Analyzing Transformation of Product Life Cycle Assessment in Terms of Circular Economy: Case Study

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Abstract

The paper is concerned with the range of the possible transformations of product life cycle assessment in terms of circular economy. Using a particular product of electrical engineering, the authors conduct a system analysis of the inputs and outputs of its manufacture including the necessary links to the logistic chains and the possible impacts on the product life cycle. Data were collected in a small enterprise where the product parameters were gained and verified with information on the product's part and material composition (such as from a list of parts), input and output raw materials and energies, input and output auxiliary and spare parts as well as on water consumption, emissions into the atmosphere and soil, plus the amount of solid waste produced.

The results of the research can be used by small or medium-sized companies as a starting point for product life cycle assessment, but they can also be used to create a comparative category of a selected product of the electrical industry in Czech conditions, as well as within the European Union or in a global sense. The originality of the results is given by the choice of a small and medium company representing the chosen manufacturer, the comprehensiveness of data, expression in physical units of the total energy, primary fuel and energy, raw material and water consumption, CO2 emissions into the atmosphere and solid waste for all the material life cycle stages, production, transport, use and waste including the evaluation of the undesired values of quantities for the chosen product.

Keywords: *circular economy, product life cycle, sustainability, waste*

Introduction

Among the long-term priorities of the EU or the European Commission for the future of Europe are issues concerning the environment, (see, the 7th Environment Action Programme[1]), energetic union and measures eliminating the impacts of the waste management and climate change. Already in 2015, the European Commission adopted Closing the Loop — an EU action plan for the circular economy[2] where manufacture (including the design of production processes), consumption and waste management are defied as forming the basis for circular economy. Circular economy is a method of production and consumption that, through sharing, reusing, repairing, rebuilding, and recycling, increases the value of the existing products, and raw materials. In this way, the product life cycles are extended and waste minimized. In other words, even if a product itself cannot be used, the raw materials and components are processed to create a new value[3+4+5]. Circular economy aims to transform linear economy into a circular one.

Along with the above metamorphoses, as a consequence of various technological impacts related to Industry 4.0 (such as IoT, big data, autonomous robots, additive production[6], etc.), economies are being transformed, trade models altered and the position itself of the industrial production changed in the value chain. An integral part of such changes is logistics, which, being instrumental in resolving the problem of transforming the linear model into circular economy, is also an inseparable part of the cornerstones of Industry 4.0, helping create the value chain or manage the waste logistic chain. Not long ago, the consumer was the endpoint of a logistic chain. However, a consumer will only consume part of a product, leaving behind the packaging and waste of both organic and inorganic origin. Circulation of materials and products influence the economically and ecologically successful execution of processes such as reconditioning and the corresponding supply chain management[7].Nowadays, logistics or, rather, control of the supplier chain is becoming increasingly important due to the joint efforts of UN[8], EU[9] to attain the objectives of sustainable development of new management requirements with new management approaches put in place to control the supplier chain – dubbed sustainable supply chain management (e.g. The role of production or The role and types of logistics[10]).

A condition necessary for the future circular economy to be successful is the environmental principles applied to each product, based on the Directive 2005/32/EC of the European Parliament and of the Council establishing a framework for the setting of eco-design requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council[11], subsequently, Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of eco-design requirements for energy-related products as well as other adopted standards[12] (e. g. ČSN EN ISO 14040 (010940) Environmental Management - Life Cycle Assessment - Principles and Outlines, ČSN EN ISO 14064-1, ČSN EN ISO 14067 etc.).

The principles of assessing each product in terms of its impacts on the environment as well as their methods and approaches form a basis for the future circular economy. One of these instruments is Life Cycle Assessment (LCA), a comprehensive method for assessing the environmental aspects of a product at each of its life-cycle stages: raw materials extraction, production, transportation, use, waste disposal. The LCA method is used by worldwide-recognized software tools such as Boustead Model, CMLCA, GaBi, or other specialized forms of tools such as DST, IWM and IWM 2, ORWARE and others.

