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VOLUMETRIC METHOD FOR DETERMINING KG CO_2 EQ. AND ENERGY REQUIREMENTS FOR THE PRODUCTION OF POWER TOOLS AT AN EARLY STAGE OF PRODUCT DESIGN

SHORTENED VERSION OF PHD THESIS

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ABSTRAKT

Emise kg CO_2 eq. vznikají v různých fázích životního cyklu výrobku a mají významný vliv na globální oteplování. K posouzení těchto negativních vlivů slouží metoda Life Cycle Assessment (LCA), která umožňuje určit uhlíkovou stopu, energetické nároky na výrobu materiálů, výrobní procesy, transport, užití a konec životního cyklu. Tyto analýzy jsou časově náročné, nákladné na zaškolení a vyžadují hmotnostní a materiálové charakteristiky výrobků.

Navržená metoda VEME (Objemová hodnotící metoda ecodesignu) využívá objemových vlastností výrobku a jeho strukturálního a materiálového složení. Pro dosažení cíle bylo analyzováno 134 kusů nářadí (vyrobeno 1989 až 2018) se začleněním do 10 typových skupin podle druhu nářadí. 3D skenováním byl určen objem výrobku s následnou materiálovou analýzou a po té byla použita metoda Oil Point Method (OPM), která je založena na LCA. Nářadí bylo posuzováno ve třech možných variantách konce životního cyklu (skládkování, spalování a recyklace 90 %). Ze získaných dat byla provedena simulace Monte Carlo pro každý vzorek nářadí *n* = 1 000 s 95% spolehlivostí. Byly stanoveny rovnice pro určení energetických požadavků na výrobu nářadí, emisí kg CO_2 eq. (pro 11 světových zemí), údajů na balení a transport zboží.

S 90% recyklací je možné uspořit až 32,4 % energie oproti skládkování. Ze všech 134 vzorků bylo 9,7 %, u kterých byla recyklace až o 6,2 % energeticky náročnější než skládkování. Důvodem jsou vysoké energetické nároky na recyklace materiálů.

Nová metoda najde využití při navrhování výrobků v průmyslovém designu, ale i v oblastech ekonomického zhodnocení způsobu a místa výroby. Lze jej využít i pro rozšíření energetického štítkování výrobků, které by zahrnovalo energetickou náročnost výroby, transport a balení.

KLÍČOVÁ SLOVA

Life Cycle Assessment, environmentální dopady, CO_2 emise, průmyslový design, energetické předpovědi, eco-design, cirkulární ekonomika, VEME metoda, LCA

ABSTRACT

Emissions of kg CO_2 eq. occur at different stages of the product life cycle and have a significant impact on global warming. The method used to assess these negative impacts is Life Cycle Assessment (LCA), which enables the determination of the carbon footprint, energy requirements of materials production, manufacturing processes, transport, use, and end of life (EoL). These analyses are time-consuming, costly to train, and require mass and material characterisation of products.

The proposed VEME (Volumetric Evaluating Method of Ecodesign) method uses the volumetric properties of the product and its structural and material compositions. To achieve the objective, 134 power tools (manufactured from 1989 to 2018) were analysed with the inclusion of 10 types of categories based on the type of tool. 3D scanning was used to determine the volume of the product followed by material analysis and then the Oil Point Method (OPM), which is based on LCA. Tools were evaluated in three possible EoL variants (Landfilling, Combustion, and Recycling 90%). From the data obtained, a Monte Carlo simulation was performed for each tool sample of n = 1,000 with 95% confidence. Equations were established to determine the energy requirements for tool production, emissions of kg CO_2 eq. (for 11 world countries), packaging and transport data.

With 90% recycling, energy savings of up to 32.4% are possible compared to landfill. Of the 134 samples, 9.7% were recycled, where recycling was up to 6.2% more energy intensive than landfilling. This is due to the high energy requirements of the recycling materials.

The new method will find applications in product design in industrial design, but also in the areas of the economic evaluation of production method and location. It can also be used to extend the energy labelling of products to include the energy intensity of production, transport, and packaging.

KEYWORDS

Life Cycle Assessment, environmental impacts, emission CO_2, industrial design, energy prediction, eco-design, circular economy, VEME method, LCA

BIBLIOGRAPHICAL REFERENCE

SOVJÁK, Richard. *Volumetric Method for Determining kg CO_2 eq. and Energy Requirements for the Production of Power Tools at an Early Stage of Product Design (Shortened Version of PhD Thesis).* Brno, 2022, 80 p. Brno University of Technology, Faculty of Mechanical Engineering, Institute of Machine and Industrial Design. Supervisor of the thesis doc. akad. soch. Ladislav Křenek, ArtD.

