific data are shown in Table S2.

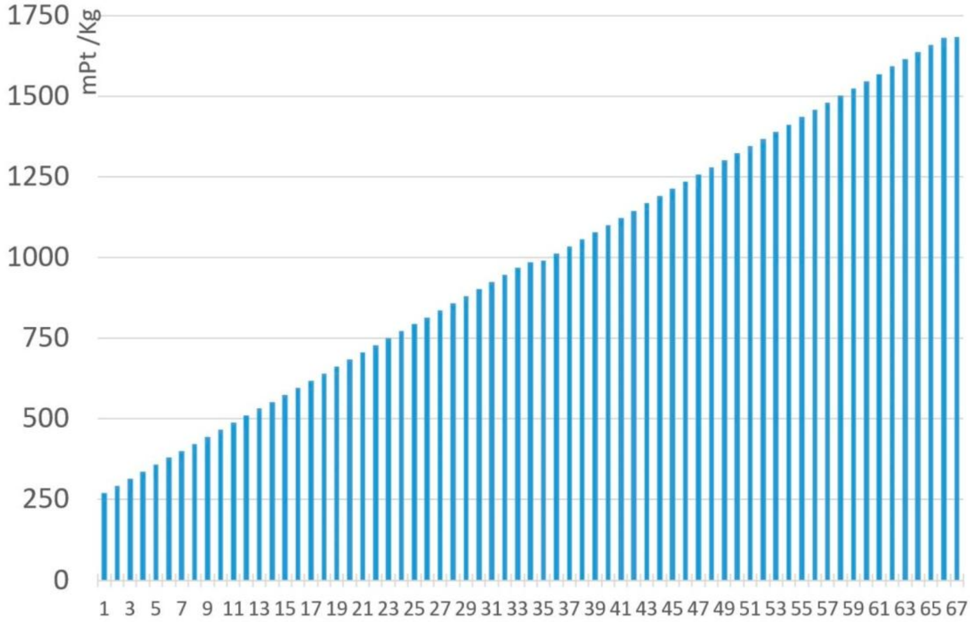

Figure 10. Environmental impact (RMA + Production). of 1 kg NiZn for the 67 ferrites, under the ReCiPe methodology.

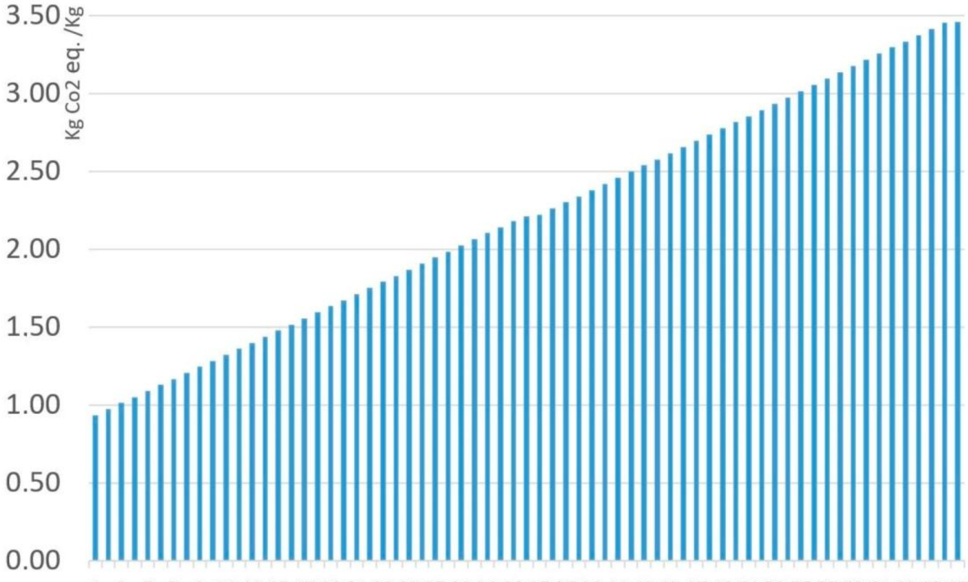

Figure 11. Environmental impact (RMA + Production) of 1 kg NiZn for the 67 ferrites, under the Carbon Footprint methodology.

The results provided in Table S2 also allow us to analyze the relevance of the two considered LCA stages: Raw Material Acquisition and Production. Table 11 shows in detail the percentages for both methodologies.

Table 11. RMA and production percentages for minimum, maximum, and average NiZn soft ferrite.

	Fe_2O_4 (%)	ZnO (%)	NiO (%)	ReCiPe RMA (%)	ReCiPe Production (%)	IPCC 2013 RMA (%)	IPCC 2013 Production (%)
Minimum	68.5	28.6	2.9	93.57	6.43	72.86	27.14
Average	69	16	15	98.23	1.77	88.55	11.45
Maximum	70	3.2	26.8	98.97	1.03	92.67	7.33

As can be seen in the previous table, RMA environmental impact percentages also make the highest contribution to the environmental impact, and their relevance increases as the overall impact does for both methodologies. Production processes represent between 1.03% and 6.43% under the ReCiPe methodology, again showing the high relevance of raw material consumption. This production percentage range is wider than the one calculated for MnZn ferrites, as NiZn ferrites also have a wide range of environmental impact results. This is mainly due to the presence of nickel, another material with a high environmental impact. These production processes are, again, more relevant under the Carbon Footprint methodology (7.33–27.14%).

For both methodologies, and for both ferrites, the Raw Material Acquisition generates most of the impact; therefore, the composition has been confirmed as the key to determining the impact of MnZn and NiZn ferrites.

Table 12 shows the environmental results for the EcoInvent "Ferrite production {GLO}" dataset, used in this paper as a benchmark. The EcoInvent ferrite composition has a higher manganese content than the MnZn soft ferrites previously analyzed in this article and no nickel content. As previously explained, the presence of manganese generates a relevant environmental impact—in this case, 21.6% higher than the maximum MnZn ferrite examined in this article. Figure 12 shows that, as the EcoInvent ferrite composition has a high manganese oxide content (30%, higher than the composition ranges for MnZn soft ferrites), this presence also creates the highest environmental impact, almost 97.3% under ReCiPe and 70% under the Carbon Footprint. Nevertheless, the rest of the composition and the production processes are very low in ReCiPe. Under the Carbon Footprint methodology, production processes generate 16.5%, whereas ZnO and iron oxide content generates 8.7% and 4.9% respectively.

Table 12. EcoInvent ferrite dataset environmental impact in the ReCiPe and Carbon Footprint methodology.

Fe_2O_3 (%)	ZnO (%)	MnO (%)	ReCiPe (mPt/kg)	IPCC 2013 (kg CO_2 eq.)
55.0	15.0	30.0	2704.0	1.5387

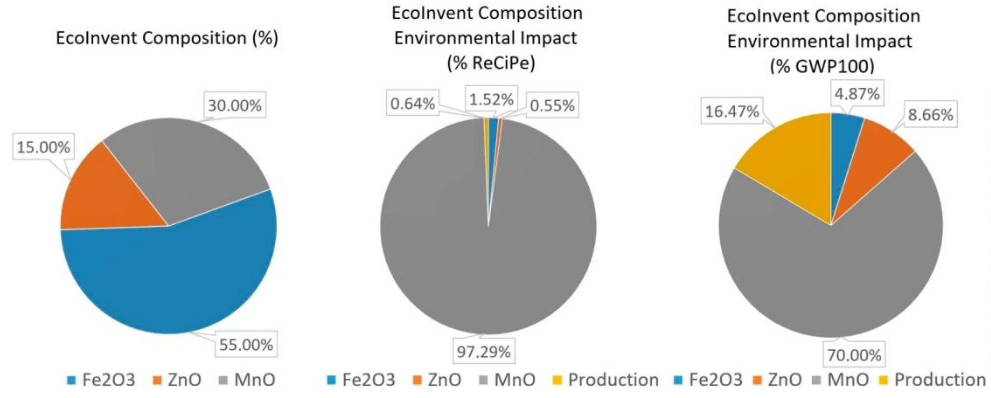

Figure 12. EcoInvent soft ferrite environmental impact in the ReCiPe and Carbon Footprint methodologies.

These results show the relevance of accurately calculating the environmental impact of soft ferrites based on their composition. Although the RMA and production percentages tendencies are similar, the overall results in both categories present significant differences, especially for soft ferrites with low manganese or nickel content, which have a much lower environmental impact than the ones provided by EcoInvent.

The use of the EcoInvent dataset is valid when the consumption of soft ferrites is not relevant. However, it would lead to significant errors if it is used in products with a high presence of soft ferrites. These results are of interest for materials scientists, engineers, and LCA practitioners as they can help to better select soft ferrites, being able to calculate their environmental impact considering its composition, which is not currently possible using only the standard EcoInvent dataset.

4. Conclusions

This article shows the importance of considering material composition to accurately assess the environmental impact of MnZn and NiZn soft ferrites. To do that, the EcoInvent "Ferrite production {GLO}" has been used as a benchmark, customizing it to analyze the composition ranges of MnZn and NiZn soft ferrites. The EcoInvent v3.4 database was used to develop the life cycle inventory. The software used to perform the LCA was SimaPro 8.4, developed by Pré Consultants. The ReCiPe EndPoint (H/A) and IPCC 2013 Carbon footprint GWP100a have been used to perform the environmental impact study.

