Comparative Hybrid Life Cycle Assessment and Life Cycle Costing for the production of Magnesium Alloys for Recourse Efficiency

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Abstract

Magnesium alloys have high strength and light weight characteristics and are therefore commonly used in the automotive and military industries. Work is ongoing to develop new materials with improved properties, alongside which, the environmental impacts of any novel materials must be quantified.

The aim of this work is to quantify the environmental and cost impacts of the four magnesium alloys to understand which material combination leads to the lowest impact. This will aid industrial decision making with regards to product development and aid in the overall reduction of magnesium impact at a manufacturing level. Those alloys are the established WE43, ZK60 and AZ31 alloys and the novel MgZnCa alloys.

The results show that, of the four alloy structures studied, the WE43 alloy has both the highest GWP impact and the highest cost. Furthermore, the highest impact with regards to toxicity is attributed to the AZ31 alloy due to the use of aluminium in the sutructure.

Overall, this work supports the use of the new MgZnCa alloy as it leads to the lowest environmental impacts over those studied and does not incorporate rare earth, or other critical materials.

1. Introduction

The high strength and light weight characteristics of magnesium alloys lead to their extensive use in automotive and military applications. When heavier alloys, like steels, are replaced with magnesium alloys it leads to an increase in the energy efficiency of a product during the use phase. Some magnesium alloys also contain rare earth metals, such as neodymium and yttrium, which have been categorised as critical materials in the most recent European Commission report on critical raw materials [1, 2].

While material substitution can lead to a reduction in the impact of the use phase of a product, and therefore lead to substantial savings over the life cycle of said product, it is also important to understand how the composition of the alloy itself impacts the environment [3]. With this in mind, this report outlines the comparison of four magnesium alloy compositions with respect to their environmental and cost impacts. The hybrid life cycle assessment (LCA) and life cycle costing (LCC) methodologies, for the production of 1kg of each alloy composition, are outlined and the results presented with additional composition level analysis regarding the material use and laboratory process steps.

The aim of this work is to quantify the environmental and cost impacts of the four magnesium alloys to understand which material combination leads to the lowest impact. This will aid industrial decision making with regards to product development and aid in the overall reduction of magnesium impact at a manufacturing level. Those alloys are the established WE43, ZK60 and AZ31 alloys and the novel MgZnCa alloys.

This report is structured as follows: the LCA and LCC methodologies are discussed in section 1; section 2 details the results; the results are then analysed in section 3; the limitations of the study are highlighted in section 4 and finally the conclusions of the report are detailed in section 5. Supplementary material is available in the Appendix.

2. Methodology

The LCA process is a well-established methodology which has been widely published in many fields; it follows four standard steps, as outlined by ISO 14040:2006 [4]. These steps are shown in Figure 1. The 'goal and scope definition' of the LCA, which is shown in the system boundary in Figure 2, is established to represent the product or service which is to be measured [3, 5].

The Life Cycle Inventory (LCI) for this study was collected according to the production of 1kg of each alloy composition in a laboratory environment. In each case the production method described is the same (die casting (prior to the laboratory production process, cold rolling and furnace heating)), only the alloy composition and therefore the associated specific heat capacity is changed.

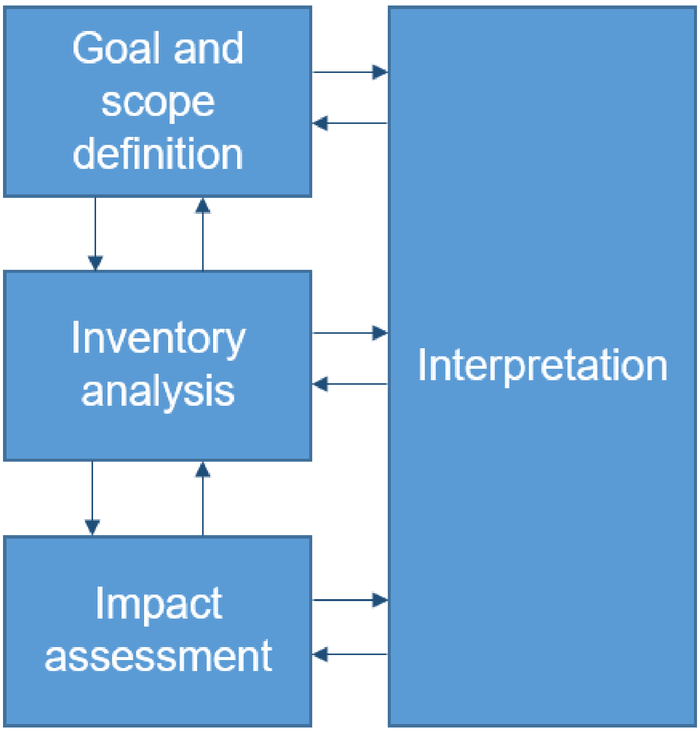

Figure 1 LCA framework [4]

The supply chain inputs were matched to the appropriate environmental inputs using the Ecoinvent database [6]. Where data was not available for a material in the Ecoinvent databased, data were derived on the basis of previously published guidelines using substitution based on chemical characteristics or functional similarities [3, 7].

A total of ten impacts were chosen to be compared in this study; global warming potential (GWP), acidification potential (AP), eutrophication potential (ET), freshwater aquatic ecotoxicity potential (FAETP), freshwater sediment ecotoxicity potential (FSETP), marine aquatic ecotoxicity potential (MAETP), marine sediment ecotoxicity potential (MSETP), human toxicity potential (HTP), land use and cumulative energy demand (CED). Each of these impact categories is explained further in Appendix 1.

The data was then uploaded into the SCEnAT*i* decision support tool. The use of the hybrid LCA methodology through the SCEnAT*i* decision support system captures the supply chain inputs that may not be accounted for by a process LCA methodology [8]. In this case the following 'missing inputs' were applied to the system boundary of the chosen supply chain:

- Other general purpose machinery
- Recycling of metal waste and scrap
- Steam and hot water supply
- Telecommunications
- Computer services and related activities
- Research and development
- Collection of waste