Table 1: Total waste production (tonne) in EU from 2010 to 2020

Region\Time	2010	2012	2014	2016	2018	2020
European Union - 27 countries (from 2020)	2 212 900 000	2 242 540 000	2 243 790 000	2 258 910 000	2 338 230 000	2 152 930 000
Euro area - 19 countries (2015-2022)	N/A	N/A	N/A	N/A	N/A	N/A
Belgium	61 345 803	53 839 470	57 965 392	63 152 384	68 187 479	68 061 590
Bulgaria	167 396 268	161 252 166	179 677 011	120 508 475	129 751 823	116 387 350
Czechia	23 757 566	23 171 358	23 394 956	25 381 426	37 847 614b)	38 486 186
Denmark	16 217 736	16 713 822	20 808 843	20 981 931	21 445 206	20 135 564
Germany	363 544 995	368 022 172	387 504 241	400 071 672	405 523 624	401 156 266
Estonia	19 000 195	21 992 343	21 804 040	24 277 879	23 185 581	16 181 973
Ireland	19 807 586	12 713 021	15 166 830	15 251 689	13 986 757	16 192 033
Greece	70 432 705	72 328 280	69 758 868	72 332 353	45 240 333	28 943 897
Spain	137 518 902	118 561 669	110 518 494	128 958 523	137 822 935	105 624 359
France	355 081 245	344 440 922	324 462 969	322 685 297	343 307 326	310 373 987
Croatia	3 157 672	3 611 678	3 724 563	5 366 953	5 543 310	6 003 760
Italy	158 627 618	154 427 046	157 870 348	163 827 838	172 502 773	174 887 620
Cyprus	2 372 750	1 875 308	1 978 699	2 467 042	2 302 144	2 219 531
Latvia	1 498 200	2 309 581	2 621 495	1 909 631	1 773 726	2 852 792
Lithuania	5 578 134	5 678 751	6 200 450	6 674 238	7 080 538	6 695 731
Luxembourg	10 441 469	8 397 228	7 072 758	10 020 519	9 014 397	9 215 222
Hungary	16 735 423	16 310 151	16 650 639	15 938 077	18 369 585	16 063 842
Malta	1 352 994	1 456 213	1 672 810	1 951 928	2 507 070	3 000 546
Netherlands	121 145 468	121 194 466	132 362 297	141 024 020	145 245 469	125 138 771
Austria	46 799 579	48 045 089	55 868 298	61 225 037	65 666 128	68 906 034
Poland	158 661 957	162 382 959	179 179 899	182 005 677	175 473 691	170 233 670
Portugal	13 640 079	13 359 517	14 368 003	14 739 135	15 894 873b)	16 601 514
Romania	201 432 951	249 354 926	176 607 415	177 562 905	203 017 193	141 364 457
Slovenia	5 986 106	4 546 506	4 686 417	5 494 362	8 220 679	7 518 375
Slovakia	9 384 112	8 425 384	8 862 778	10 606 966	12 401 870	12 775 926
Finland	104 336 944	91 824 193	95 969 888	122 869 183	128 251 735	116 082 531
Sweden	117 645 185	156 306 504	167 026 886	141 625 718	138 667 585	151 823 910

Legend: Not Available (N/A), Estimated (e), Eurostat Estimate (s), Break in time series, provisional (bp), Break in time series (b), Provisional (p). *Source: Eurostat (2023)*

Table 2: Total waste production (tonne) in EU from 2010 to 2020

Region\Time	2010	2012	2014	2016	2018	2020
European Union - 27 countries (from 2020)	2 212 900 000	2 242 540 000	2 243 790 000	2 258 910 000	2 338 230 000	2 152 930 000
Euro area - 19 countries (2015-2022)	N/A	N/A	N/A	N/A	N/A	N/A
Iceland	510 941	529 351	815 148	1 067 319	1 293 511	1 060 903
Liechtenstein	312 180	466 547	569 067	502 581	437 823	N/A
Norway	9 432 997	10 721 599	10 614 914	11 131 594	14 137 718	14 040 663
Switzerland	N/A	N/A	N/A	N/A	N/A	N/A
United Kingdom	241 808 706	241 506 743	262 992 726	272 064 636	282 393 639	N/A
Montenegro	N/A	1 014 139	1 092 741	1 685 006	1 222 758	1 246 833
North Macedonia	2 327 590	8 472 343	2 186 612	1 424 859	1 140 253	1 484 596
Albania	N/A	N/A	N/A	N/A	N/A	N/A
Serbia	33 615 918	55 002 570	49 128 311b)	48 965 314	51 102 914	58 655 708
Turkey	63 540 624	67 383 777	73 075 119	75 534 641	97 294 071	107 608 312
Bosnia and Herzegovina	N/A	4 456 556	5 540 772	6 127 022	6 747 605	6 753 458
Kosovo (under United Nations Security Council Resolution 1244/99)	N/A	1 166 619	1 039 803	2 855 990	2 961 225	2 592 828

Legend: Not Available (N/A), Estimated (e), Eurostat Estimate (s), Break in time series, provisional (bp), Break in time series (b), Provisional (p). *Source: Eurostat (2023)*

Concerning the Czech Republic, according to the Czech Statistical Office, the total waste production, starting with 32,267,000 tons (3,076 kg per capita) continuing with a slight drop in 2012 of 30,023,000 tons (2,857 kg per capita) and a maximum in 2021 of 39,896,000 tons (3,790 kg per capita), stayed almost level in the years 2018 (37,784,000 tons or 3,547 kg per capita) and 2020 (38,503,000 tons or 3,597 per capita)[18]. Similarly, related to the total waste production, according to the data provided by the Czech Statistical Office, the domestic material consumption has a cyclic character[19].

Due to these high figures of waste production and aiming to extend the life cycles of products, the European Commission decided to revise the rules governing waste management to achieve what has come to be known as circular economy. The first references to circular economy can be found in the 1970's with authorships unclear. Many authors mention a direct link to environmental economy[20, 21] and industrial production ecology[22] or logistics[23].

Experimental part

The research methodology was a combination of qualitative, basic and descriptive research. The conceptual phase of the research process included a standard problem definition based on the legal requirements of environmental impact assessment and the latest requirements of the circular economy. For the research, the following questions were formulated.

1. What legislative conditions influence the environmental assessment of the product life cycle?
2. What links exist between the product assessment during its life cycle and circular economy?
3. What quantities of total energy, primary fuels and energy, raw materials, water, emissions into the atmosphere, CO2 equivalent, into water or solid waste may be created for a single product at each stage of the logistic chain?

With the research concentrating on small and medium companies in the Czech Republic where the main manufacture of parts and the subsequent assembly of the final product take place. The small and medium manufacturing company was chosen as the object of research, seen as a system in terms of the system theory, (NUTS classification CZ064 – South Moravia Region). For this particular research, a single product was chosen of electrical engineering industry manufactured in the South Moravian Region destined for the end user.