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STATEMENT

I hereby declare that I have written the PhD thesis *Volumetric Method for Determining kg CO_2 eq. and Energy Requirements for the Production of Power Tools at an Early Stage of Product Design* on my own according to advice of my supervisor doc. akad. soch. Ladislav Křenek, ArtD. and sources listed in references.

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Author's signature

CONTENTS

1 INTRODUCTION

The subject of this dissertation thesis is the development of a new method to determine the energy requirements for the production and assessment of power tools and kg CO_2 eq. emissions using volumetric product characteristics. Currently, products/services are environmentally assessed using quantitative, qualitative and semi-quantitative methods [1]. The quality of the output from these analyses is strongly dependent on the type and characteristics of the input data. If qualitative input data is used, we cannot expect high-quality quantitative results from impact analyses. For quick and indicative impact analyses, e.g., Checklists, 10 Golden Rules, LiDS Wheel, Guidelines, Spiderweb [4, 8, 15, 16]. These qualitative tools are suitable for user groups that do not have a deep understanding of LCA issues. In the design process itself, no strong link and responsibility of the designer is established for the choice of materials used and the subsequent negative impact on the environment [10, 22].

An important quantitative methodology/methods/tools for determining the full life cycle impacts of a product/service is the use of tools based on LCA (Life Cycle Assessment), OPM (Oil Point Method), MECO matrix [5, 11, 17]. The LCA tool provides a wealth of data on the actual birth, operation and recycling of each material, as well as its dependent technological processes [1, 4]. Software tools such as SimaPro, Gabi, openLCA and others are used for LCA assessment. However, the results of the different tools are different. [5, 11, 13]

Today's era requires meaningful management of raw materials, but also their reintegration into raw material resources for their further use [23]. The requirements for the economic use of materials with the aim of reducing negative environmental impacts (eco-design) are embedded in the Kyoto (Paris) Protocol and EU Directives 2009/125/EC, 2006/121/EC (REACH), the WEEE Directive [63] and standards EN ISO 14006, EN ISO 14040 [2].

The proposed VEME (Volumetric Evaluating Method for Eco-design) method is a completely new approach that allows one to determine the energy requirements for the production of power tools, but also kg CO_2 eq. emissions according to the volume proportions and the nature of the product. The method allows to calculate the energy requirements for production and emissions of kg CO_2 eq. in three End of Life variants (Landfilling, Combustion and Recycling 90%). The new method provides an effective quantitative eco-design tool without knowledge of complex mechanisms and very expensive LCA programs with an immediate indicator of the energy impacts on production and emissions kg CO_2 eq. The VEME method finds application in product design/optimisation, recycling and production optimisation due to the increasing prices of emission allowances in the EU [57].

2 CURRENT STATE OF THE KNOWLEDGE

2.1 Using Eco-Design Tools in Industrial Design

[22] **LOFTHOUSE, Vicky.** Investigation into the role of core industrial designers in ecodesign projects. *Design Studies*. 2004, 25(2), 215-227. doi: 10.1016/j.destud.2003.10.007. ISSN 0142694x. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0142694X03000516

The thesis focuses on the relationship of the industrial designer with other professions involved in product design and also on the sustainable development of raw material resources. The author of the paper highlights the lack of knowledge of the industrial designer on the appropriate use of materials and his role in the early stages of product design. The designer designs products with a sensitivity to ergonomics, aesthetics, psychology, marketing, and construction in individual or group sessions with clients. The experience comes from Cranfield University's three-year collaboration with Electrolux AB.

Conclusions

An industrial designer should not only be an expert in the fields of art, ergonomics, aesthetics, marketing, but also, especially, in the appropriate use of the properties of materials. It should take into account the choice of materials in the product, thereby reducing the negative environmental impact because the choice of materials is an integral part of functional design. Many of the proposed eco-design tools are aimed at the life cycle assessment of the product and are mainly used by design engineers. The use of LCA tools is demanding in terms of knowledge of materials, manufacturing, and raw material processes, and for this reason the use of these tools by industrial designers is complex.

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[10] **UEDA, Edilson Shindi, Tadao SHIMITSY and Kiminobu SATO.** The role of industrial designers in Japanese companies involved in eco-redesign process. In: *Proceedings of 6th Asian Design International Conference*. Tsukuba, Japan, 2003.

The purpose of the study was to determine the knowledge of LCA and the interest of industrial designers in the product design process. The study was prepared for a dissertation entitled: *"The Role of Industrial Designers Toward Environmental Concern for Sustainable Product Development and Ecodesign Strategy"*. Four research questions were set to answer the knowledge about eco-design tools and the challenges of putting them into practice.