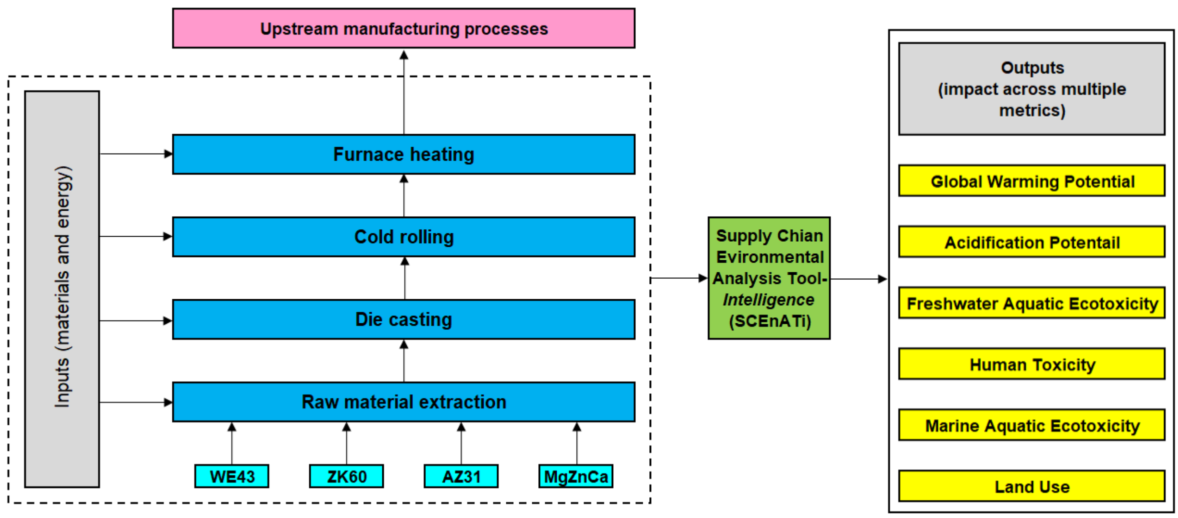

Figure 2 The system boundary of the magnesium alloy LCA; all process steps enclosed within the dotted lines are included in the LCA.

SCEnAT*i* also allows the LCC of the chosen supply chain to be developed. As no primary data was available to complete this step, secondary costing data was taken from web sources [9]. The Multiregional Input Output (MRIO) stored within SCEnATi provided indirect cost analysis for the supply chain in question [8].

Finally, SCEnATi translates the inputted data from the carbon accounting module of the mapped supply chain into a supply chain carbon map to identify carbon hotspots and quantify their impacts (see Appendix 2).

3. Results

The results of the hybrid LCA are outlined within this section of the report. An overall summary of the hybrid LCA result for each alloy composition is provided; composition level analysis of each alloy is shown; the electrical energy distribution of the laboratory production process is outlined; the percentage contributions of each step within the system boundary to the GWP impact are detailed; the material embedded energy is shown and the toxicological impact of each material composition is show.

Table 1 Summary of the hybrid LCA result for each alloy composition.

Alloy	Total GWP (kg CO_2-eq)	Total Cost (£)	Direct GWP (%)	Direct Cost (£)	Indirect GWP (%)	Indirect Cost (£)
WE43	123.65	17.26	99.9	16.28	0.1	0.98
ZK60	122.63	15.16	99.9	14.25	0.1	0.91
AZ31	123.45	14.56	99.9	13.61	0.1	0.94
MgZnCa	122.62	14.57	99.9	13.67	0.1	0.90

Table 1 shows that the WE43 magnesium alloy has the highest GWP of the four alloy compositions studied, throughout the whole supply chain, and has the highest production cost. The lowest GWP impact, can be attributed to the production of the MgZnCa magnesium alloy, whereas the lowest cost alloy is AZ31. It can be seen that for all four alloys, the direct (process) LCA contributes for 99% of the overall GWP impact and only 1% of the GWP impact is caused by the indirect (hybrid) LCA. The indirect (hybrid) costs of all four alloy compositions represent approximately 8% of the total cost.

3.1. Composition level analysis

The percentage contributions of each alloying element within each alloy composition is shown.

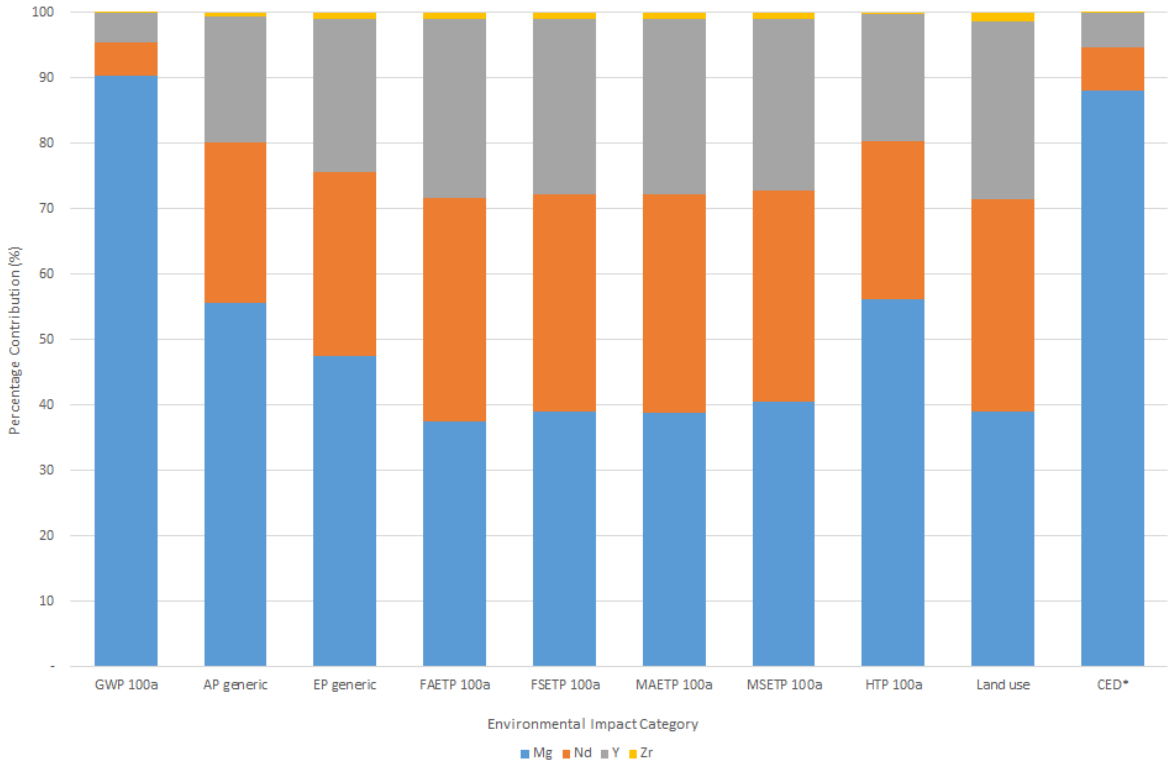

*Figure 3 Percentage contribution of each alloying material of the WE43 alloy for the environmental impacts investigated. *Cumulative energy demand.*

The magnesium content of the WE43 alloy causes 90% of the total GWP impact within the system boundary studied and the percentage contribution of the magnesium content for the CED of the alloy is almost 88%. The use of Nd and Y in the WE43 alloy causes the impact of the remaining categories to be spread across these three materials (shown in Figure 3).

Figure 4 shows that, again magnesium has the highest contribution towards the GWP (97.9%) and CED (98.6%) impact categories but Zn causes a significant proportion (over 15%) of the impact over the remaining categories.