The scope of a solution was defined in order to include all the necessary inputs and outputs related to each phase of the manufacture from the raw materials, semi-finished products, and the energy needed for production to the product itself and its disposal and subsequent reuse of the waste or landfilling of non-reusable waste. This procedure actually copies the system analysis approaches dubbed Cradle to Grave[24] (see the below Figure 1).

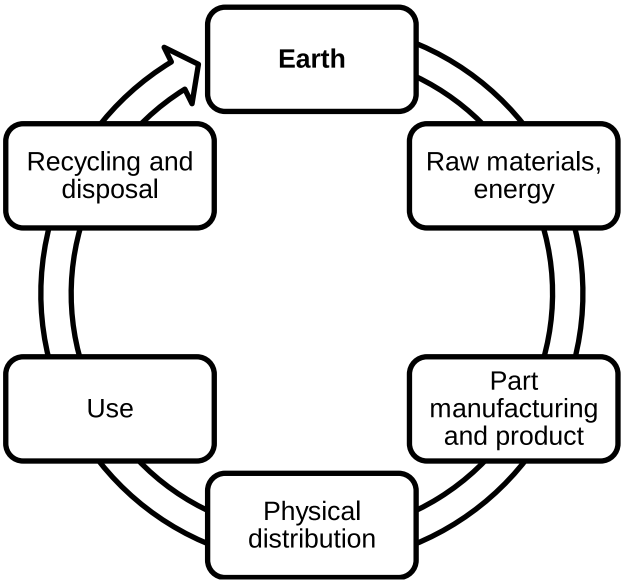

Figure 1: Cradle to Grave principle

Source: Author's own based on Bogue (2014)

To this end, the input (primary) data was assembled on the material structure of the product, wrappings, manufacturing operations for each product part and assembly group, the related transport of parts from the subcontractors, product assembly, packaging, and distribution (user standard) and procedures of product disassembly after its life cycle. The secondary data on the manufacture of essential raw materials (such as refined oil), semi-finished products (such as plastic granules) and energies (such as electric energy) were taken from the publicly available databases (such as Boustead Model).

Based on the product documentation, a complete list was set up of parts or assemblies (supplied part) with their names, weights, exact material specifications, and chemical composition. Such list also included information on the distance between the manufacturing plant and the place of assembly in Brno, and the transportation vehicle used for transport to Brno.

The research included the manufacturing processes of primary raw materials, their extraction and dressing, transport to further processing, manufacture of semi-finished parts (such as Al-ingots, steel profiles, plastic granules) and energies (fuel extraction and transportation, energy production) as input of the manufacture of a selected product. The manufacture and technology scope of the research included the manufacture of aluminium castings (i.e. pressure casting, trimming, tumbling, and blasting), next, metal part pressing and working, drying of plastic granules, plastic part pressing, overflow re-granulation, storing, assembling, and testing of parts, plus the non-productive activities.

Next, an analyse was made of parts (casting, forming, pressing), transportation of parts and assemblies from the manufacturing plant (including packaging) to the place of assembly in the Czech Republic or Brno. The calibration of the production equipments corresponded to the needs of the technological procedures, which were given in the production documentation. The product assembly including non-productive activities - production engineering, administration, sanitary facilities. It also included the product distribution in the Czech Republic (including its commercial packing and transport container), product use (consumption including its service (spare parts), collection of parts after their life cycles (model calculation in the Czech Republic conditions), disassembly and re-use of the secondary materials and disposal of waste.

Data were collected in a small enterprise where the product parameters were gained and verified with information on the product's part and material composition (such as from a list of parts), input and output raw materials and energies, input and output auxiliary and spare parts as well as on water consumption, emissions into the atmosphere and soil, plus the amount of solid waste produced.

The data management system was at a basic level. The data collection was carried out using prepared documents and forms. Documents, forms and data had been exchanged repeatedly until the data required were comprehensive and representative. The measured values were recorded in the measurement diary.

The most time-consuming stage was getting data from the subcontractors providing parts as this part of data collection and the subsequent calculation had to include consultations with the product manufacturer's team of experts.

Research limitations

The research was limited in time, material and space. The time constraint was of two types. The first-time constraint relates to the frequency or availability of basic global statistical data at the level of the EU and the Czech Republic. The second time limit was related to the duration of the pandemic restrictions of one of the waves of SARS-CoV-2 disease, which determined the possibility of repeating the measurements carried out. The material limitation is given by the age and condition of the production equipment, which is required by the production documentation and technological procedures in the production and assembly process of the production company. The space limitation was based on the layout and floor plan of the production hall (including adjacent warehouses). This was analogously manifested in the possibility of determining and expressing the energy demand of the transport of material flows.

Due to the complexity of the manufacturing processes for the chosen product, the transport of semi-finished parts from their manufacturers to the manufacturers of parts was not the subject of the research or the worldwide distribution of the product from the warehouses in Germany of the transport of spare parts from Brno to other service storage rooms. It was also rather difficult to measure the manufacture of casting and pressing moulds and that of the assemblies bought (such as cables, electric motors) as well as of the parts not manufactured in the Czech Republic.

When calculating detailed specific parameters for the manufacture of 1 kilogram of castings and for the production of 1 kilogram of plastic parts (without materials specification), these parameters were subsequently recalculated into values per-piece. The reason was that it was unrealistic to determine the relevant inputs and outputs for each particular product part.