Both types of soft ferrites have been chosen as they share a common working area, which means that, for some applications, engineers can choose between both soft ferrite materials. This research will allow scientists and engineers to compare these ferrites based not only on cost and properties, but also on environmental impact, as this mainly depends on the composition, and varies significantly from the environmental results of the EcoInvent ferrite dataset.

For MnZn ferrites, the environmental impact calculated with the ReCiPe EndPoint methodology varies from 1572 mPt/kg to 2224 mPt/kg—a variation of 41.5%—whereas when using the Carbon Footprint methodology it varies 26%, from 1.025 to 1.292 kg CO_2 eq. per kg. These values mainly depend on the total content of manganese, which can change from 17% to 24.5%. These values are also significantly different from the ones from the EcoInvent ferrite dataset: 2704 mPt/Kg and 1.54 kg CO_2 eq. per kg.

In the case of NiZn soft ferrites, the environmental impact varies almost by 520% using the ReCiPe EndPoint methodology, from 272 up to 1682 mPt/kg and, around 270% in the Carbon Footprint methodology, from 0.94 up to 3.46 kg CO_2 eq. per kg. NiZn values are always lower than the EcoInvent ferrite under the ReCiPe methodology, but may be lower or higher than the EcoInvent under the Carbon Footprint, depending on its nickel content. NiZn ferrite also shows a wider range of impact results, with this type of ferrite being more sensitive to the percentage of nickel content than MnZn ferrites are to the manganese content. These results are, therefore, of interest for materials scientists, engineers, and LCA practitioners, as they can help them with the selection of soft ferrites while considering the environmental impact.

The main factors that influence the results are the presence of manganese and nickel, respectively. They have a high environmental impact per kg in both methodologies and are also considered as strategic materials by the EU. In fact, the EU shows that their supply risk has been increasing over the last years, constituting a potential issue for European manufacturers.

For the analyzed soft ferrites, production processes are not a critical factor in the environmental impact. However, these production processes are much more relevant under Carbon Footprint than under the ReCiPe methodology, mainly due to their energy consumption (electricity, coal, and natural gas).

The article highlights the importance of considering exact material composition when calculating the environmental impact. Comparing both soft ferrite types under ReCiPe, most NiZn have a lower impact than MnZn. However, this conclusion is not valid when analyzed under Carbon Footprint.

The EcoInvent ferrite dataset should only be used when ferrites are not relevant to the LCA, as more accurate calculations for MnZn and NiZn ferrites show that results can be 10 times lower than for EcoInvent (for the minimum impact of NiZn when using the ReCiPe methodology), or up to 124% higher (when analyzing the maximum impact of NiZn under Carbon Footprint).

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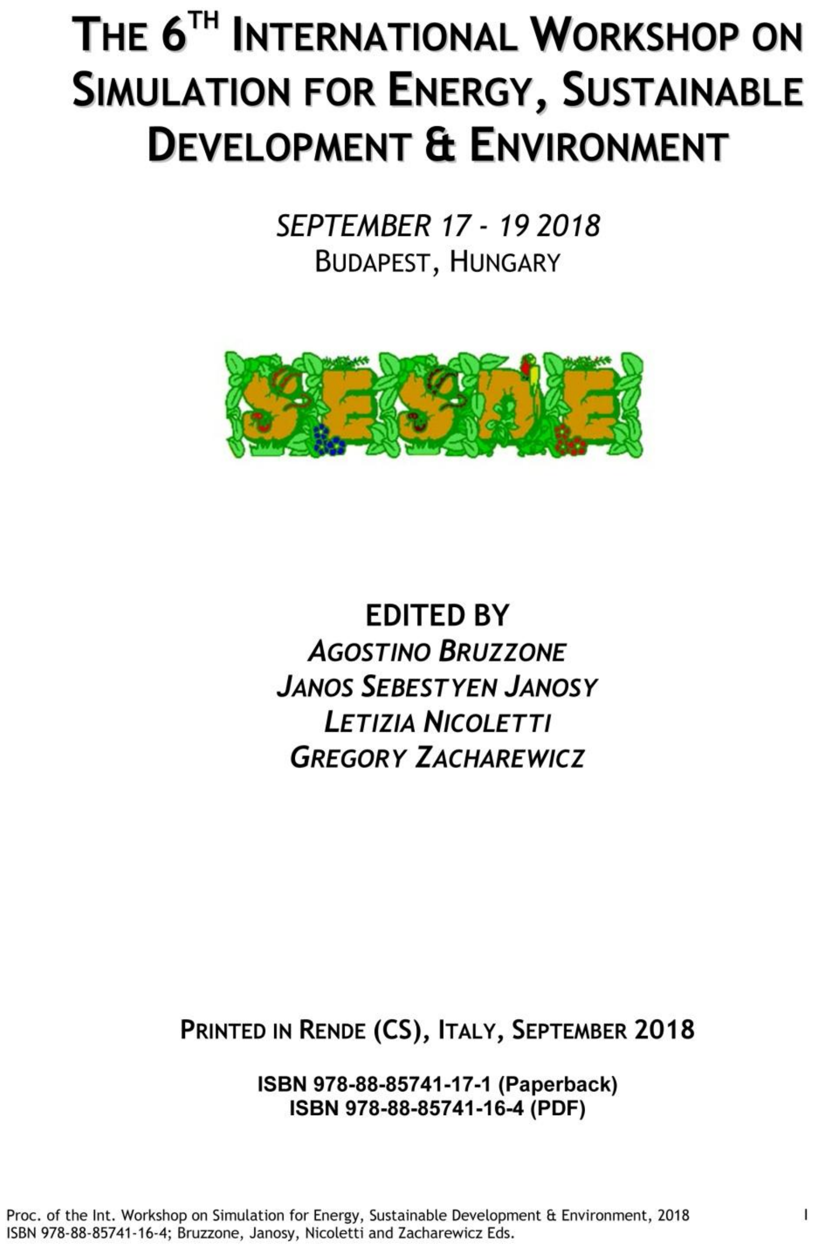
9.7. WORKSHOP ON SIMULATION FOR ENERGY, SUSTAINABLE DEVELOPMENT & ENVIRONMENT: DESIGN METHODOLOGY CONSIDERING ENVIRONMENTAL IMPACT AND CRITICAL RAW MATERIALS, APPLICATION ON INDUCTION HOBS.



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DESIGN METHODOLOGY CONSIDERING ENVIRONMENTAL IMPACT AND CRITICAL RAW MATERIALS, APPLICATION ON INDUCTION HOBS

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ABSTRACT

The target of this paper is to show a methodology developed to establish the influence of material composition on the environmental impact, considering the presence of critical and strategic raw materials.

A Life Cycle Assessment (LCA) has been performed to calculate the environmental impact, analyzing all the life cycle stages of the product. In order to achieve a more precise environmental impact analysis, EcoInvent database has been updated with primary data from product supplier's data. Also, a new software tool, "Sustainable Electronics" was developed and used to calculate the environmental impact and raw material consumption.

This methodology has been implemented on an induction hob, as it is a multipart product made of several components from electronics boards to metallic and plastic parts. The application of this methodology shows the huge influence of material composition on the environmental impact of the product, helping engineers to design more sustainable products.

Keywords: Critical Raw Materials, Life Cycle Assessment, Environmental Impact, Design Methodology, Induction Hobs.

1. INTRODUCTION

During the last decade, there is a huge concern among the European society about materials supply risk and their economical vulnerability. That was the reason why in 2008, the European Commission established the European Raw Materials Initiative. The main purpose of this initiative was to ensure the access to raw materials in the European Union, since more than 30 millions of industrial jobs depend on their availability (European Commission 2017).

Those raw materials with high economic importance and supply vulnerability are considered as critical. In order to ensure and improve citizen's quality of life, they need to be taken into consideration (Andrea et al. 2017), not only in Europe (European Commission 2017) but also globally (ESRC 2015).

The methodology to determine the criticality of a material takes into account data along last 5 years and parameters such as priority, quality or availability. It establishes that a raw material is consider as critical when the combination of two parameters, economic importance and supply risk, are above the limit defined by the European Commission (European Commission 2017).

As a result of the initiative and following the explained methodology, in 2011 the European Commission created the first list of critical raw materials from the non-energy and non- agricultural candidate materials considered as strategic. This document is updated approximately every three years. In 2011, 14 materials were considered as critical out of 41 potential candidates. While in the 2014 report, 20 critical materials were determined out of 54 strategic materials analyzed. Finally, in the last report, presented in 2017, 43 from 78, comprising 24 individual and 3 grouped materials (European Commission 2017).

Critical materials suppose a negative contribution not only for the economic vulnerability or supply risk but also for environmental risk. So in order to perform an exhaustive environmental impact assessment, the influence of all materials needs to be considered.