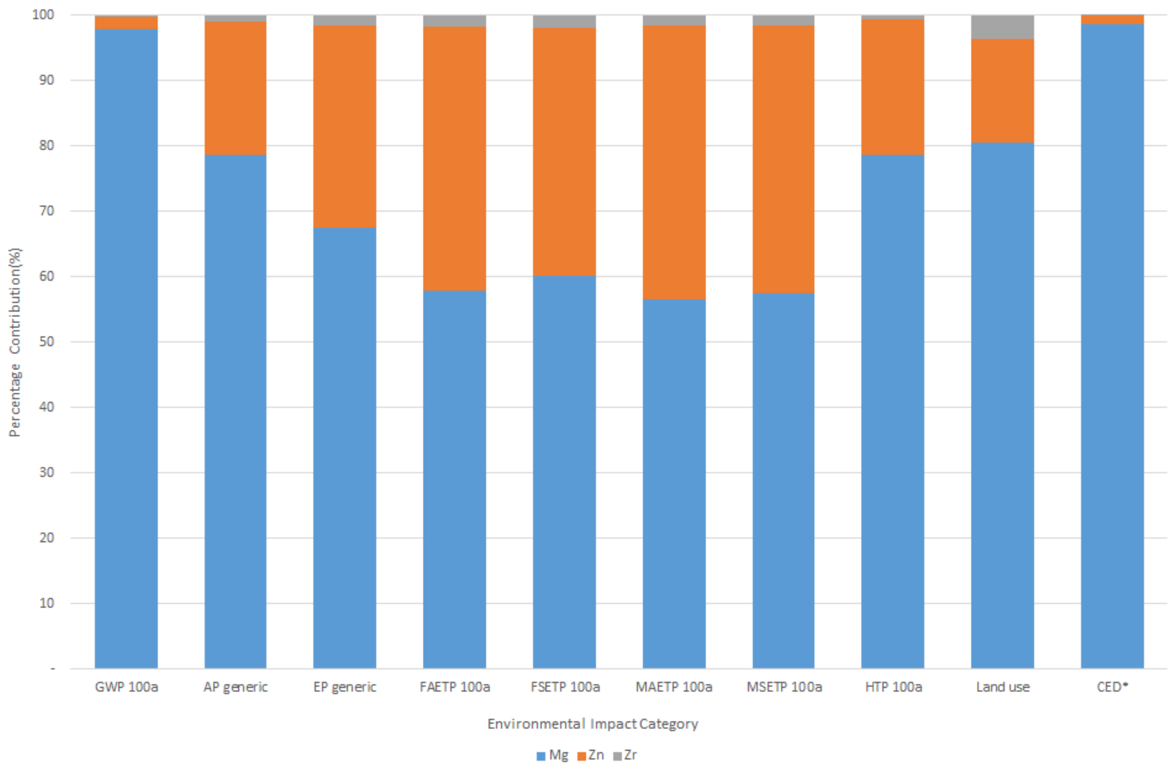

*Figure 4 Percentage contribution of each alloying material of the ZK60 alloy for the environmental impacts investigated. *Cumulative energy demand.*

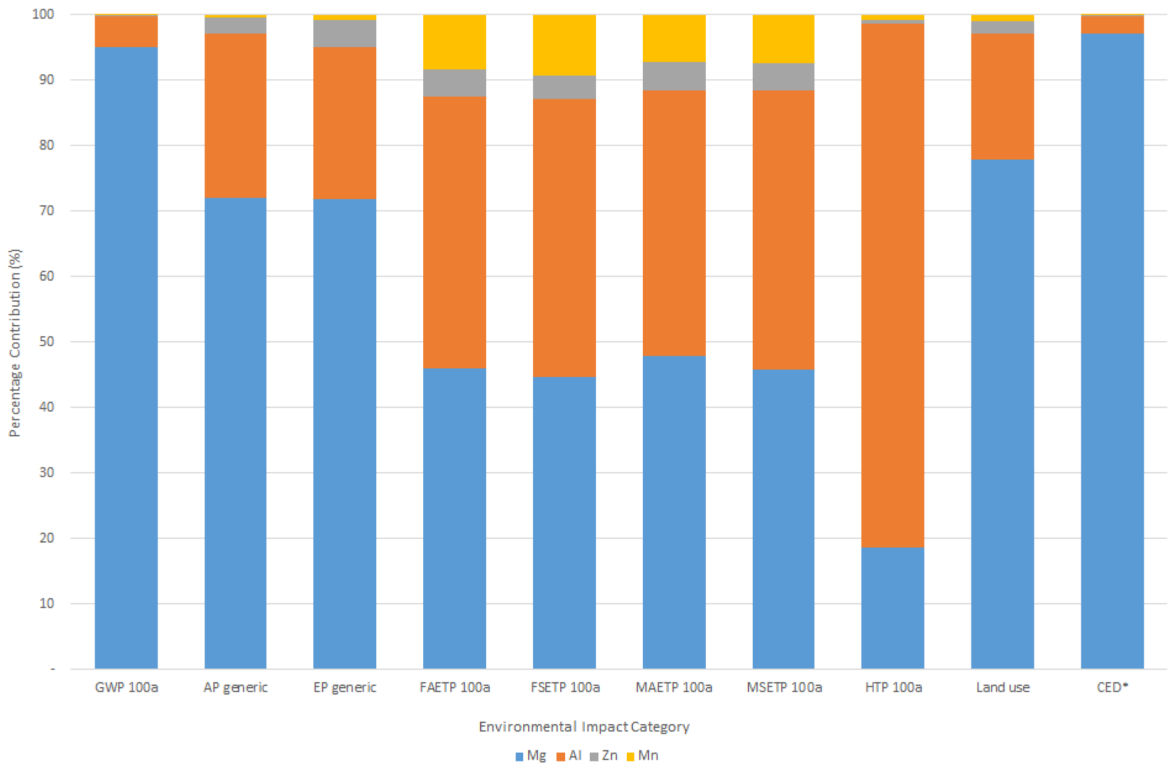

*Figure 5 Percentage contribution of each alloying material of the AZ31 alloy for the environmental impacts investigated. *Cumulative energy demand.*

Figure 5 shows, again, that the magnesium content of this alloy has the highest percentage contribution to both the GWP (95%) and CED (97%) impact categories. The impact of Al is similar to, and in some cases overshadows, the impact of Mg.