Despite the above facts, the selected methodology has limitations given by the complexity of the chosen product, whose impact on the final figures of the total energy, primary fuel and energy (energy and weight), water consumption, and emissions into the atmosphere is not included in the research results. As far as emissions are concerned, this may be represented by the fact that the research does not cover the transport of semi-finished parts (such as Al-ingots, plastic granules) from their manufacturer to the manufacturer of parts, as well as the transport of spare parts from Brno to the service storage rooms. Concerning other categories (such as the total energy consumption, primary fuel and energy values, raw-material and water consumption), the research does not cover the manufacture of metal parts (apart from Al-castings); manufacture of casting (Al-castings) and pressing (plastic parts) moulds; assemblies (such as electric motor, cables, electric parts, etc.), but also some fixed output (such as waste water).

Data processing

To quantify the relevant input and output data, the material composition of the product was calculated as relating to one piece. The data aggregation consisted of classifying steels as low-alloyed (cl. 11-14) and alloyed (cl. over 15); eliminating the low content of fillers in plastics (up to 30% of weight), eliminating the differences between the polystyrene foam and regular polystyrene plastic. The casting and plastic part manufacture parameters per 1 kilogram (with no material specified) were recalculated to relate to one product manufactured. The input and output data related to the non-productive part of the manufacture were recalculated into values per piece based on the corresponding number of all products manufactured in the previous year.

Concerning the transport, the calculation was related to the distances and transport vehicles used (transport by road - passenger car up to 3.5 t, over 3.5 t, and transport by sea); the distribution was assumed to be into the warehouse in Germany (world) and into regional logistic centres (Czech Republic); the calculation included entitlement to the transport to the product service site (twice per life cycle) and to the gradually created electric-waste take-back system. Necessary was also the calculation of spare part consumption (unit, control board) and, mainly, the consumption of electric power by the maximum product power demand (units and lighting) and the product's service life (efficiency of 0.9).

Research results

While the environmental attributes of sustainability accelerate the metamorphosis of enterprise models into newborn structures, it is logistics in its managerial, technical, and transport form that is an indispensable attribute of such transformations. When explaining the principles of circular economy, Clift (2016) speak about different levels of global supply chains, regional supply cycles, and local economies or repeated use, remanufacturing, and recycling. Another difference, as pointed out by the same authors, is the fact that circular economy, in contrast to all other fields of management, is based on the preservation of value rather than on the philosophy of value added[25]. The increased interest in and importance of circular economy is corroborated by the high frequency of occurrence of this term in renowned databases (see Table 3) as well as confirm by Web of Science bibliometric networks construction in VOSviewer v. 1.6.18 (see Figure 2).

Table 3: Frequency of occurrence of circular economy in selected major databases at the end of 2022

Database	Frequency of Occurrence
Science and Direct	59848
Springer	68561
Scopus	20703
Emerald	7261
Web of Science	19898
Google	219000000

Source: Author's own

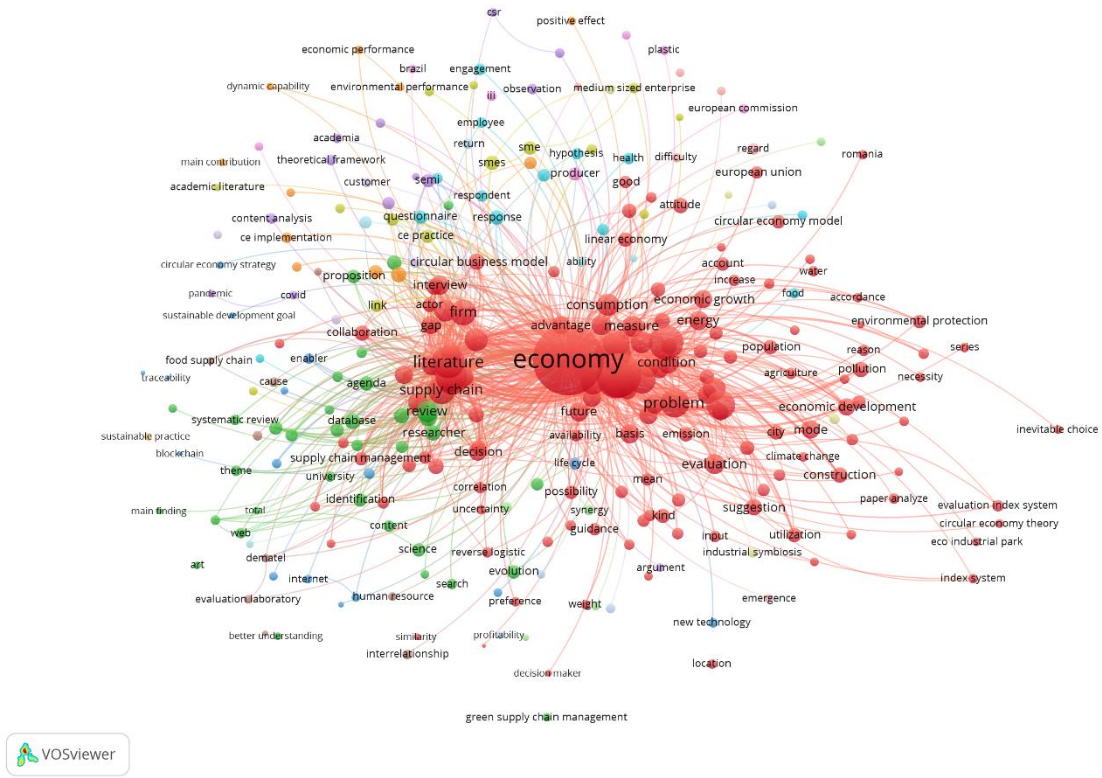

Figure 2: Bibliometric networks construction of circular economy in Web of Science database

Source: Author's own in VOSviewer (v. 1. 6.18)

The well-known economic and managerial approaches to the decomposition of linear economy and the corresponding linear logistic network structures, in addition to mentioning particular entities, start to draw attention to environmental impacts. According to Clift (2016), a great deal of the industries concentrate on issues of environment and flows, as well as storing, which together represents accumulation of input and output flows of materials, products and goods[25]. All the above-mentioned trends have led the team of authors to efforts to improve the present state of product life cycle assessment in relation to transformation into circular economy.