The supply of these raw materials is often necessary to develop better eco-efficient technologies and innovations. In addition, nowadays the design of products should be more environmentally responsible (Pina et al. 2015) (Camañes et al. 2014). The ecodesign trend emerged at the beginning of 90s in Europe, and it was over the last decade when the design of products has been hugely influenced by environmental legislation. Several laws have emerged in order to reduce the environmental impact of products and services by mean of ecodesign (ISO 2011) (European Parliament 2005) (European Parliament 2009), to reduce the use of hazardous or toxic substance and chemical control (European Parliament 2006) (European Parliament 2003); other laws are focused on the reduction of electrical and electronic equipment waste (European Parliament 2012).

Recent studies have shown that a key aspect when ecodesigning a product, is considering its material composition, as it has a significant influence on the environment. That is why this paper is focused on materials composition and their specific influence on the environmental impact.

In the household appliance industry, the reduction of products environmental impact supposes a huge contribution for market competitiveness. Any decrease of environmental impact can produce significant improvements in the companies, increasing their profits and their market competitiveness (Muralikrishna and Manickman 2017) (Plouffe et al. 2011).

Induction technology is an emerged cooking technology, where one of the most contributions to household appliances industry is its innovative technology, as heat is created directly in the pot from the generation of magnetic fields.

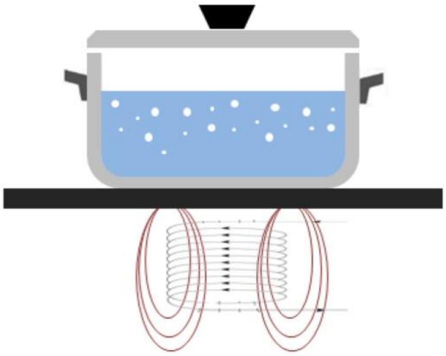

Figure 1: Magnetic Fields

Despite induction is not the most popular technology between electric hobs, the number of units sold from 2002 to 2008 increases around 24% per year. Increasing the number of units sold since it was developed and included into the market. Last 2007, more than a million of induction hobs were sold, 19.8% of the total market. During 2008, the number of units was increased in 22% and in 2010, 2.5 millions of units were sold in Europe; they rose 18% in 2012 and in 2017 around 12% (European Commission 2011).

2. ENVIRONMENTAL ASSESSMENT METHODOLOGY

Many Life Cycle Assessment (LCA) models are performed by means of professional databases as EcoInvent, developed by Swiss Centre for life cycle inventories, and one of the most used LCA databases (Martínez et al. 2015). Nevertheless, the main weakness of mentioned databases is that they include generic data that sometimes is not adjusted and adequate for specific products (Elduque et al. 2015a) (Elduque et al. 2015b).

2.1. General approach

The methodology explained in this paper is based on a LCA model updated with customized datasets. Although many materials and components are included on EcoInvent database, these are generic compositions, which usually do not match the composition of the product to be analyzed. This generates uncertainty on the environmental assessment results. Our methodology considers, not only the materials present in the final product but also the overall consumption of material and waste generation required. This innovative methodology allows engineers to calculate the environmental impact while developing their products, considering the exact composition, and knowing in each moment how changes in material composition affect the overall environmental impact. Also, it has been applied to components such as SMD transistors, diodes, aluminum parts and ceramic glasses. The results show that the presence of some precious metals like gold and critical raw materials as neodymium highly increases the environmental impact, despite being in low quantities.

Over the years, LCA methodology has been applied to analyze the environmental impact of several products from buildings (Pérez and Cabeza 2017) (Fraile-Garcia, et al. 2016) (Fraile-Garcia, et al. 2015), mobile telephones (Moberg et al. 2014) or waste containers (Galve et al 2016) to denim cloths (Periyasamy et al. 2017), food packaging (Fernández et al. 2013) or wine production (Jiménez et al. 2014).

There are several studies assessing life cycle environmental impacts of house hold appliances such as refrigerators (Monfared et al. 2014), washing machines (Ardente and Mathieux 2014), microwaves (Gallego-Schmid et al 2018) or dishwahsers (Johansson and Björklund 2010), however no single study exists in the field of induction hobs, focused on the material composition and critical raw materials as a key influence on the environmental impact.

2.1.1. Life Cycle stages

LCA methodology is performed in this paper to calculate the environmental impact, considering it throughout the all life cycle of the product. In order to perform an exhaustive LCA, it is really important to analyze in detail materials, processes, power consumption, transports, use, end of life… that affects the whole product and its entire life.

3. DESIGN METHODOLOGY APPLIED TO INDUCCTION HOBS (METHODOLOGY DEVELOPED)

In this paper, a new design methodology is proposed. It consists on updating EcoInvent database making it more precise by introducing data obtained from suppliers or manufacturers.

3.1. Dataset improvement methodology

The main objective is to consider the specific composition of each component to analyze the total environmental impact, following EcoInvent methodology but considering the real composition of products and components. In addition, several scenarios are considered in order to calculate the quantity of critical raw materials.

3.2. Inventory data and Assumptions

The life cycle inventory for this study has been performed by means of EcoInvent v3.4, one of the most used databases and developed by Swiss Centre for Life Cycle Inventories.

SimaPro 8.4, developed by Pré Consultants, has modeled the LCA. Following ReCiPe methodology and Carbon Footprint, the LCA has been executed. Where the first one, ReCiPe combines midpoint and endpoint method to validate CML and Eco Indicator 99 systems and the second one, Carbon Footprint establishes the correspondence between the emissions of gas which generates greenhouse effect and CO_2 amount with same effect.

3.3. Software development

In order to implement the methodology developed and focusing on electronic components, a new software tool has been developed (Gómez et al. 2016). The Software "Sustainable Electronics" developed by the authors has the purpose of calculating the environmental impact and raw material consumption, determining the quantity of Critical Raw Materials on electronic components. It also allows the users to compare between several designs considering the exact composition, depending not only on the environmental impact but also assessing the consumption of critical and strategic raw materials.

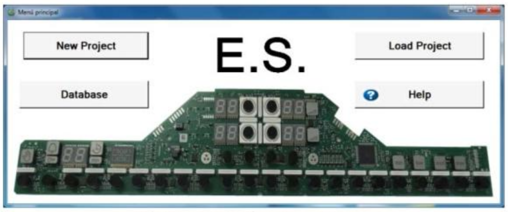

Figure 2: Software Screen

In comparison to other software, this allows the user to analyze the environmental impact of several design scenarios customizing Life Cycle Inventory included in the database.

As explained previously, nowadays there is an increasing concern over Critical Raw Materials; that is the reason why the software evaluates the environmental impact and shows the quantity of critical and strategic materials contained in the electronic component analyzed. There is a screen where the 27 critical materials considered by the EU are shown and the screen also includes the rest strategic materials evaluated by the EU in 2017.

4. METHODOLOGY APPLICATION

In this study, the innovative methodology previously explained has been applied on a specific multipart product: an induction hob. In addition, LCA was performed with the purpose of determining the influence of the materials composition.

4.1. Induction hob

Induction hobs are complex products, composed by many parts and components such as electronics boards, metallic parts, plastic housings, ceramic glass or wires.

Figure 3: Top Side Induction Hob

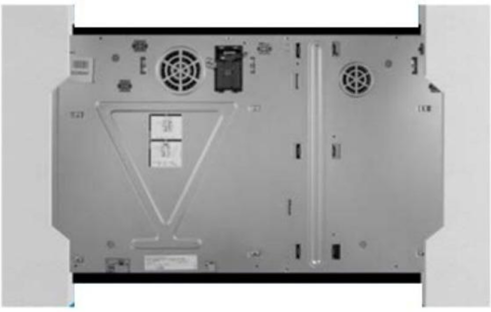

Figure 4: Bottom Side Induction Hob

Figure 5: Packaging, Wires and Documentation Induction Hob.

The environmental burden produced by all the components of an induction hob (electrical, electronic and mechanical ones) will be assessed to examine the percentage of each part in the total impact of the appliance and also in order to analyze the influence of the material composition on the environmental impact.

On one side, among electronics of an induction hob are included components such as printed circuit boards, diodes, transistors or resistors; on the other side, metallic parts comprise aluminum, stainless steel, iron or cooper parts. Besides, as mentioned before exist plastic or ceramic glass parts, which all together create the complex structure of the induction hob assembly.

Due to the complexity of the product and also because of the significant amount of parts and different materials used to manufacture each induction hob the design methodology previously explained has been applied on induction hobs, considering the material composition and the presence of critical raw materials in electronics and mechanical components included in an induction hob.

4.2. Electronics Inventory

Due to the technological change among our society the use and consumption of electrical and electronic components is emerging, in consequence the sales of those components are increasing exponentially. The increase of electrical and electronic demand together with low costs of electronic devises generates a fast advancement in technology and in consequence, huge amounts of waste of electrical and electronic equipment (WEEE).

The study of electronic components in this paper is focused on diodes and transistors, both integrated in the electronic boards and included in the analyzed induction hob.