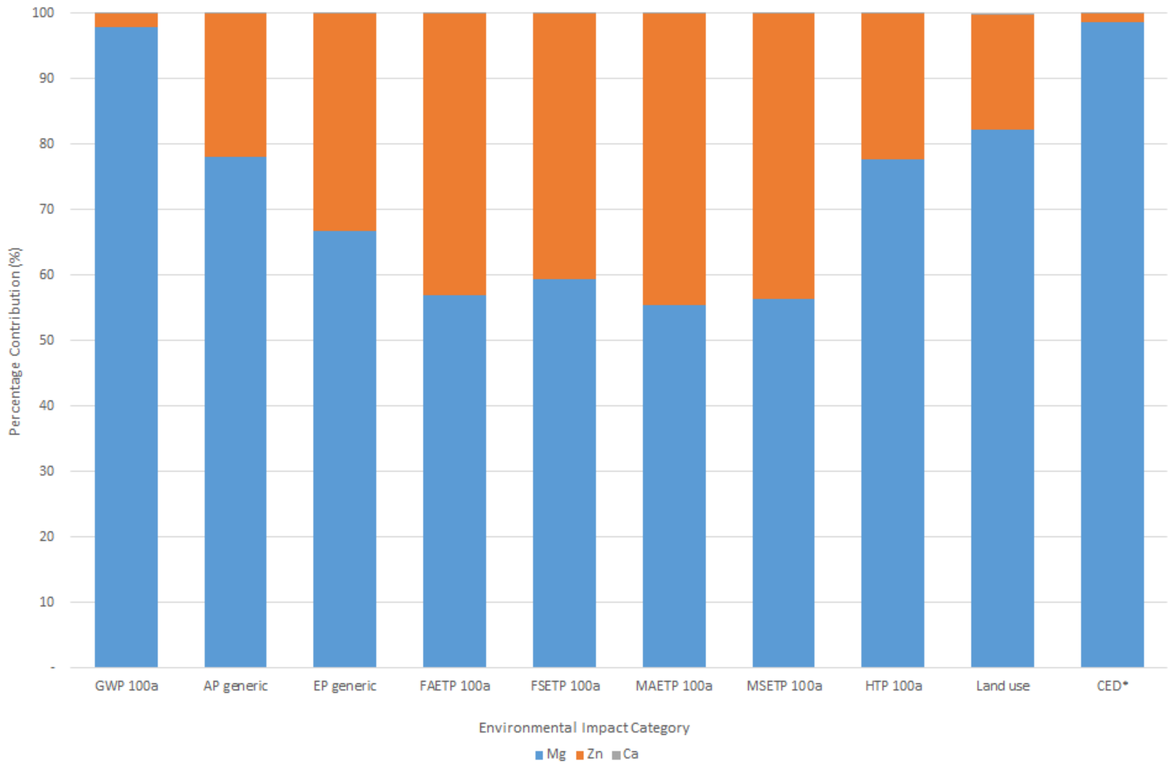

*Figure 6 Percentage contribution of each alloying material of the MgZnCa alloy for the environmental impacts investigated. *Cumulative energy demand.*

Similarly, to the ZK60 alloy, the use of Zn leads to a significant proportion (over 15%) of the impact over the majority of impact categories; only the GWP and CED are affected extensively by the use of magnesium leading to a percentage contribution of 98% and 98.5% respectively. The impact of Zn is discussed above.

3.2. Energy distributions

3.2.1. Primary energy distribution

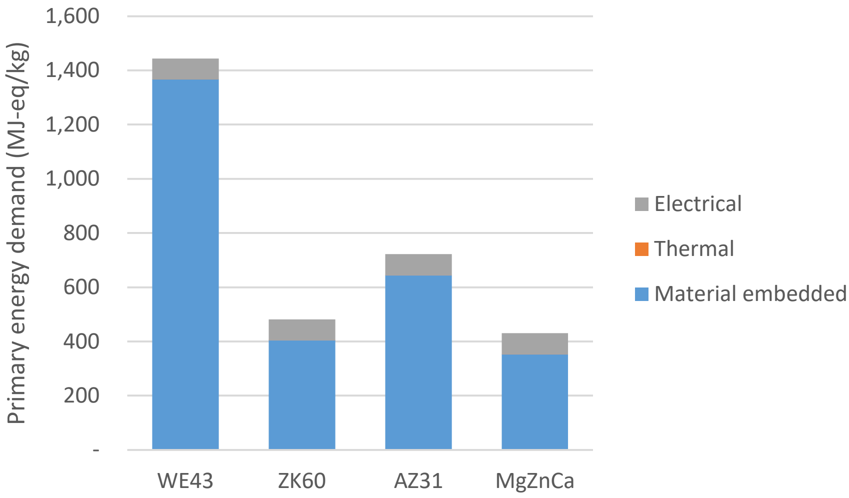

Figure 7 The primary energy demand comparison for the WE43, ZK60, AZ31 and MgZnCa alloys.

The total primary energy demand for each alloy studied is shown in Figure 7, this outlines the material embodied energy, electrical energy and thermal energy. The electrical and thermal energy demand is broken down further in Figures 8 and 9 and the material embedded energy is outlined in Table 3.

3.2.2. Electrical energy distribution

The electrical energy distribution of the manufacturing processes performed in the laboratory are shown in Figure 8.

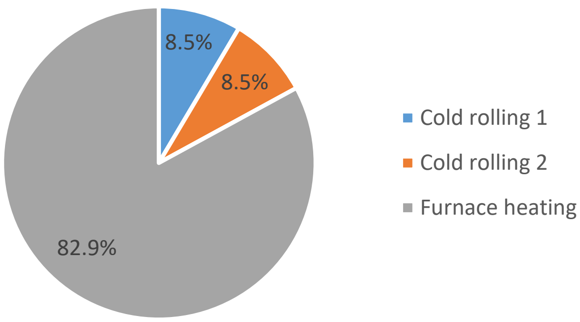

Figure 8 The percentage electrical energy contributions of each laboratory production process for all magnesium alloy compositions. The die casting process, performed prior to laboratory processing, is not included in this chart.

2.3 Thermal energy distribution

The thermal energy distribution of the manufacturing processes performed in the laboratory are shown in Figure 9.

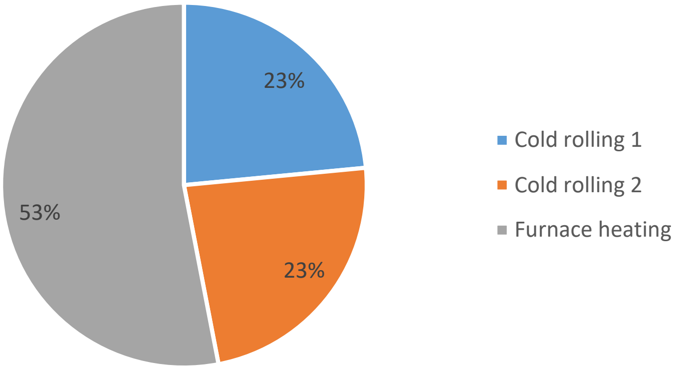

Figure 9 The percentage thermal energy contributions of each laboratory production process for all magnesium alloy compositions. The die casting process, performed prior to laboratory processing, is not included in this chart.

Table 2 The specific heat capacities and resulting thermal energy demands of each alloy studied

Alloy	**Specific heat capacity (J/kg K)**	**Total thermal energy demand (MJ-eq/kg)**
WE43	1000	0.016805
ZK60	960	0.016132
AZ31	990	0.016637
MgZnCa	960	0.016132

2.4 Input global warming potential

Table 3 Percentage contributions of each input with respect to the GWP of the four Mg alloy compositions studied.