The commitment of sustainability and sustainable development is given by the UN Agenda 2030, which is incorporated in the 10 priorities of the European Commission, which is the basis of the Sustainable Development agenda adopted by the European Commission in November 2016.

The importance of environment and its protection as well as the potential impacts on the environment are included in the applicable ISO standards for the environmental management system (such as ČSN EN ISO 14001 and 14004), the specified requirements of audits and auditors' qualification, the assessment of the environmental profile (i.e. ČSN EN ISO 14031), assessment of the life cycle of products (such as ČSN EN ISO 14044) and EC Ecolabel (i.e. ČSN ISO 14020, ČSN ISO 14021 and 14024), as well as environmental communication (i.e. ČSN ISO 14063) and methods of compliance verification, etc.

In the event of the product lifecycle management, international standards also include the directives issued by the European Parliament (such as the Directive of the European Parliament and of the Council 2005/32/ES on setting a framework for determining the requirements of environment protection during the development and design[11] (dubbed ecodesign) of power appliances and on a change in the directives of the European Parliament and of the Council 92/42/EEC and 96/57/ES a 2000/55/ES; Directive of the European Parliament and of the Council 2009/125/ES of 21st October 2009 on setting the framework for determining the requirements of the ecodesign of products related to energy consumption. To summarize, this is a normative hierarchy, aimed to apply sustainability at all production levels, i.e., from strategy to systems and processes (such as marketing, development, manufacture, etc.), to the resulting product. In recent years, it has been clear that the processes conceived in the above way, despite some functional limits (such as the principle of assessing the lifecycle by standards ISO 14040 and 43), begin to be insufficient with the focus of further development shifting to a higher hierarchy level of what is called circular economy. The below schema demonstrates the development stages and the differences (see Figure 3).

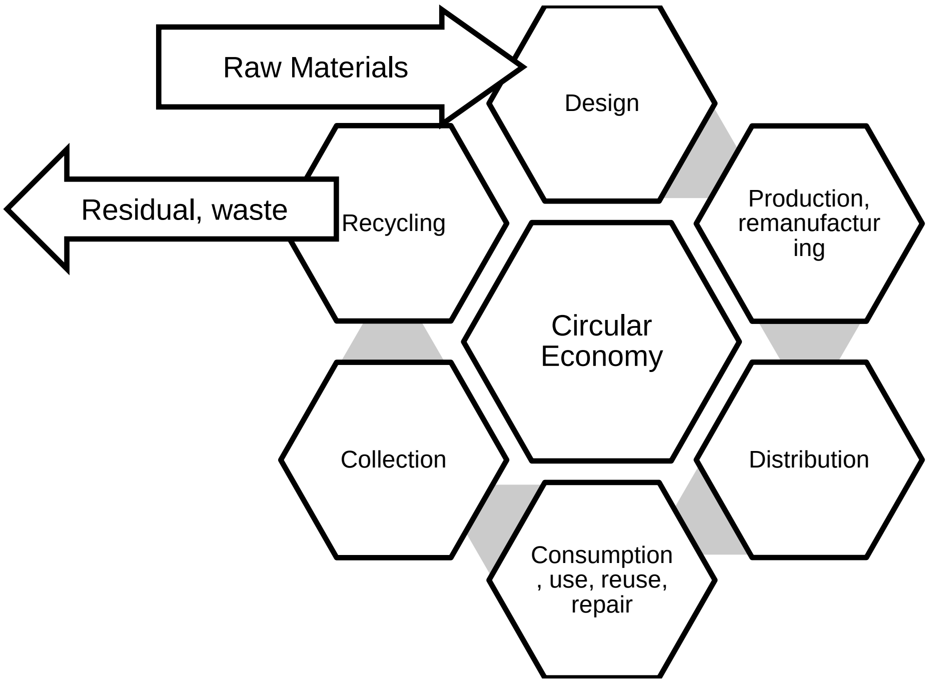

Figure 3: Definition of Circular Economy

Source: Author's own based on European Parliament (2018)

Even if the concept and principles of circular economy are not entirely new, first attempts start to appear at standardizing the implementation of these approaches, incorporating them in company standards (such as BS 8001:2017). Such attempts are also criticised concerning their metrics, indicators as well as the implementation itself[34].

The structuralisation of the research of the product lifecycle assessment, as well as the decomposition of the logistic chain into the conditions of circular economy (Figure 4) complied with both the requirements of ISO 14040 and ISO 14044 and the system approaches[35] of the logistic chain decomposition[36;37;38].

Thus, the research was broken down to stages with materials representing the manufacture of primary raw materials, semi-finished products and energies, the manufacture representing the manufacture of parts and product assembly (including the non-productive plants); the transport being defined as the transport of the parts to be assembled, the distribution of the products, the transport of the products for servicing and disposal; the use of the product during its lifecycle, and the waste disassembly of the product, use of the acquired raw materials including the disposal of waste.