4.2.1. Electronics Inventory: Diodes

Diodes are simple semiconductor components, non lineal dispositive made of two electrodes, anode and cathode. An induction hob uses several types of diodes and also a high quantity of them, but here the study is focused on Zener diodes. They are two-terminal diodes that allow electrical current only in one direction, giving a stable voltage between terminals.

This subsection is focused on Zener diodes included in the induction hob, their weight is around 8miligrams and the main target of the study is to analyze the influence of their material composition on the environmental impact.

The composition of the studied diodes includes materials such as tin, silver, gold, nickel, antimony, manganese… where the higher environmental impact is caused mainly by gold, follow by silver and manganese. The impact created by these materials on the environmental is really harmful, even although small quantities of them are included in the diode's composition.

4.2.2. Electronics Inventory: Transistors

Transistors are one of the most important electronic elements, due to the importance advance that their invention supposed for the electronic industry. They are considered as essential component for electronic devices due to their low electric power consumption.

Most of the main manufacturers of transistors are focused on the size reduction, whereas the environmental impact reduction supposes for the manufacturers an increase of market competitiveness, an improvement of their benefits and costs saves.

This study is focused on surface-mount device (SMD) transistors included in induction hobs, with dimensions in the region of 3 mm x 1.74 mm x 1.3 mm and 8 miligrams of weight.

Several SMD transistors have been analyzed, and it has been concluded that transistors that generate higher impact for the environment are the ones with higher quantities of gold in their composition (Gómez et al. 2015). Also, there are materials considered as critical by the European Union included in the composition of studied SMD transistors, they are cobalt, silicon and chromium; whose presence in the composition of the transistors suppose supply risk and they are affected by the economical importance of the material.

4.3. Mechanical Inventory

Mechanical components are essential for any type of induction hob, the main purpose of mechanical parts is placing each component, electronic and non electronic ones (electronic boards, wires, inductors…) and fix them during the whole life of the product.

Induction hobs include an extensive range of non electronic or mechanical components, such as aluminum or steel parts, ceramic glass, ferrites… In this section all of these parts and materials have been analyzed, studying also their environmental impact contribution.

4.3.1. Mechanical Inventory: Aluminum

Six cast aluminum alloys have been analyzed in order to study the influence of composition on the environmental impact (Gómez et al. 2016). They are Al Si9, Al Si9Cu3(Fe)(Zn), Al Si10Mg(Fe), Al Si9Cu3Zn3Fe, Al Si5Mg and Al Si12Cu1(Fe).

Once they have been analyzed and compared, it can be confirmed the importance of the selection of material composition not only for cost saving and mechanical properties improvement, but also for the impact that they generate on the environment.

The highest environmental impact in Recipe methodology is obtained by alloy Al Si9Cu3Zn3Fe with 1.01 pts per kg, in contrast the lowest impact belongs to Al Si9 alloy with 0.61 pts per kg. Analyzing all the alloys, it can be concluded that environmental impact is highly influenced by the materials included in the composition, where copper and tin are the materials with higher influence.

4.3.2. Mechanical Inventory: Steel

Steel is hugely included in the mechanical inventory, because most of the structural elements are made of it: in components such as the cover frame, screws and springs. There are five different types of steel included in the induction hob; all of them have been analyzed considering their composition and following the explained methodology.

In the 5 types of steel studied, the environmental impact varies from 0.2380 points per Kg to 0.6763 points per Kg in Recipe methodology; where the highest impact is created by stainless steel. The elements included in the analyzed steels that mainly contribute to increase the environmental impact are silica, chrome and boron.

4.3.3. Mechanical Inventory: Ceramic Glass

Ceramic glass part is the outer component of the induction hob; main characteristics of this part are hardness, temperature resistance and ease of cleaning.

There are several types of ceramic glass depending on the composition. Also the aesthetic of this piece is changeable and the client can choose between a large amount of them; there are several types of beveled surfaces and a huge variety of colors available.

As in the previous components, the environmental impact has been analyzed from real material composition of the seven types of ceramic glass analyzed.

Once the analysis of the ceramic glass types was performed, it can be established that tin and neodymium are the elements that highly contribute to increase the environmental impact. In addition, some critical raw materials considered by the European Union such as barite and magnesium together with neodymium are included in the composition.

4.3.4. Mechanical Inventory: Ferrite

Ferrites are ceramic compounds made of iron oxides and metallic cations like cobalt, manganese-zinc alloys or iron. They are mainly used in electronic devices such as transformers, electromagnets or electronic inductors. The main properties of ferrites are their low coercitivity with a high resistivity, high permeability and low losses.

In this study, the main purpose consists on showing the importance of considering the exact material composition of a component when analyzing environmental impact. That can be achieved comparing the results between EcoInvent ferrite dataset and the customization of it considering the exact material composition of manganese-zinc soft ferrites (MnZn).

The environmental impact in Recipe methodology varies from around 1570 mPt/Kg to more than 2220 mPt/kg, depending on material selection. Whereas the environmental impact calculated from EcoInvent dataset is more than 2700 mPt/Kg, which suppose a result 72% higher than the minimum environmental impact, obtained from a composition based on Iron Oxide and 21.5% more than the maximum, with a composition based on Manganese Oxide. The variation of the environmental impact results is created by the difference on the quantity of Manganese included in the dataset, which is higher on EcoInvent.

5. SOFTWARE APPLICATION

As it has been previously exposed, “Sustainable Electronics” software allows the users to consider environmental impact and critical raw materials content while designing or selecting new components or parts.

The software has been developed by means of Visual Basic .NET, trying to create a friendly interface for the users. It is made of three main blocks: new project/load project, databases and results; following the software structure shown in Figure 6.

By means of block “new project” the user is able to create and name a new project, whereas in block “load project” an existing project can be selected. Finally, in “BBDD Components” section the user can manage the database available in the tool.

Although this software has been firstly developed for electronic components, it was enlarged to include mechanical and structural components such as aluminum or glass ceramic components. In that way, the user is able to perform an exhaustive life cycle assessment, considering the whole life cycle stages. It allows the user to know the exact quantity of critical raw materials included in the analyzed product and also the impact they generate on the environment. Once the inventory data is updated, it seems to be easy for the user to get results and calculate the environmental impact of the components.

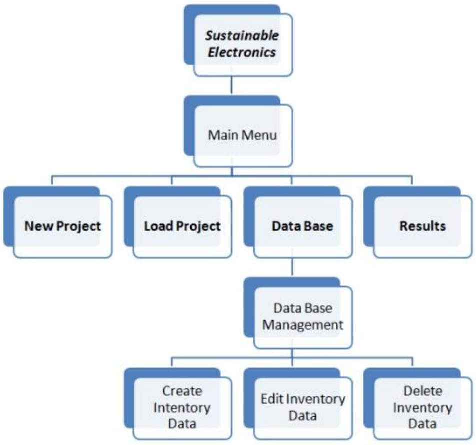

Figure 6: Software Structure

6. RESULTS AND DISCUSSION

Once implemented the methodology on the components included on an induction hob (electronic and mechanic), it is shown the huge influence of material composition on the environmental impact. Besides the impact created by the materials on the environment, the presence of critical raw materials has been assessed.

Material engineers are able to compare materials based not only on cost and properties but also taking into account materials’ environmental impact.

Through the entire paper, it has been proved that the presence of certain materials highly contribute the increase of environmental impact values, specially in electronics components. That is the case of gold, cobalt, silicon and chromium included in transistors. And tin, silver, gold, nickel, antimony and manganese included on diodes composition.

In the case of mechanical inventory, the elements with higher environmental impact values are cooper and tin in the studied aluminum alloys; silica, chrome and boron in components made of steel; tin and neodymium on glass ceramics analyzed and finally in ferrites the environmental impact is mainly created by manganese.

Materials such as manganese, barite, and magnesium are included in the 2017 list of critical and strategic materials due to its high economic importance and supply risk in the European Union industry.

7. CONCLUSIONS

The article highlights the relevance of considering the exact materials composition in the calculation of the environmental impact.

In order to achieve more accurate environmental impact results and higher sensitivity when designing, it is really important to contemplate the exact material composition. Thereby, engineers are able to assess how few modifications on the composition and properties of materials such as steel, aluminum or ceramic glasses generate changes on the environmental impact. The influence of these changes can be calculated in detail by means of the methodology explained in this paper. In contrast, the influence of material composition on the environmental impact cannot be calculated by means of generic databases, where the material composition is not considered.

ACKNOWLEDGMENTS

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Patricia Gómez finished her degree in Industrial Engineering at the University of Zaragoza in 2013. She works at BSH Home Appliances Group – Spain. Since September 2014 she is a PhD candidate in Mechanical Engineering at the University of Zaragoza. Her work focuses on ecodesign taking into account materials composition and critical materials. She has researched on the influence of material composition of SMD transistor on the environmental impact.

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Carlos Javierre is a Professor at the University of Zaragoza in the Mechanical Engineering Department and PhD Co-Director of Patricia Gómez. He is part of the I+ research group. His main research interests include mechanical engineering, life cycle assessment and environmental impact. Some of his latest publications are the study of the influence of environmental conditions on the dimensional stability of components injected with PA6 and PA66; or the analysis of the environmental impact of the injection moulding process of high-density polyethylene parts by carrying out a life cycle assessment.