	Total GWP impact (process LCA)			
	123.400	122.381	123.201	122.365
	% of GWP impact			
Input	**WE43**	**ZK60**	**AZ31**	**MgZnCa**
Materials	12.905	12.179	12.764	12.168
Electrical energy (laboratory processing)	0.952	0.960	0.953	0.960
Thermal energy (laboratory processing)	0.001	0.001	0.001	0.001
Die casting	86.142	86.860	86.282	86.871

The data shown in Table 3 fully breaks down the GWP impact of all four of the alloy compositions to show the percentage contribution to the impact caused by the materials, electrical and thermal energy use in the laboratory and the die casting process (prior to the laboratory). The results show that the die casting process has the highest overall contribution while the combined electrical and thermal energy use of the laboratory processed have the lowest contribution.

2.5 Material embedded energy of the alloying elements

Table 4 The percentage contribution of the material embedded energy of each alloying element within the four alloy compositions studied.

Magnesium alloy	Total material embedded	Composition	% contribution of each alloying element
WE43	289.860	Mg	87.979
		Nd	6.604
		Y	5.309
		Zr	0.108
ZK60	262.526	Mg	98.566
		Zn	1.288
		Zr	0.146
AZ31	272.611	Mg	97.154
		Al	2.620
		Zn	0.161
		Mn	0.065
MgZnCa	262.182	Mg	98.590
		Zn	1.397
		Ca	0.013

The percentage contribution of the material embedded energy of each alloying element of the four different alloy compositions are shown in Table 4. In each case, the overriding impact is from base element, magnesium. Although, the use of Nd and Y in WE43, results in the lowest contribution of Mg due to the impact of these rare earth alloying elements.

2.6 Toxicological impact of each alloy

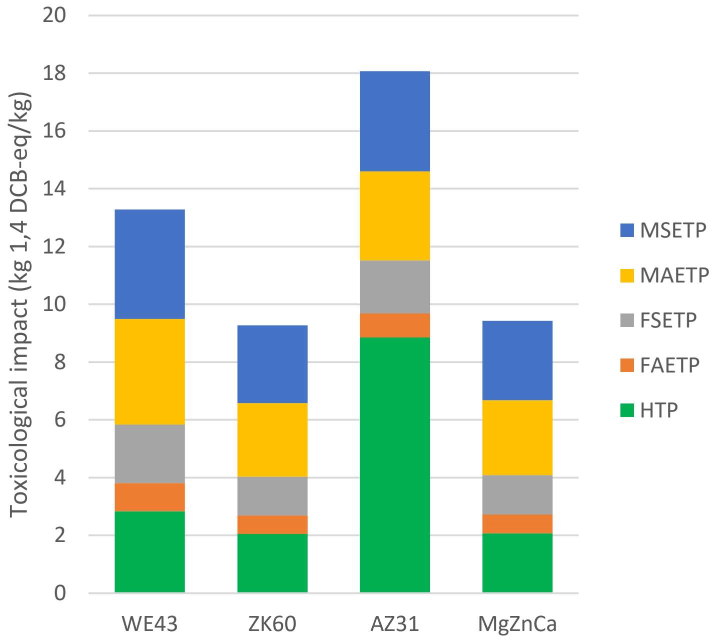

Figure 10 The total toxicological impact comparison for the WE43, ZK60, AZ31 and MgZnCa alloys.

The toxicological impacts of all four alloy compositions are shown in Figure 10. The AZ31 alloy composition leads to the highest toxicological impact, this can be broken down further to show that 80% of the HTP impact of this alloy is caused by the use of Al.

2.7 The upstream impact

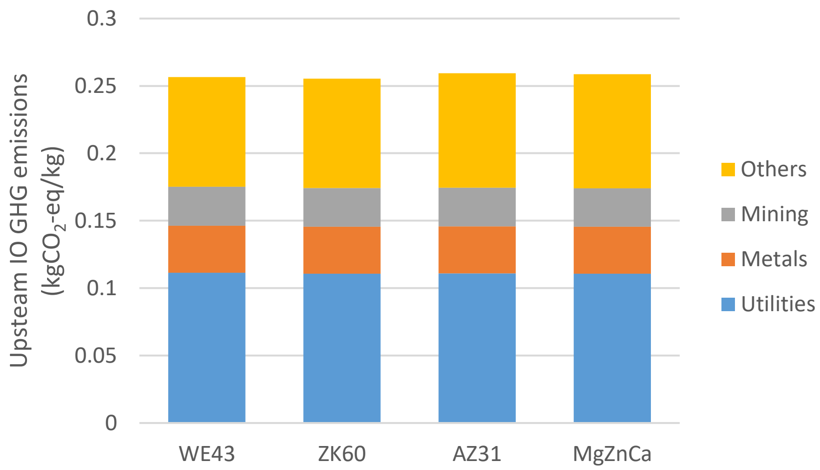

Figure 11 The upstream IO GHG emissions comparison for the WE43, ZK60, AZ31 and MgZnCa alloys.

Figure 11 shows the distribution of the upstream IO GHG impact, the three highest industries shown are mining, metals and utilities; "others" represents the following industries: business services, transport and communication, minerals, chemicals, fuels, equipment, agriculture, wood and paper, trade, food, construction, textiles and forestry.

4. Discussion

3.1 Costings

In the absence of primary costings data, the individual costs of each element were derived from up-to-date web sources, such as "Investmentmine" [9, 10]. The LCC of this report would be strengthened with the use of industry led, primary data.

Table 1 shows the total cost of each alloy, this cost is then broken down into direct costs and indirect costs. The direct costs are those relating to the materials and processes included within the process system boundary (see Figure 2) for the functional unit of 1kg of material produced, for example, the total direct of WE43 are £16.28. The indirect costs of the system are calculated through the hybrid methodology and therefore use Multiregional Input-Output (MRIO) tables to determine the additional costs to the supply chain which are not covered by the process methodology; the indirect costs of WE43 are £0.98.

3.2 Component level analysis

Overall, the GWP impact of the elements used in the production of each alloy ranges from 12.168 kg CO_2-eq (MgZnCa) to 12.905 kg CO_2-eq (WE43). This small range in results is due to the high proportion of Mg used as the base element for each alloy. The differences in the impacts of each material are more clear over the additional eight impact categories, as the impacts are affected by the choice of alloying element.

While at the functional unit level there is little difference in the overall impact of the materials, if these impacts were multiplied up to meet industry production levels the difference in impact would be considerably higher.

Figure 3 shows that the use of Nd and Y in the alloy structure leads to high impact contributions (above 10%) for the AP, EP, FAETP, FSETP, MAETP, MSETP, HTP and Land use impact categories. Nd and Y are rare earth materials; the separation and refining processes required to produce these materials are both energy intensive and environmentally hazardous, consequently leading to high impacts over these categories [11]. These materials have also been classified as "critical" by the 2018 "Report on Critical Materials for the EU" [2]. Rare earth elements are considered to be important for the progress of technology and quality of life and are also economically important whilst being at risk with regards to supply [2]. Overall, with this information in mind, the reduction, or preferably the removal, of rare earth materials from magnesium alloys would improve the overall environmental and cost impacts of the alloys.