For the selected product (1 piece) of electric engineering industry manufactured and assembled in the Czech Republic, intended for the end user, the values were obtained of the total energy consumption, primary fuel and energy (energy and weight category), raw materials consumption, water consumption, with the emissions into the atmosphere, CO2, water and solid waste emissions being analyzed during the following lifecycle.

In the case of total energy of the selected product it was power that assumed unfavourable values and, in the case of oil fuels, it was transport. (see Table 4)

Table 4: Total energy of the selected product in units of measure

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
power	400.74	413.46	92.59	800.31	2.31	1709.41
oil fuels	416.75	0.44	979.35	258.53	0	1655.07
other fuels	372.24	55.73	113.95	217.07	0	758.99
Total	1189.73	469.63	1185.89	1275.91	2.31	4123.47

Source: authors' own

In the primary fuel and energy category, only for energy the values were critical, namely, for the gas and water materials, followed by the oil values in transport and coal in use. (see Table 5). Such values may be accounted for by the methods and resources of power generation in the Czech Republic.

Table 5: Primary fuels and energies – energy of the selected product in units of measurement

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
coal	83.44	294.97	34.64	624.26	1.64	1038.95
oil	410.72	6.96	940.89	269.90	0.03	1628.50
gas	324.73	74.82	176.81	163.01	0.11	739.48
hydro	309.20	5.54	1.03	12.42	0.03	328.22
nuclear	41.80	82.81	32.40	182.42	0.46	339.89
lignite	4.05	<0.01	<0.01	10.40	<0.01	14.45
wood	31.53	<0.01	<0.01	0.18	<0.01	31.71
sulphur	1.35	<0.01	<0.01	<0.01	<0.01	1.35
biomass	0.62	3.34	0.01	6.39	0.01	10.37
hydrogen	1.04	<0.01	<0.01	2.23	<0.01	3.27
restored	-19.51	<0.01	-0.02	1.71	<0.01	-17.82
wastes	0.32	1.17	0.02	2.19	<0.01	3.70
Total	1189.29	469.61	1185.78	1275.11	2.28	4122.07 [a)]

Legend: a) the sum does not include minor resources which accounts for the difference as compared to Table 4
Source: Author's own

Table 6: Primary fuels and energies – weight in kilograms of the selected product

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
coal	2.20	10.00	1.20	22.00	0.06	35.46
crude oil	9.10	0.15	21.00	6.00	<0.01	36.25
gas/cond.	6.30	1.40	3.40	3.00	<0.01	14.10
coke/metal.	0.72	0.03	0.04	0.09	<0.01	0.88
lignite	0.28	<0.01	<0.01	0.70	<0.01	0.98
wood	3.60	<0.01	<0.01	0.04	<0.01	3.64
Total	22.20	11.58	25.64	31.83	0.06	91.31

Source: Author's own

Although the raw materials consumption (see Table 7) achieves negligible values, it is abnormal for the raw materials bauxite, NaCl, clay, fluorite, iron ore, calcite, sand, copper ore, and sulphur. This is mainly due to all these raw materials being applied and representing the material basis, i.e. the product composition.

Table 7: Raw materials consumption for the selected product in kilograms [a)]

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
bauxite	18.00	<0.01	<0.01	<0.01	<0.01	18.00
salt (NaCl)	0.69	<0.01	<0.01	0.01	<0.01	0.70
clay	0.17	<0.01	<0.01	<0.01	<0.01	0.17
fluorite	0.32	<0.01	<0.01	<0.01	<0.01	0.32
iron ore	1.90	0.08	0.11	0.24	<0.01	2.33
calcite	0.48	0.02	0.02	0.06	<0.01	0.58
sand	0.35	<0.01	<0.01	0.08	<0.01	0.43
copper ore	0.60	<0.01	<0.01	0.14	<0.01	0.74
sulphur (elem.)	0.15	<0.01	<0.01	<0.01	<0.01	0.15
oxygen	0.15	<0.01	<0.01	0.03	<0.01	0.18
nitrogen	0.27	<0.01	0.01	0.39	<0.01	0.67
air	4.60	<0.01	0.01	0.35	<0.01	4.96
biomass	0.07	0.38	<0.01	0.72	<0.01	1.17
Total	27.75	0.48	0.15	2.02	<0.01	30.44

Legend: a) oil is presented as energetic raw material in Table 5 *Source: Author's own*

Water consumption (see Table 8) achieves the highest value in the first part, i.e., material, which applies to all resource types, which might have a considerable significance considering the current changes.

Table 8: Water consumption of in kilograms of the selected product

Source	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
conditioned water	307.00	45.00	1.90	33.00	<0.01	386.90
river water	59.00	<0.01	<0.01	2.80	<0.01	61.80
sea water	469.00	<0.01	0.70	13.00	<0.01	482.70
ground water	0.39	<0.01	<0.01	0.06	<0.01	0.45
non-specified	208.00	8.90	19.00	152.00	0.05	387.95
Total	1043.39	53.90	21.60	200.86	0.05	1319.80

Source: Author's own

As can be expected, emissions into the atmosphere, (see Table 9), achieve the highest values during manufacture (that is, materials) and, subsequently, during transport.