Capítulo 10

Anexos

10. ANEXOS

10.1. APÉNDICE PUBLICACIONES CIENTÍFICAS

Influence of the Material Composition on the Environmental Impact of surface-mount device (SMD) Transistor. (Apartado 10.1).

- Revista: Journal of Cleaner Production.
- Año de publicación: 2015.
- Factor de impacto: 4,959.
- Categoría: Q1, 16/225, Environmental Sciences
- Contribución del doctorando: Revisión del estado del arte. Cálculos de impacto ambiental sobre transistores SMD mediante software SimaPro, basados en base de datos EcoInvent pero con actualización de la misma. Redacción del artículo en inglés.

Environmental Assessment Tool to analyze the presence of Critical and Valuable Raw Materials. (Apartado 10.2).

- Congreso: 27th EMSS 2015, European Modelling & Simulation Symposium.
- Año de publicación: 2015.
- Factor de impacto / Categoría: Publicación en proceedings del congreso, publicado en Scopus, no se clasifica como revista indexada.
- Contribución del doctorando: Aprendizaje e implementación del lenguaje de programación Visual Basic .NET. Desarrollo de software para calcular impacto ambiental mediante la metodología desarrollada e implementación del mismo. Redacción del artículo en inglés.

Environmental Assessment Tool to analyze the presence of Critical and Valuable Raw Materials. (Apartado 10.3).

- Revista: International Journal of Service and Computing Oriented Manufacturing
- Año de publicación: 2016.
- Factor de impacto / Categoría: Revisión por pares; no se clasifica como revista indexada.
- Contribución del doctorando: Aprendizaje e implementación del lenguaje de programación Visual Basic .NET. Desarrollo de software para calcular impacto ambiental mediante la metodología desarrollada e implementación del mismo. Redacción y corrección del artículo en inglés.

Influence of the composition on the environmental impact of cast aluminum alloy. (Apartado 10.4).

- Revista: Materials
- Año de publicación: 2016.
- Factor de impacto: 2,654.
- Categoría: Q2, 82/275, Material Science
- Contribución del doctorando: Revisión del estado del arte. Cálculos de impacto ambiental de distintas aleaciones de aluminio mediante herramienta informática SimaPro, comparativa según composición de los materiales e influencia sobre el impacto ambiental. Redacción del artículo en inglés.

Influence of the Composition on the Environmental Impact of Soft Ferrites. (Apartado 10.5).

- Congreso: The 3rd International Electronic Conference on Materials Sciences, ECMS 2018.
- Año de publicación: 2018.
- Factor de impacto / Categoría: Publicado en proceedings del congreso “The 3rd International Electronic Conference on Materials Sciences”. Congreso organizado por revista Materials.
- Contribución del doctorando: Revisión del estado del arte. Cálculos de impacto ambiental y comparativa medioambiental entre dos tipologías de ferritas. Uso del software y base de datos EcoInvent. Redacción del artículo en inglés.

Influence of the Composition on the Environmental Impact of Soft Ferrites. (Apartado 10.6).

- Revista: Materials
- Año de publicación: 2018.
- Factor de impacto: 2,467.
- Categoría: Q2, 111/285, Material Science
- Contribución del doctorando: Revisión del estado del arte. Cálculos de impacto ambiental y comparativa medioambiental entre dos tipologías de ferritas. Uso del software y base de datos EcoInvent. Redacción del artículo en inglés.

Design methodology considering environmental impact and critical raw materials, application on induction hobs. (Apartado 10.7).

- Congreso: The 6th International workshop on simulation for energy, sustainable development and environment.
- Año de publicación: 2018.
- Factor de impacto / Categoría: Publicación en proceedings del congreso, publicado en Scopus, no se clasifica como revista indexada.
- Contribución del doctorando: Revisión del estado del arte. Desarrollo de una metodología para el diseño considerando la composición de los materiales, aplicación sobre cocinas de inducción. Redacción del artículo en inglés.

En las siguientes páginas se muestran los archivos .pdf, de las revistas citadas en este apartado, generados por la sección Journal Citation Reports incluidos en la página Web of Knowledge.

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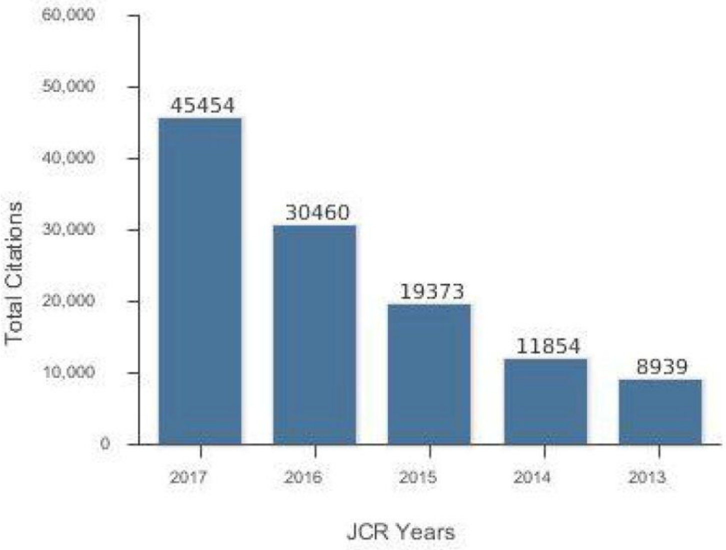

Journal Citation Report : Impact factor

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	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile
2017	6/33	Q1	83.333	7/50	Q1	87.000	21/242	Q1	91.529
2016	5/31	Q1	85.484	6/49	Q1	88.776	17/229	Q1	92.795
2015	5/29	Q1	84.483	5/50	Q1	91.000	16/225	Q1	93.111
2014	NA	NA	NA	10/47	Q1	79.787	24/223	Q1	89.462
2013	NA	NA	NA	9/46	Q1	81.522	29/216	Q1	86.806
2012	NA	NA	NA	8/42	Q1	82.143	29/210	Q1	86.429
2011	NA	NA	NA	10/45	Q1	78.889	45/205	Q1	78.293
2010	NA	NA	NA	10/45	Q1	78.889	50/193	Q2	74.352
2009	NA	NA	NA	14/42	Q2	67.857	69/181	Q2	62.155
2008	NA	NA	NA	14/38	Q2	64.474	89/163	Q3	45.706
2007	NA	NA	NA	21/37	Q3	44.595	100/160	Q3	37.813
2006	NA	NA	NA	20/35	Q3	44.286	103/144	Q3	28.819
2005	NA	NA	NA	20/37	Q3	47.297	102/140	Q3	27.500
2004	NA	NA	NA	20/35	Q3	44.286	99/134	Q3	26.493

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JCR Year	ENGINEERING
2016	24/861-Q1
2017	14/867-Q1
2012	77/827-Q1
2013	62/837-Q1
2014	47/838-Q1
2015	29/850-Q1

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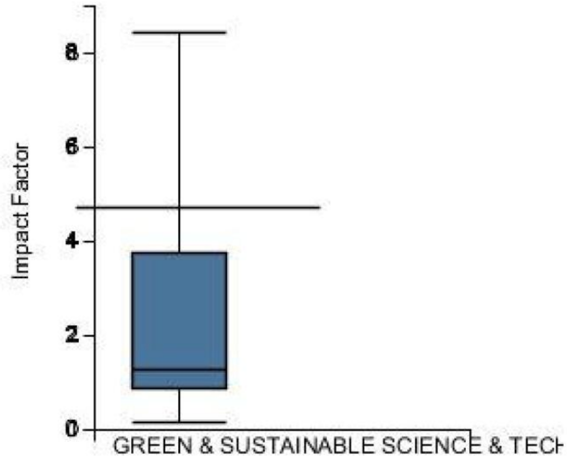

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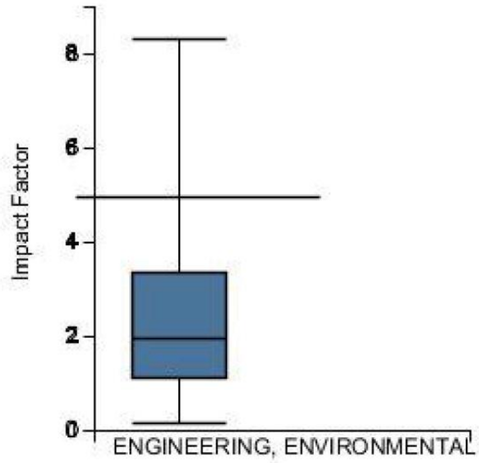

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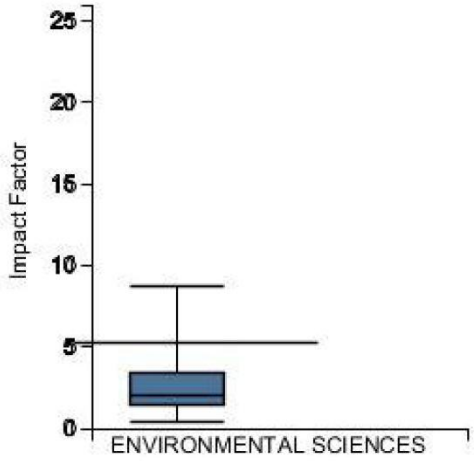