It is the use of Zn in the ZK60 and MgZnCa alloys that has a high contribution to the remaining impact categories (except CED) (see Figures 4 and 6) while Figure 5 shows that the highest contributor to the remaining impact categories (except CED) in the AZ31 alloy is Al. Norgate et al. [12] have compared the environmental impacts of metal production. Their works does not assess the range of impacts chosen in this study but shows that the Bayer refining and Hall-Heroult smelting processes for aluminium production lead to a CED of 211 MJ/kg, GWP of 22.4 $kgCO_2$-eq/kg and AP of 0.131 $kgSO_2$-eq/kg. In comparison, the electrolytic process for zinc production leads to only 48 MJ/kg for the CED, 4.6 $kgCO_2$-eq/kg for the GWP and 0.055 $kgSO_2$-eq/kg for the AP [12]. Overall, these results mirror the results presented in this study and therefore support the reduction of aluminium use in the AZ31 alloy. Furthermore, savings on the environmental impact of the alloy could be made by choosing the imperial smelting method for zinc production which has the following environmental impacts associated with it: CED, 36 MJ/kg; GWP, 3.3 $kgCO_2$-eq/kg; AP, 0.036 $kgSO_2$-eq/kg [12].

3.3 Energy distribution

The electrical and thermal energy distributions are shown in Figures 8 and 9, all four alloy types undergo the same manufacturing processes and therefore this figure represents all for alloys. 6.57 MJ-eq/kg is required for each cold rolling process and 63.93 MJ-eq/kg is required for the furnace heating process step.

While the proportion of thermal energy demand is the same for each alloy (Figure 9), the total thermal energy requirement for each alloy varies depending on the specific heat capacity, these are detailed in Table 2. The increased specific heat capacity (100 J.kg K) of the WE43 alloys leads to the highest thermal energy demand of the four alloy compositions studied.

The electrical and thermal energy requirements for the production of these alloys are likely to reduce in an industrial setting due to the use of machinery which is larger and more efficient [13]. While this assumption can be made, this report would be much more robust with the use of primary industry data.

3.4 Material embedded energy

The material embedded energy demand is also known as the cumulative energy demand which is the sum of the material energy demand on natural resources (fossil, nuclear, solar, primary forest, wind, water and biomass) [3].

It is the use of neodymium in the WE43 alloy that leads to the highest material embedded energy at 638.11 MJ-eq/kg (47.7%); yttrium also has a high impact at 384.7 MJ-eq/kg (28.15). These impacts are related to those discussed in section 3.2 regarding rare earth elements. In the ZK60 and MgZnCa alloys, the use of magnesium leads to the highest impact (68.07% and 78.04% respectively). While the use of magnesium in the AZ31 alloy also leads to a high impact (32.75%), the aluminium content of the alloy leads to a 38.6% impact on material embedded energy. Factors such as ore grade, energy source, fuel type, transportation and the choice of technology can have an effect on the environmental impact of mined material [12]. As discussed in section 3.2 the use of the imperial smelting process will lead to a reduction in the associated zinc material embedded energy when compared with the electrolytic processing method. Also, as ore grades decrease, this increases the associated impacts due to the requirement of additional infrastructure and energy [11, 12].

3.5 Toxicology analysis

The HTP, FAETP, FSETP, MAETP and MSETP impact categories are all measured in kg 1,4 DCB-eq and can therefore be aggregated and compared. Figure 10 shows that the alloy with the highest toxicological impact of the four compositions studied was AZ31. While the wt% contribution of Mg leads to high impact contributions from this material, the aluminium use in

AZ31 (0.0287 wt%) leads to high toxicological percentage contributions; FAETP (41.5%), HTP (79.9%), MAETP (40.5%), FSETP (42.5%) and MSETP (42.6%). With respect to the highest contribution to HTP, although aluminium is perceived as a 'safe' material it has been found to lead to excitotoxin damage (damage to nerve cells), is liked to inflammatory issues and is recognised as a mutagen [14].

3.6 Upstream IO GHG emissions

The hybrid LCA process allows those impacts that are unknown to the modeller, and would usually be left out of a process LCA, to be captured using MRIO tables. For all four alloy compositions the three highest upstream impacts arise from the utilities (43%), metals (13%) and mining (11%) industries. These impacts only contribute towards 0.1% of the overall GWP impact and therefore few savings could be made within the whole supply chain by targeting savings in these areas.

5. Limitations

The main limitations to this work are the lack of primary data; up-to-date, industry based, material and process costs would lead to a more accurate result and therefore allow better informed decision making. While the data for the laboratory based process steps, namely furnace heating and cold rolling, used in this study is primary data, the die casting process information used in this study was taken from the EcoInvent database. Similarly, to the costing information, relevant industrial data on this processing step would result in improved LCA and LCC results.

6. Conclusions

The study outlined above aims to determine the environmental and cost impacts of the four alloys investigated (WE43, ZK60, AZ31 and MgZnCa). At a laboratory level, using a functional unit of 1kg of material produced. The results relating to these aims are displayed and discussed. Overall the WE43 alloy leads to the highest environmental impact with regards to GWP (123.65 kg CO_2-eq/kg) and also the highest cost per kg (£16.28). With regards to the toxicological impact of the alloys, the AZ31 has the highest impact, this I due to the aluminium content of the alloy.

While this report would be enhanced through the use of primary industrial data, the results presented in this work use a robust and widely employed methodology that supports the use of MgZnCa alloy as it leads to the lowest environmental impact, over all categories and does not employ the use of rare earth materials.

References

[1] DARE. (06/03/2018). Available: http://darealloys.org/research-programme-overview/magnesium-alloys-that-are-less-dependent-on-rare-earths/

[2] "Commission Staff Working Document Report on Critical Raw Materials and the Circular Economy," European Commission2018.