Table 9: Emissions into the atmosphere for the selected product in milligrams

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
dust (PM10)	310 000	24 000	84 000	98 000	120	516 120
CO	93 000	29 000	700 000	180 000	130	1 002 130
CO2	37 000 000	35 000 000	73 000 000	88 000 000	180 000	233 180 000
SOx as SO2	250 000	120 000	200 000	480 000	680	1 050 680
NOx as NO2	140 000	75 000	770 000	260 000	380	1 245 380
HCl	1 300	5 800	660	13 000	32	20 792
hydrocarbons /non-specified/	62 000	7 200	390 000	96 000	39	555 239
organic substances	5 300	<1	<1	57 000	<1	62 300
CH4	140 000	89 000	230 000	120 000	150	579 150
aromatic hydrocarbons	620	<1	310	20	<1	950

Source: Author's own

The CO_2 equiv. emissions (see Table 10) achieve negligible values.

Table 10: CO_2 equivalent emissions of the selected product in kilograms

Duration	**Selected product LCA phase**					**Total**
	materials	**production**	**transport**	**use**	**waste**	
20 years	46	41	89	96	<0,01	272
100 years	40	37	80	91	<0,01	248
500 years	38	36	77	89	<0,01	240

Source: Author's own

Emissions into water (see Table 11) achieve negligible values of Na+, Cl-, insoluble substances, soluble substances in manufacture, (which means materials).

Table 11: Emissions into water of the selected product v milligrams

Type	**Selected product LCA phase**					**Total**
	materials	**manufacture**	**transport**	**use**	**waste**	
CHSK	23 000	25	280	22 000	<1	45 305
BSK	2 500	<1	61	4 900	<1	7 461
Na+	120 000	4	110	24 000	<1	144 114
Cl-	220 000	7	210	26 000	<1	246 217
soluble organic substances	5 500	1	100	59 000	<1	64 601
insoluble substances	1 100 000	9 000	8900	28 000	14	1 145 900
soluble substances	220 000	1	31	50 000	<1	270 032
SO42-	44 000	<1	24	8 900	<1	52 924

Source: Author's own

The solid waste value is critical (see Table 12) in manufacture (that is, materials) mineral waste, waste rock, and repeatedly landfilled waste. In the event of disassembly, application of raw materials, and waste disposal (that is, waste) the value is insufficient for plastics, industrial mix, incinerable components, and solid waste for recycling. Although all these values corroborate the accentuation of the LCA requirements, this is a challenge for the future circular economy.

Table 12: Solid waste of the selected product in kilograms

Type	Selected product LCA phase					Total
	materials	manufacture	transport	application	waste	
pasteboard-wrapping	<0.01	<0.01	<0.01	0.77	<0.01	0.77
paper	0.45	<0.01	<0.01	<0.01	<0.01	0.45
plastics	0.37	0.23	<0.01	<0.01	2.70	3.30
non-specified	0.43	<0.01	0.25	<0.01	<0.01	0.68
mineral waste	11.00	0.07	0.09	0.91	<0.01	12.07
slag + ashes	1.20	2.30	0.10	1.50	<0.01	5.10
industrial mix	0.12	-0.04	0.26	-0.07	1.30	1.57
chemicals/N	0.10	0.12	0.31	<0.01	<0.01	0.53
chemicals/O	0.08	0.02	0.23	0.03	<0.01	0.36
incinerable	0.01	<0.01	<0.01	0.86	2.40	3.27
for recycling	<0.01	0.10	<0.01	0.33	4.30	4.73
restored	66.00	2.00	0.24	12.00	<0.01	80.24
waste rock	25.00	<0.01	<0.01	5.80	<0.01	30.80
communal	-0.01 [a)]	0.97	<0.01	<0.01	<0.01	0.96
Total	104.75	5.77	1.48	22.13	10.70	144.83

Legend: a) negative values refer to waste consumption by recycling or in power generation

Source: Author's own

Results and discussion

The results of the investigation into the conditions of the legislative framework for an environmental assessment of the product lifecycle (i.e., Research Question 1) have shown that the sustainability axiom is an integral part of the ISO 1404X standards (ČSN ISO 1404X for the Czech Republic) with direct links to the EU documents from 2005 up to the present.

For the existing links between the product assessment in its lifecycle and the circular economy (i.e. research question 2) it has been proved that it is the circular economy which is the next development stage of the Cradle to Grave principles and application of the ISO 1404X environmental standards. Over the past two years, efforts have been gradually increasing to standardize and normalize the requirements of particular criteria and metrics (such as BS 8001:2017) of circular economy for the everyday operation of companies.

The last research question (i.e., research question 3) has shown that the results for the end user of the production processes of the selected electrical engineering product achieve the most critical values almost in every category of the logistic chain (see the below Table 13). Although the LCA values attained by the manufacturer are positive, in terms of circular economy, there will be a necessity to extend the assessment of the product's environmental aspects to areas that, as yet, cannot be monitored in a simple way, that is, subcontractor-based manufacture or second or third level of the logistic chain (such as moulds); transport from the manufacturers of semi-finished parts to the manufacturers of parts, comprehensive worldwide distribution or transportation of parts or the related values of emissions.

Table 13: Critical values of the selected product along the logistic chain

	Materials	Manufacture	Transport	Application	Waste
Total energy			oil fuels	electric power	
primary fuel and energy	gas, hydro	oil	coal, nuclear		
raw material consumption	bauxite, NaCl, clay, fluorite, iron ore, calcite, sand, copper ore, sulphur				
water consumption	conditioned water, river water, sea water, ground water				
emissions into the atmosphere	dust		CO, NOx as NO_2, hydrocarbons	organic substances	
emissions into water	Na+, Cl-, insoluble substances, SO4-			discernible organic substances	
solid waste	Mineral waste, waste rock, repeatedly landfilled waste				plastics, industrial mix, incinerable, for recycling.