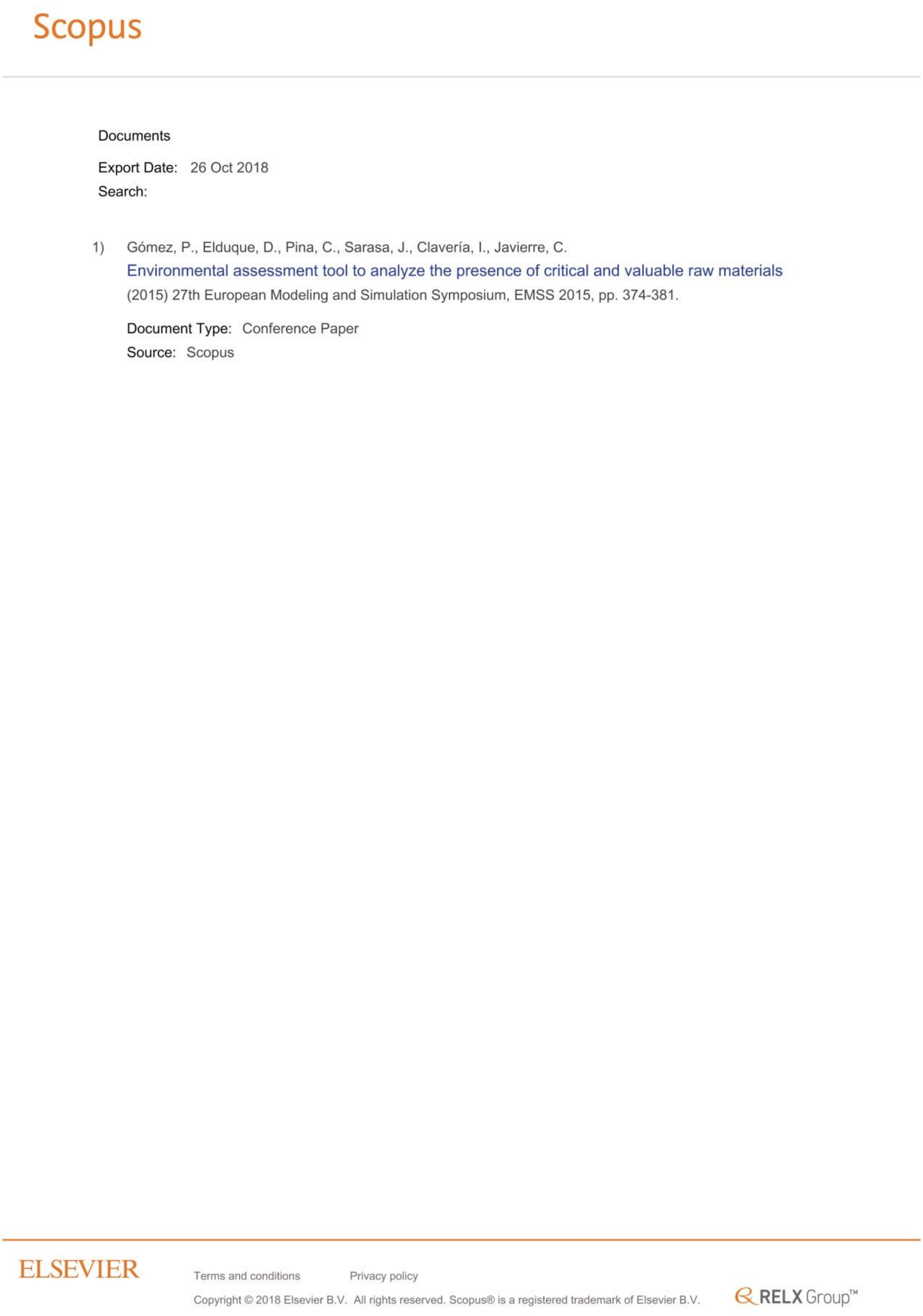

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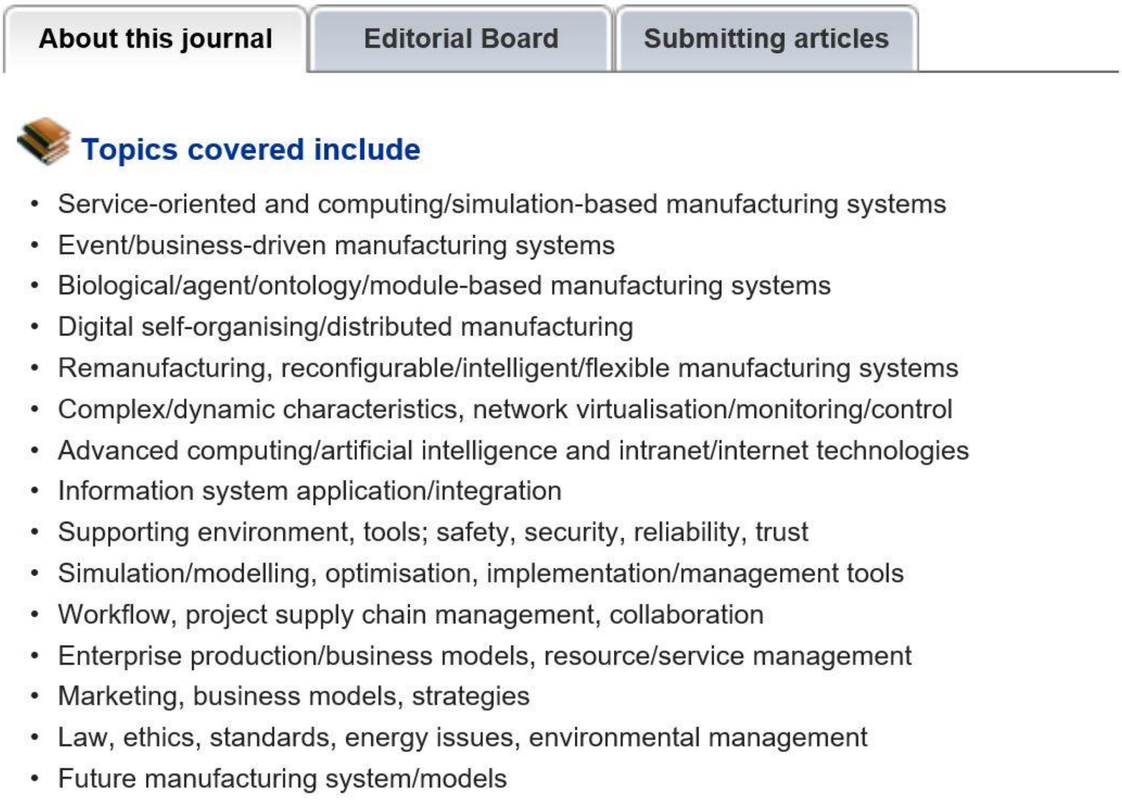
1) Gómez, P., Elduque, D., Pina, C., Sarasa, J., Clavería, I., Javierre, C.
Environmental assessment tool to analyze the presence of critical and valuable raw materials
(2015) 27th European Modeling and Simulation Symposium, EMSS 2015, pp. 374-381.

Document Type: Conference Paper
Source: Scopus



Topics covered include

- Service-oriented and computing/simulation-based manufacturing systems
- Event/business-driven manufacturing systems
- Biological/agent/ontology/module-based manufacturing systems
- Digital self-organising/distributed manufacturing
- Remanufacturing, reconfigurable/intelligent/flexible manufacturing systems
- Complex/dynamic characteristics, network virtualisation/monitoring/control
- Advanced computing/artificial intelligence and intranet/internet technologies
- Information system application/integration
- Supporting environment, tools; safety, security, reliability, trust
- Simulation/modelling, optimisation, implementation/management tools
- Workflow, project supply chain management, collaboration
- Enterprise production/business models, resource/service management
- Marketing, business models, strategies
- Law, ethics, standards, energy issues, environmental management
- Future manufacturing system/models

A few essentials for publishing in this journal

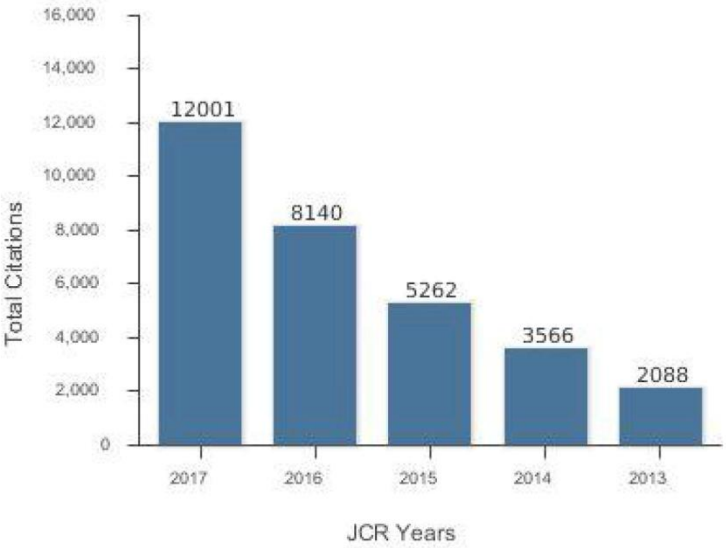
- Submitted articles should not have been previously published or be currently under consideration for publication elsewhere.
- Conference papers may only be submitted if the paper has been completely re-written (more details available here) and the author has cleared any necessary permissions with the copyright owner if it has been previously copyrighted.
- All our articles go through a **double-blind review** process.
- All authors must declare they have read and agreed to the content of the submitted article. A full statement of our Ethical Guidelines for Authors (PDF) is available.
- There are **no charges** for publishing with Inderscience, unless you require your article to be Open Access (OA). You can find more information on OA here.