[3] T. Ibn-Mohammed, L. S. C. Koh, I. M. Reaney, A. Acquaye, D. Wang, S. Taylor*, et al.*, "Integrated Hybrid Life Cycle Assessment and Supply Chain Environmental Profile Evaluations of Lead-based (Lead Zirconate Titanate) versus Lead-free (Potassium Sodium Niobate) Piezoelectric Ceramics," *Energy & Environmental Science,* vol. 9, pp. 3495-3520 10.1039/C6EE02429G, 2016.
[4] BSI, "BS EN ISO 14040:2006 Environmental Management- Life cycle assessment- Principles and framework," 2006.
[5] A. Ahmed, I. Hassan, T. Ibn-Mohammed, H. Mostafa, I. M. Reaney, L. S. C. Koh*, et al.*, "Environmental life cycle assessment and techno-economic analysis of triboelectric nanogenerators," *Energy & Environmental Science,* vol. 10, pp. 653-671, 2017.
[6] Ecoinvent. (http://www.ecoinvent.org/ accessed 19/09/2017, 17th May 2018). Available: http://www.ecoinvent.org/
[7] G. Geisler, T. B. Hofstetter, and K. Hungerbühler, "Production of fine and speciality chemicals: procedure for the estimation of LCIs," *The International Journal of Life Cycle Assessment,* vol. 9, pp. 101-113 10.1007/bf02978569, 2004.
[8] A. Lake, A. Acquaye, A. Genovese, N. Kumar, and S. C. L. Koh, "An application of hybrid life cycle assessment as a decision support framework for green supply chains," *International Journal of Production Research,* vol. 53, pp. 6495-6521 10.1080/00207543.2014.951092, 2015.
[9] (June 2018). *Investment Mine*. Available: http://www.infomine.com/investment/
[10] J. H. Miah, S. C. L. Koh, and D. Stone, "A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing," *Journal of Cleaner Production,* vol. 168, pp. 846-866, 2017/12/01/ 2017.
[11] L. Smith, T. Ibn-Mohammed, S. C. L. Koh, and I. M. Reaney, "Life cycle assessment and environmental profile evaluations of high volumetric efficiency capacitors," *Applied Energy,* vol. 220, pp. 496-513, 6/15/ 2018.
[12] T. E. Norgate, S. Jahanshahi, and W. J. Rankin, "Assessing the environmental impact of metal production processes," *Journal of Cleaner Production,* vol. 15, pp. 838-848, 2007/01/01/ 2007.
[13] H. Walker, L. Di Sisto, and D. McBain, "Drivers and barriers to environmental supply chain management practices: lessons from the public and private sectors," *Journal of Purchasing and Supply Management,* vol. 14, pp. 69-85 https://doi.org/10.1016/j.pursup.2008.01.007, 2008.
[14] C. Exley, "Human exposure to aluminium," *Environmental Science: Processes & Impacts,* vol. 15, pp. 1807-1816, 2013.
[15] A. P. Acero, C. Rodriguez, and A. Ciroth. (2014 http://www.openlca.org/wp-content/uploads/2016/08/LCIA-METHODS-v.1.5.5.pdf, 29th May 2018). *Green Delta*. Available: http://www.openlca.org/wp-content/uploads/2016/08/LCIA-METHODS-v.1.5.5.pdf

Appendix 1

A total of ten impacts were chosen to be compared in this study; global warming potential (GWP), acidification potential (AP), eutrophication potential (ET), freshwater aquatic ecotoxicity potential (FAETP), freshwater sediment ecotoxicity potential (FSETP), marine aquatic ecotoxicity potential (MAETP), marine sediment ecotoxicity potential (MSETP), human toxicity potential (HTP), land use and cumulative energy demand (CED). Each of these impact categories is explained in more detail below.

The GWP, given as kg CO_2-eq, is a calculates climate change and is based on the UN's Intergovernmental Panel on Climate Change (IPPC) factors with a time horizon of 100 years (other time horizons can also be assessed but this is the most common). Factors taken into consideration are the effect of greenhouse gases on biodiversity, climate phenomenon and temperature [15].

AP, expressed as kg SO_2-eq, is a measure of acidification due to the release of SO_2 and NO_x into the atmosphere leading to acid rain. Acidification leads to a reduction in biodiversity and damage to the ecosystem, this usually takes place in foreign regions to the initial gas release [15].

When nutrients build up in ecosystems due to the release of ammonia, NOx, nitrates and phosphorus in the air and water, this is called eutrophication which leads to adverse effects such as the growth of algae which reduces populations and water quality. The EP measures this change as either kf PO_4^3-eq or kg N-eq, depending on the reference model [15].

The FAETP, FSETP, MAETP and MSETP address the impact of toxic substances in each of the associated ecosystems. The maximum tolerable concentration of materials, such as heavy metals, in water for ecosystems is calculated using the European Union's toxicity model and is expressed as kg 1,4-DB-eq [15].

Human toxicity is measured by the HTP, which is calculated based on the toxicity of a compound and its potential does, the units used at kg 1,4-DB-eq. The aim of the impact category is to determine the harm of a chemical when it is released to the environment. The indicators used are cancer, respiratory diseases, non-carcinogenic effects and effects to ionising radiation.

The consumption of a material, based on natural resources such as fossil, nuclear, solar and wind defines the CED, this is also known as the material embedded energy and is expressed as MJ-eq [3].

Appendix 2

This section provides the supply chain carbon map produced by the SCEnATi decision support tool. The output is colour coordinated; a red box represents a very high impact, above 10%; high impact (5-10%) is shown in orange; medium impact (1-5%) is given in yellow; low impact (less than 1%) is depicted in green.