Conclusions

The research presents the preferences and attitudes of designers towards eco-design. The socio-cultural principles are preferred over the technological aspect. Designers working in large companies (Sony, NEC, etc.) have an awareness of eco-design, but their knowledge is minimal. The same problems apply to designers. According to published research, the biggest barriers to reducing environmental impacts in the production process are economic demands at 36% and technical problems at 22%.

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[25] **SOVJÁK, Richard.** Studying Knowledge about Eco-design Tools at Department of Industrial Design, Brno University of Technology. *GRANT Journal,* 2017, 5(2), 72-75. ISSN: 1805-0638.

The article dealt with the research of the knowledge from students of BUT, IMID (Department of Industrial Design) on the issue of eco-design. A total of 72 respondents were interviewed with a total participation rate of 92.73%. A total of 12 research questions were asked in the research on eco-design knowledge. Two questions were aimed at students' perceptions if they would like to gain knowledge of eco-design tools during their university studies and one to find out if they would like to be familiar with environmental impacts at an early stage of their product design. The answers obtained were evaluated according to the type of questions (Yes/No) or with free response.

Conclusions

The research introduces us to the preferences of students of BUT IMID, Department of Industrial Design in the field of eco-design. In comparison with the research conducted in Japanese companies' article: *"The role of industrial designers in Japanese companies involved in eco-redesign process"*, there was no improvement in the knowledge of product life cycle by the designers themselves. On the results in questions Q1 and Q9, it is possible to see the ignorance of eco-design tools but some interest in acquiring this knowledge. The interest in information on the environmental impacts of their designs is high among final-year Bachelor and Master students. The research provided valuable information for the future direction of the Department of Industrial Design at Brno University of Technology, Faculty of Mechanical Engineering.

2.2 Qualitative Approach

[3] **LOFTHOUSE, Vicky.** Ecodesign tools for designers: defining the requirements. *Journal of Cleaner Production*. 2006, 14(15-16), 1386-1395. doi: 10.1016/j.jclepro.2005.11.013. ISSN 09596526. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0959652605002465

The paper builds on the work [22] *"Investigation into the role of core industrial designers in ecodesign projects"* and analyses important criteria that set requirements for the simplified use of eco-design tools by industrial designers. It also reflects the requirements of designers for the visual or graphical processing of eco-design tools in order to reduce the time requirements for the processing of the analyses. These requirements are reflected in the online application "Information/Inspiration", which is the result of this research.

Conclusions

The study contains important requirements to meet the eco-design rules and provide the designer with a comprehensive idea of sustainable product design. The web interface, which is the result of research, provides basic information without further details. Important is the elaboration of the eco-design requirements by designers, which are further detailed in the research.

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[14] **KOTA, Srinivas and Amaresh CHAKRABARTI.** ACLODS – A holistic framework for environmentally friendly product lifecycle design. In: *Global Product Development*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, p. 137-146. doi: 10.1007/978-3-642-15973-2. ISBN 978-3-642-15972-5. Available on: http://www.cpdm.iisc.ernet.in/ideaslab/paper_scans/UID_83.pdf

The paper evaluates the current approach of designers and engineers to eco-design and suggests improvements to the product design process. The application framework is based on the six points that are the pillars of the ACLONDS framework. Data are collected and compared in a percentage bar chart at each stage with the given factors.

Conclusions

The work maps the links between existing approaches to product design and identifies areas for improvement. It was found that the least attention in the area of environmentally friendly products was in the area of product design and structure. The developed ACLODS application framework defines six application areas that will lead to improvements in the design process according to the product life cycle rules.

[15] **IAN, Thomas.** Focus 3: EMS and EIA: Topic 7: Life Cycle Analysis: Introduction and Background. *RMIT University | Melbourne | Australia* [online]. [cit. 2016-01-10]. Available on: https://www.dlsweb.rmit.edu.au/conenv/envi1128/focus3/f3_t7_q37.htm

The developed RMIT University web interface focuses on the key components of EMS and EIA, which are divided into 5 themes with 11 subthemes. It describes environmental management, analysis, reporting, and also the use of LCAs methods. The visualised LiDS Wheel eco-design tool is based on a qualitative approach to environmental issues and provides specific solutions.

Conclusions

The thesis describes environmental management techniques, an example of LCI inventory processing and LiDS Wheel analysis. The LiDS Wheel-based analysis is qualitative and does not provide detailed information on the life cycle of a product, but is used to quickly assess environmental impacts at any stage of the product life cycle.