InCites Journal Citation Reports

Clarivate Analytics

Journal Profile: Materials

Essential Science Indicators : Total Citations Graph



Journal Citation Report : Impact factor

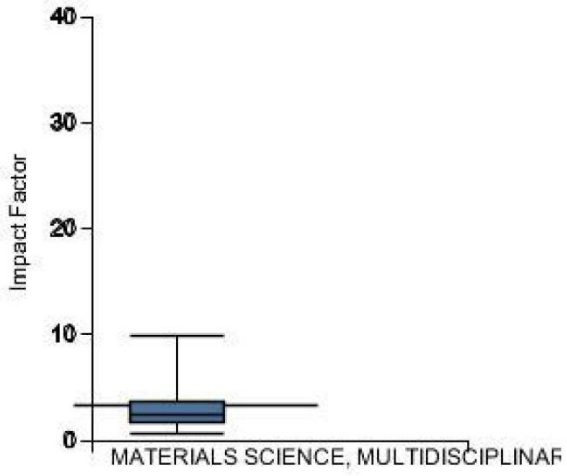
JCR Year	MATERIALS SCIENCE, MULTIDISCIPLINARY		
	Rank	Quartile	JIF Percentile
2017	111/285	Q2	61.228
2016	82/275	Q2	70.364
2015	63/271	Q1	76.937
2014	55/260	Q1	79.038
2013	81/251	Q2	67.928
2012	55/241	Q1	77.386
2011	85/232	Q2	63.578

Essential Science Indicators : Total Citations

JCR Year	MATERIALS SCIENCE
2016	66/350-Q1
2017	55/361-Q1
2012	132/325-Q2
2013	115/331-Q2

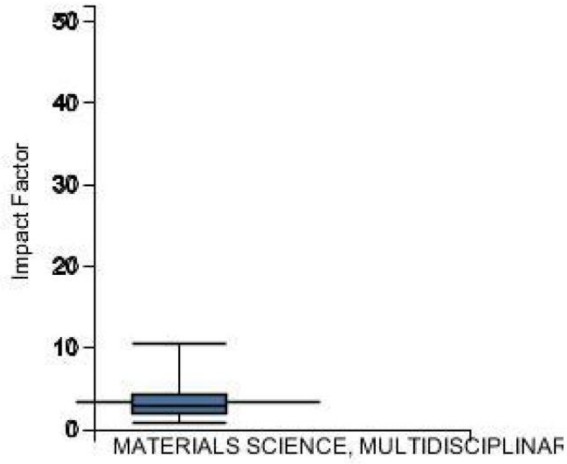
Journal Profile: Materials

Box Plot, Year: 2016, Edition: SCIE, IF: 2.654



Journal Profile: Materials

Box Plot, Year: 2017, Edition: SCIE, IF: 2.467



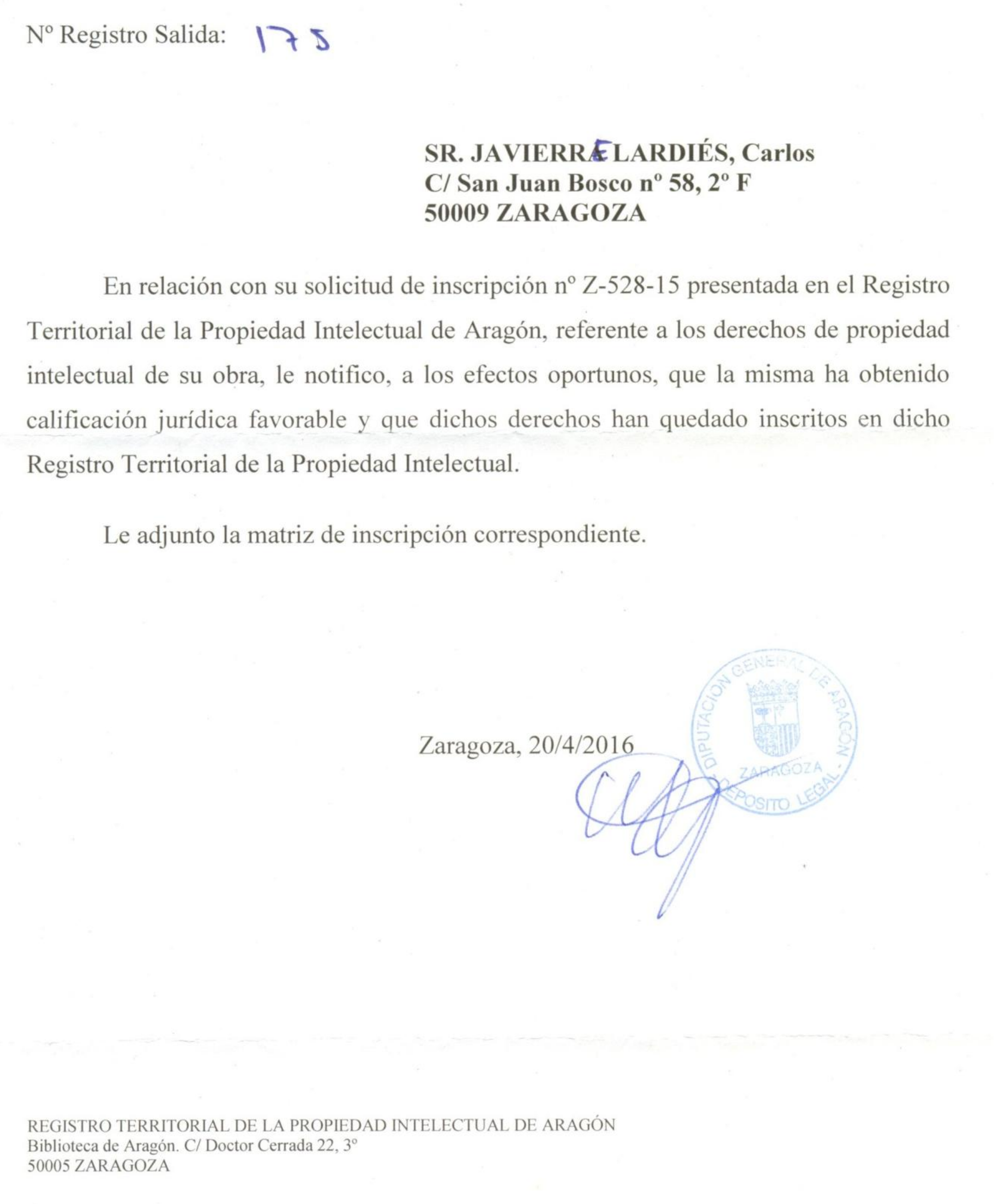
Documents

Export Date: 26 Nov 2018
Search:

1) Gómez, P., Elduque, D., Pina, C., Javierre, C.
Design methodology considering environmental impact and critical raw materials, application on induction hobs
(2018) 6th International Workshop on Simulation for Energy, Sustainable Development and Environment, SESDE 2018, pp. 15-21.