Source: Author's own

The results of the LCA analyses (see Table 13) can improve the comparing of the specific manufacturing process impacts between the EU as well as non-EU countries. In such a case, the results may be seen as a proposal for the improvement of the environmental impact of products or of selected categories of the manufacturing processes of a manufacturing company.

Next, the research results concern the selection of a suitable methodology or corresponding software tools designed for processing and subsequent comparing. The research has shown that, despite the unequivocal normative codification level of the methods recommended by the ISO 1404X standards and EU directives, the complete time, geographic, or technological scope of the analyses cannot be ensured. The simplest is the time dimension defining the time period of observation. On the other hand, concerning the remaining parameters of geographic character, it is very difficult to follow the worldwide impact as well as the manufacturing and technological attributes in all suppliers and supply degrees of the logistic structures.

Conclusion

The increased customer awareness of the importance of environment protection and the possible impacts related to the manufactured and consumed products on the one hand and the extended responsibility of the manufacturer on the other hand continually increase the interest shown in the methods of the product life cycle assessment. Each industry branch as well as the corresponding product category contains different limit values. In the event of a product chosen from the electric engineering industry, the resulting LCA values observed may be seen as favourable in individual categories, however, with problems occurring once the circular economy concepts are to be implemented. This extended the borders of the observed system (or product) with increased requirements of the description, obtaining of input data and the methods of their collection and analysis, etc. As a result, an entirely different method will be employed linking more closely the manufacturing processes and the external environment of a company.

Apart from the electrical, mechanical, and chemical engineering industries, other representatives may also be mentioned of the manufacturing industry such as automobile industry for which the 2005/64/ES EU directive specifies that a minimum of 85 % of the materials and 10 % of the energy used must be recycled, also setting a maximum of 5 % of the car weight to be landfilled. Although, in subsequent polemics on the pertinent specific values, the deadlines for the implementation of the directives are postponed, the trend embarked of stricter limits for the values observed leads to sanctions being imposed, which may entail an influence by curtailing the supply of some products. Already now, it is practically clear that, if such directives cause major problems to large companies, the question is in place of how small and medium companies will cope. The resulting critical values presented showed the necessary directions for the improvement of the manufacturing processes (such as water and energy consumption) with the overview of the life cycle assessment for the selected product indicating the best values exactly in the case of disassembly and re-use with the exception of the raw-material consumption and solid waste, that is, the recycling and re-use area. One can only trust the flexibility of small and medium companies in implementing the legislative and technological limitations at each stage of the product life cycle, to stay within the limit values pointing out the possible barriers and imperfections of the present implementation of the circular economy principles including their necessary extension to the external environment of companies.

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Analýza transformace hodnocení životního cyklu produktu z pohledu oběhové ekonomiky: případová studie

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Souhrn

Článek se zaměřuje na rozsah možností transformace hodnocení životního cyklu produktu z pohledu oběhové ekonomiky. Autoři na konkrétním produktu elektrotechnického průmyslu realizují systémovou analýzu vstupu a výstupu výrobního procesu vč. nezbytných vazeb na logistické řetězce a možných dopadů na životní cyklus produktu.

Metodologie výzkumu byla kombinací kvalitativního, základního a popisného výzkumu, jenž byla doplněna kombinací tzv. párových metod, systémové teorie (definice vstupu, výstupu systému, hranic a vazeb systému) či analýzy dokumentů (výrobní dokumentace, normy, legislativa atp.). Pro vizualizaci výsledků bibliometrické analýzy výzkumu byl použit softwarový nástroj VOSviewer (v. 1.16.18, (CWTS), Leiden University). Získaná primární data o spotřebě energie, primární paliva, surovin, vody či emise do ovzduší (vč. CO_2 ekv.), vody a hodnoty produkce pevného odpadu byla zpracována a analyzována ve standardním kancelářském nástroji Microsoft, což bylo doplněno sekundárními daty modelu hodnocení životního cyklu produktu.

Hlavní omezení provedeného výzkumu je dáno časovým rozsahem studie (kombinace frekvence, resp. dostupností základních globálních statistických údajů na úrovni EU, ČR a omezení jedné z vln onemocnění SARS-CoV-2), geografickým rozsahem (výroba dílů na území v České republice vč. Montáže v Brně), výrobně-technologickým rozsahem (výroba hliníkových odlitků, lisování kovových dílů, obrábění kovových dílů, sušení plastového granulátu, lisování plastových dílů, skladování dílů, montáž, zkoušení výrobku a částečně i nevýrobní oblasti). Sekundární omezení výzkumu pramení z dekompozice logistického řetězce a omezené možnosti zařazení údajů (tj. vstupů a výstupů) o celosvětové fyzické distribuci.

Originalita výsledků výzkumu je dána výběrem malé a střední firmy reprezentující zvoleného výrobce, komplexnosti dat, vyjádření celkové energie, primárního paliva a energie, spotřeby surovin, spotřeby vody, emise do ovzduší, CO_2 ekv., emise do vody a pevného odpadu ve fyzikálních jednotkách v průběhu všech etap životního cyklu od materiálů, výroby, přepravy, užití a odpadů vč. vyhodnocení nežádoucích hodnot jednotlivých veličin zvoleného produktu.

Klíčová slova: *Oběhová ekonomika, životní cyklus produktu, trvale udržitelný rozvoj, odpady.*