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[16] **LUTTROPP, Conrad and Jessica LAGERSTEDT.** EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *Journal of Cleaner Production*. 2006, 14(15-16), 1396-1408. doi: 10.1016/j.jclepro.2005.11.022. ISSN 09596526. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0959652605002556

The paper describes "The 10 Golder Rules" tool and its use with sample examples that were solved in the study at KHT Stockholm and by Bombardier in Sweden. It also introduces possible modifications to the tool for optimal product life cycle assessment.

Conclusions

The paper summarises the environmental tools that have been incorporated into "The 10 Golden Rules". They take into account the requirements of designers and engineers to quickly navigate and work with eco-design tools. The 10 Golden Rules tool has to be optimised for different design sectors (interior, construction) due to different input data.

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[9] **PLATCHECK, E.R., L. SCHAEFFER, W. KINDLEIN and L.H.A. CÃNDIDO.** Methodology of ecodesign for the development of more sustainable electro-electronic equipments. *Journal of Cleaner Production*. 2008, 16(1), 75-86. doi: 10.1016/j.jclepro.2006.10.006. ISSN 09596526. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0959652606003763

The paper describes a methodology for the optimization and development of electronic devices. It focuses on product development and evaluates the process according to a 4-phase methodology that includes product life cycles. The approach using the methodology was able to reduce the environmental impact.

Conclusions

The results of the research show the potential of the proposed optimization tool, which has been shown to reduce the burden on the ecosystem. The drawback of the paper is the factual non-validation by the LCA methodology that could accurately determine the potential of the established methodology.

2.3 Quantitative Approach

[24] *ISO 14044:2006: Environmental management — Life cycle assessment — Requirements and guidelines*, 2006. Geneva: International Organization for Standardization.

The most important standard for environmental protection in the context of life cycle assessment is Environmental Management — Life Cycle Assessment — Requirements and Guidelines. It replaces the former EN ISO 14040:1997, EN ISO 14041:1998, EN ISO 14042:2000 and EN ISO 14043:2000.

Conclusions

It is also necessary to be aware of the high cost and financial complexity of implementing complex LCA methodologies in the context of reducing environmental burdens. A significant problem in the implementation of eco-design tools is the time-consuming nature of the assessment and compilation of the basis for the analysis. Comprehensive LCAs can be processed in computer programs such as SimaPro, openLCA, GaBi, PRé Consultants, Umberto.

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[12] **BEY, Niki.** *The Oil Point Method: A tool for indicative environmental evaluation in material and process selection*. Lyngby, 2000. Dissertation thesis. Technical University of Denmark. Available on: http://polynet.dk/lenau/niki_bey_phd_thesis.pdf

The dissertation thesis is based on the evaluation of the environmental impact of products at an early stage of design. The thesis provides a time-saving methodology based on LCA with quantified output. The output is OPM units, which indicate the energy in MJ in 1 kg of crude oil. The work includes OPM values for more than 70 materials, 20 production processes, and 20 other life cycles.

Conclusions

The proposed OPM methodology provides a rapid tool for assessing environmental impacts at any stage of a product's life. The disadvantage of using them in an early design stage is the need to know the individual weights or volumes of the components. In the absence of the required material, it can be supplemented with the LCA tool. The work also includes examples of OPM design for a vehicle, windows, vacuum cleaner and other products.

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[17] **HOCHSCHORNER, Elisabeth.** *Life cycle thinking in environmentally preferable procurement* [online]. Stockholm: Royal Institute of Technology, 2008 [cit. 2016-01-10]. ISBN 978-917-1789-105. Available on: http://www.diva-portal.org/smash/get/diva2:13528/FULLTEXT01.pdf

The dissertation thesis consists of published articles related to the environmental impact assessment of materials in the military industry using the LCA, LCC, MECO and ERPA matrix. It also summarises the characteristics of 15 eco-design tools described in the thesis.

Conclusions

Articles published related to the MECO matrix tool focus on the applicability of the simplified LCA tool. The MECO method has positive results with respect to the ERPA method, which is dependent on input information. Both methods have the potential to be used for the Cradle-to-Gate life cycle assessment at the product design stage.

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[18] **SINGHAL, Pranshu, Salla AHONEN, Gareth RICE, Markus STUTZ, Markus TERHO and Hans VAN DER WEL.** Key Environmental Performance Indicators (KEPIs): A new approach to environmental assessment. In: *International Congress and Exhibition on Electronics Goes Green 2004+*. Berlin: Fraunhofer IRB Verlag, 2004, 697-702. Available on: http://www.lcaforum.ch/Portals/0/DF_Archive/DF27/Stutz2KEPIPaper2004.pdf

The paper analyses the environmental impacts of mobile phones (LCD, semiconductors, and rare metals). New KEPI indicators can be used to improve environmental designs. The benefit of the analysis is the reduction of the time requirements for its processing and also its simplicity.