Document Type: Conference Paper
Source: Scopus

10.2. REGISTRO DE LA HERRAMIENTA INFORMÁTICA



Nº Registro Salida: 175

SR. JAVIERR~~A~~E LARDIÉS, Carlos
C/ San Juan Bosco nº 58, 2º F
50009 ZARAGOZA

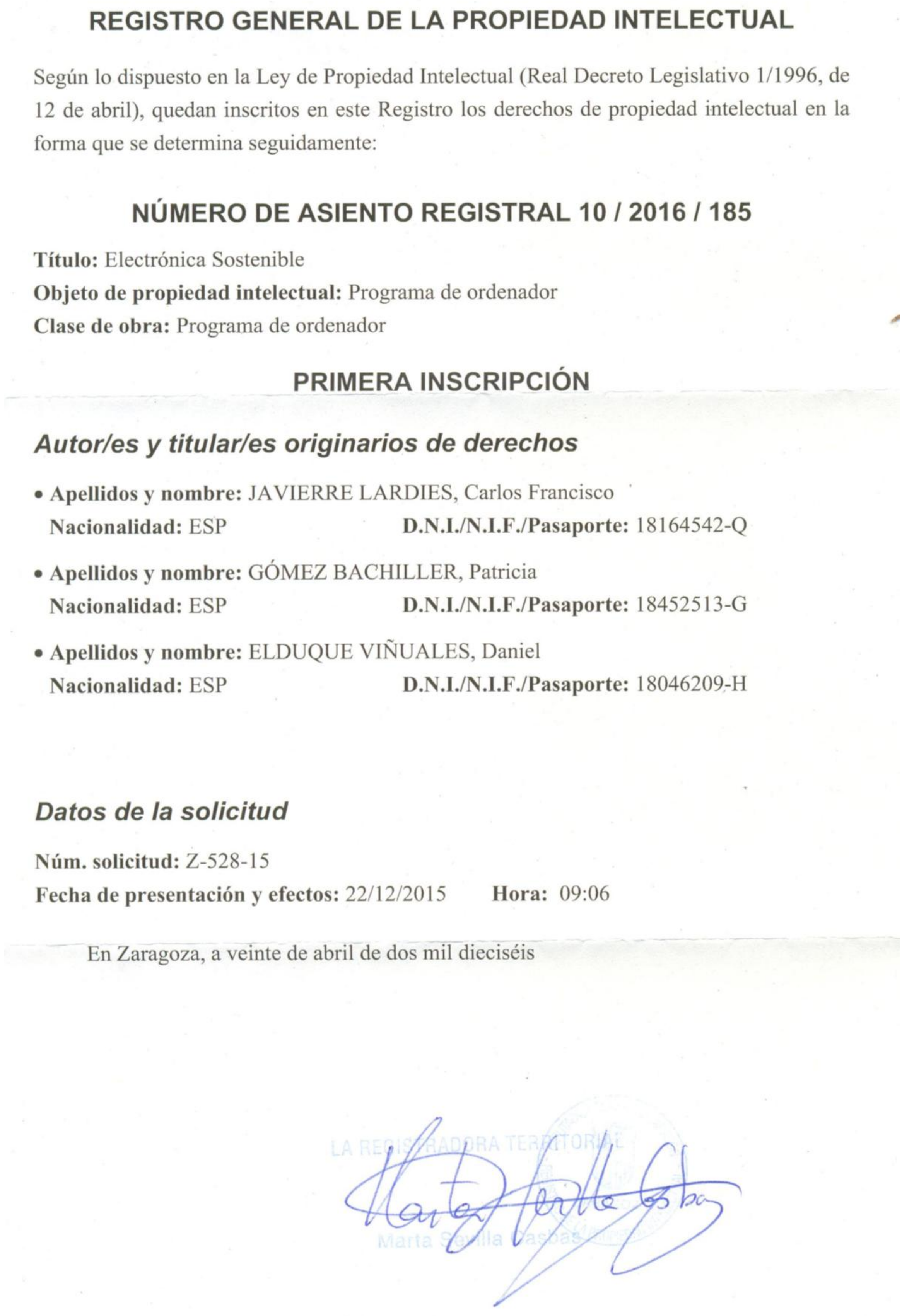
En relación con su solicitud de inscripción nº Z-528-15 presentada en el Registro Territorial de la Propiedad Intelectual de Aragón, referente a los derechos de propiedad intelectual de su obra, le notifico, a los efectos oportunos, que la misma ha obtenido calificación jurídica favorable y que dichos derechos han quedado inscritos en dicho Registro Territorial de la Propiedad Intelectual.

Le adjunto la matriz de inscripción correspondiente.

Zaragoza, 20/4/2016

DIPUTACIÓN GENERAL DE ARAGÓN
ZARAGOZA
DEPÓSITO LEGAL

REGISTRO TERRITORIAL DE LA PROPIEDAD INTELECTUAL DE ARAGÓN
Biblioteca de Aragón. C/ Doctor Cerrada 22, 3º
50005 ZARAGOZA



REGISTRO GENERAL DE LA PROPIEDAD INTELECTUAL

Según lo dispuesto en la Ley de Propiedad Intelectual (Real Decreto Legislativo 1/1996, de 12 de abril), quedan inscritos en este Registro los derechos de propiedad intelectual en la forma que se determina seguidamente:

NÚMERO DE ASIENTO REGISTRAL 10 / 2016 / 185

Título: Electrónica Sostenible
Objeto de propiedad intelectual: Programa de ordenador
Clase de obra: Programa de ordenador

PRIMERA INSCRIPCIÓN

Autor/es y titular/es originarios de derechos

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  Nacionalidad: ESP **D.N.I./N.I.F./Pasaporte:** 18164542-Q
- **Apellidos y nombre:** GÓMEZ BACHILLER, Patricia
  Nacionalidad: ESP **D.N.I./N.I.F./Pasaporte:** 18452513-G
- **Apellidos y nombre:** ELDUQUE VIÑUALES, Daniel
  Nacionalidad: ESP **D.N.I./N.I.F./Pasaporte:** 18046209-H

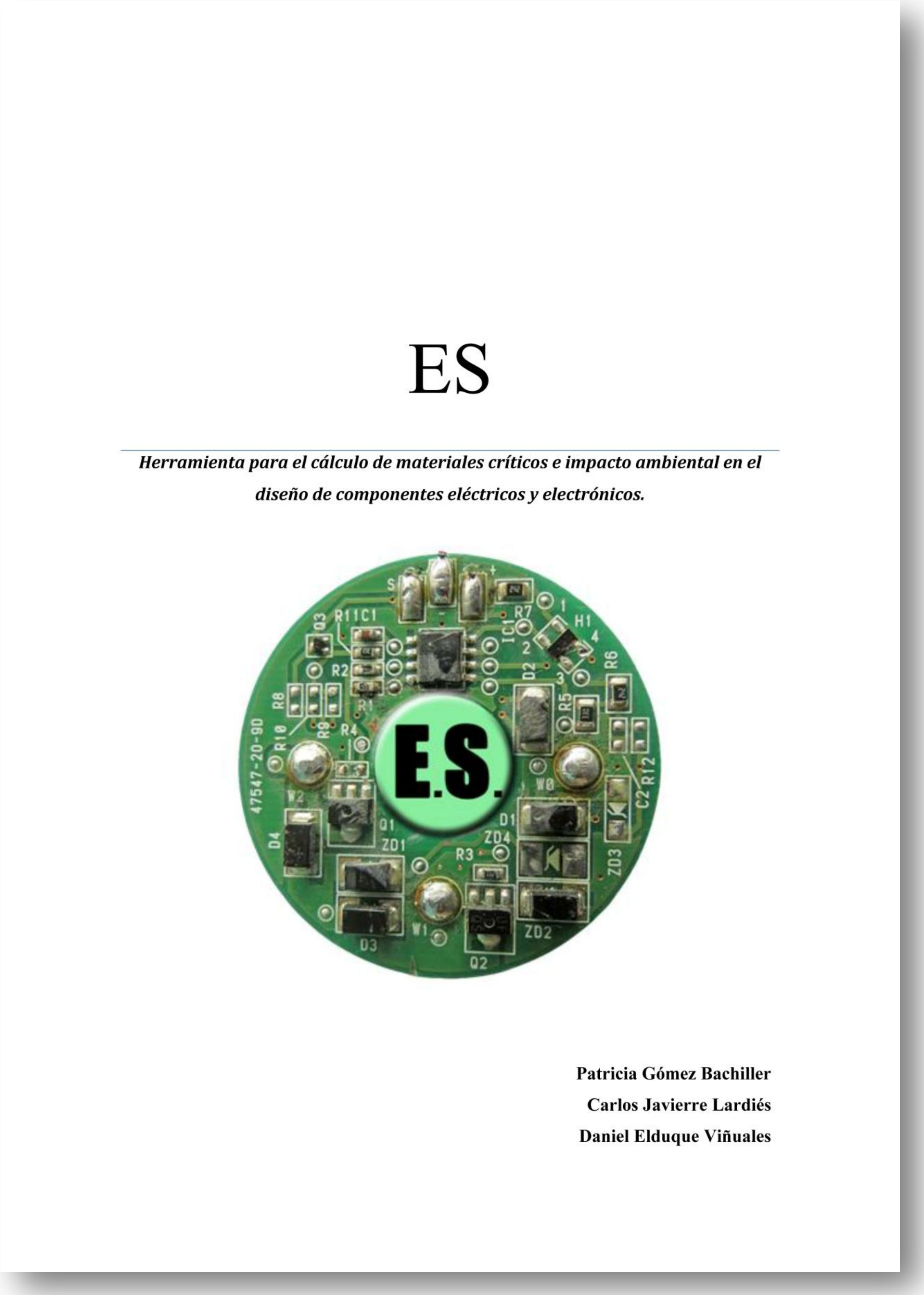
Datos de la solicitud

Núm. solicitud: Z-528-15
Fecha de presentación y efectos: 22/12/2015 **Hora:** 09:06

En Zaragoza, a veinte de abril de dos mil dieciséis

LA REGISTRADORA TERRITORIAL
Marta Sevilla Casbas

10.3. ANEXOS EN CD



ES

Herramienta para el cálculo de materiales críticos e impacto ambiental en el diseño de componentes eléctricos y electrónicos.

Patricia Gómez Bachiller
Carlos Javierre Lardiés
Daniel Elduque Viñuales