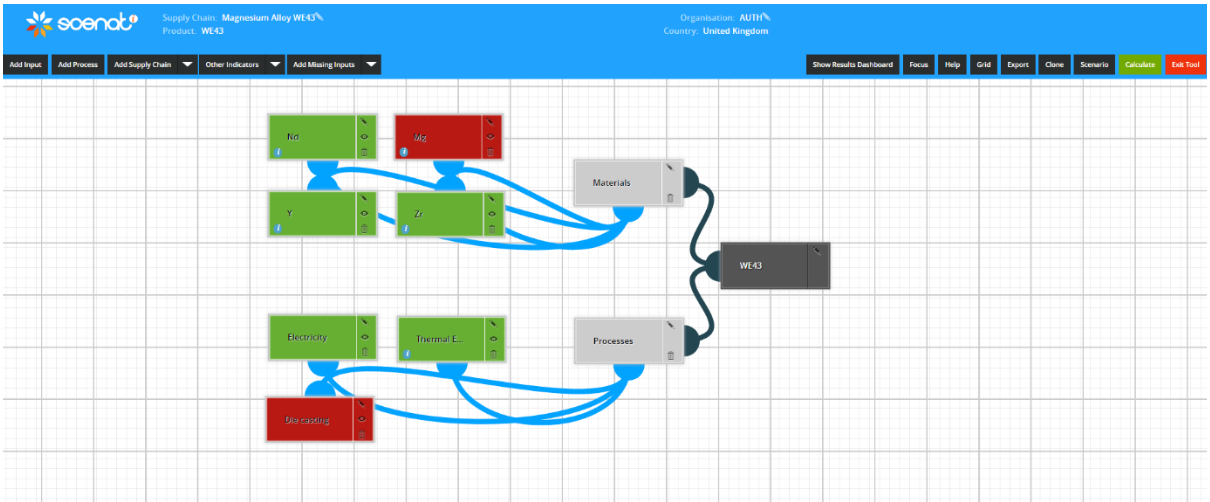

Figure A2-1 SCEnATi supply chain carbon map for the WE43 alloy

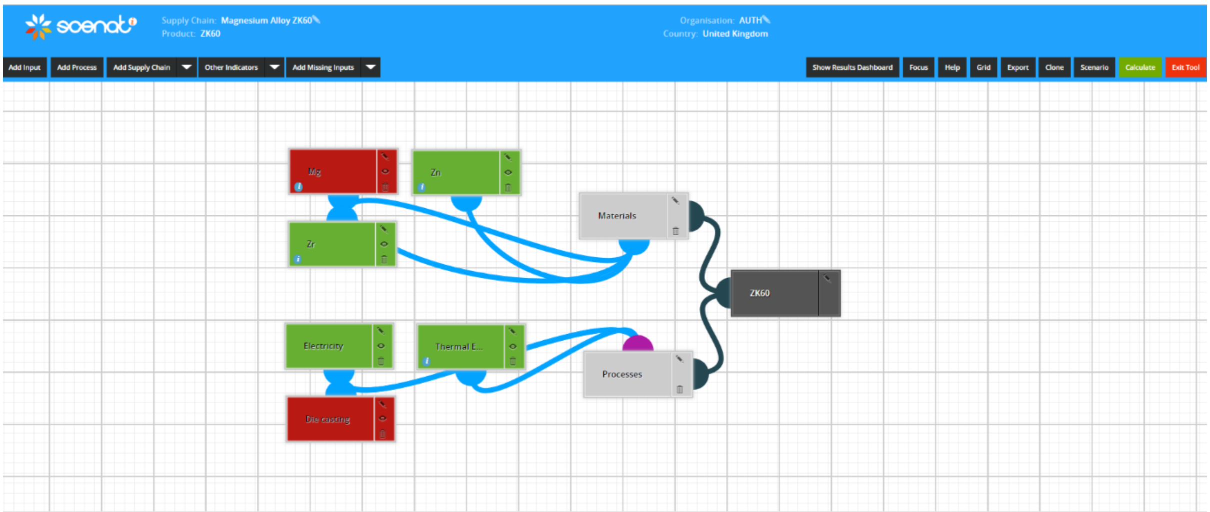

Figure A2-2 SCEnATi supply chain carbon map for the ZK60 alloy

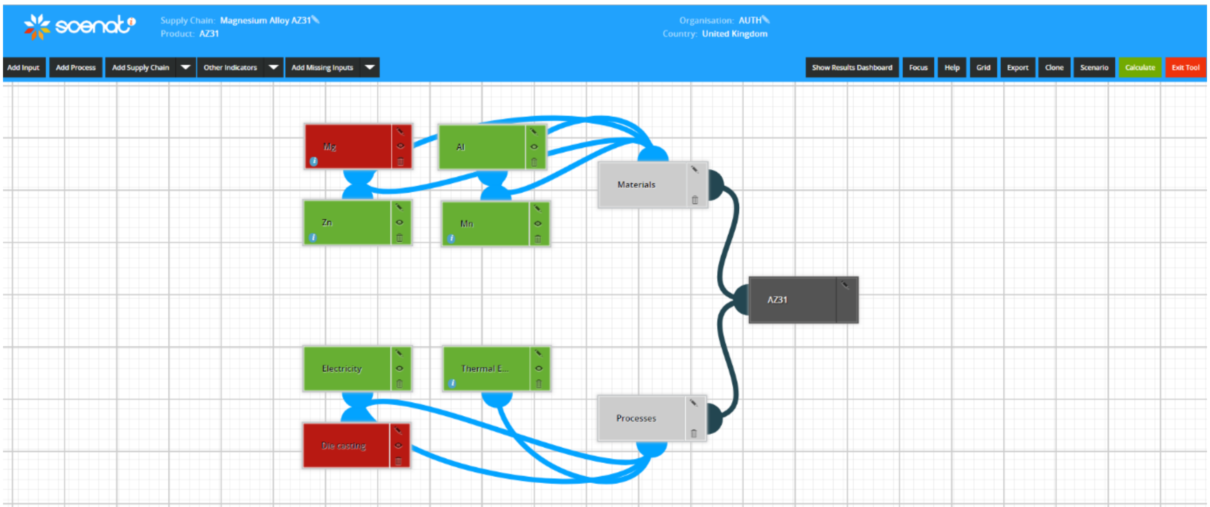

Figure A2-3 SCEnATi supply chain carbon map for the AZ31 alloy

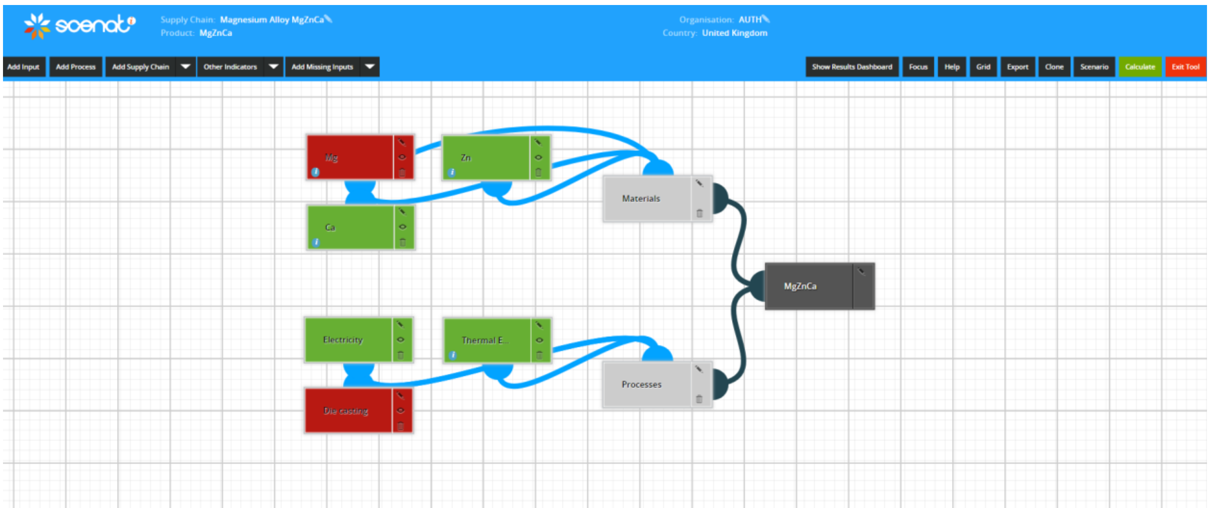

Figure A2-4 SCEnATi supply chain carbon map for the MgZnCa alloy

Appendix 3

This section provides a breakdown of the Life Cycle Inventories for each of the alloy compositions studied.

Table A3-1 LCI of WE43

Alloy component	kg/kg	Ecoinvent reference
Mg	0.9254	Magnesium production, electrolysis RoW
Nd	0.03	Neodymium oxide to generic market for mischmetal GLO
Y	0.04	Lanthanum oxide RoW
Zr	0.0046	Zirconium oxide production RoW

Table A3-2 LCI of ZK60

Alloy component	kg/kg	Ecoinvent reference
Mg	0.939	Magnesium production, electrolysis RoW
Zn	0.0554	Primary zinc production from concentrate RoW
Zr	0.0056	Zirconium oxide production RoW

Table A3-3 LCI of AZ31

Alloy component	kg/kg	Ecoinvent reference
Mg	0.9611	Magnesium production, electrolysis RoW
Al	0.0287	Aluminium production, primary, ingot RoW
Zn	0.0072	Primary zinc production from concentrate RoW
Mn	0.003	Manganese production RoW

Table A3-4 LCI of MgZnCa

Alloy component	kg/kg	Ecoinvent reference
Mg	0.938	Magnesium production, electrolysis RoW
Zn	0.06	Primary zinc production from concentrate RoW
Ca	0.002	Calcium carbonate production, precipitated RoW