Conclusions

The KEPI indicators were validated through Japanese companies that focus on the production of laptops and PCs. Product analysis using KEPIs is only possible for the same types of products (PDA vs. PDA, PC vs. laptop) that have the same functionality.

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[20] **NISSEN, Nils and Karsten SCHISCHKE.** Environmental evaluation methods: Toxic Potential Indicator (TPI). *Willkommen - Fraunhofer IZM* [online]. 2014 [cit. 2016-01-10]. Available on: http://www.izm.fraunhofer.de/en/abteilungen/environmental_reliabilityengineering/key_research_areas/environmental_assessmentandeco-design/toxic-potential-indicator--tpi-.html

The purpose of the research carried out at the Fraunhofer Institute was to determine the toxic potential in substances using German legislation. The result of the research is software aimed at calculating a potential toxicity indicator that uses existing information on chemicals as input data.

Conclusions

The software developed at the Fraunhofer Institute is simple and intuitive to use. The disadvantage is the lack of use in the entire life cycle of the product (from extraction to landfill, recycling, or incineration of waste). Input values are widespread and commonly available, for example, risk values (R-lists).

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[19] **FROELICH, Daniel and Damien SULPICE.** ECO-DESIGN TOOLS - Indicators | Eco-3e. *Eco-3e* [online]. 2013 [cit. 2016-02-21]. Available on: http://eco3e.eu/toolbox/indicators/

This paper evaluates the use of quantitative environmental tools for product life cycle assessment. The tools considered include MET Matrix, KEPIs, Global Indicators and product disassembly assessment. Introduces the input data requirements as well as the scope of their use. In the early stages of product design, eco-design tools are used to identify the problem and eliminate it.

Conclusions

The MET Matrix environmental impact assessment tool offers advantages, especially in its quantitative approach, and can be used at any stage of the product life cycle. The tool is based on the LCA methodology. The paper also outlines the issue of product disassembly.

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[21] **WEINZETTEL, Jan.** *Posuzování životního cyklu (LCA) a analýza vstupů a výstupů (IOA): vzájemné propojení při získávání nedostupných dat*. Praha, 2008. Dissertation Thesis. České vysoké učení technické v Praze.

The dissertation thesis focuses on the determination of environmental impacts using economic indicators that can be tangible or intangible in nature. Economic actors consume energy, materials, and use services, which are recorded using financial flows.

Conclusions

IO analysis allows indirect determination of environmental impacts using economic indicators. It is possible to determine energy and material flows during production, and thus quantify them in economic sectors or in the whole system. The solution of the IO analysis provides a comprehensive environmental overview of the economic entity.

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[6] **PACELLI, Francesco, Francesca OSTUZZI and Marinella LEVI.** Reducing and reusing industrial scraps: a proposed method for industrial designers. *Journal of Cleaner Production*. 2015, (vol. 86), 78-87. doi: 10.1016/j.jclepro.2014.08.088. ISSN 09596526. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0959652614009111

The research deals with the reuse of industrial waste with economic potential and environmental relevance using product design. It compares the proposed methodology and the different phases of the new solution options. It proposes a process that leads to the reuse of waste in manufacturing.

Conclusions

The research results are based on the LCA methodology, which is applicable to all stages of product life. According to the stage-by-stage methodology in the paper, waste (residues, semifinished products, and rejects) can be recycled or successfully reintroduced back into the production chain. This methodology is universal and applicable in the context of reducing the environmental burden.

[7] **KIM, Seung-Jin and Sami KARA.** Predicting the total environmental impact of product technologies. *CIRP Annals - Manufacturing Technology*. 2014, 63(1), 25-28. doi: 10.1016/j.cirp.2014.03.007. ISSN 00078506. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0007850614000109

This paper focuses on the determination of a new methodology for the environmental impact of a product system, in particular the prediction of the amount of product distribution in the market. The functionality of the methodology was verified on LCD screens for iPad 1 to iPad 4 devices. To determine the environmental impact of the amount of product distribution, an environmental impact matrix is used to simulate the SLF distribution.

Conclusions

The research results open up new possibilities for determining the overall environmental impact of products using Standard Logistic Function (SLF) to predict future behaviour. The methodology successfully simulates an increased demand with a higher functional value of the products. The advantage of using axiomatic design theory is that the environmental impact of products can be characterised by the function/characteristic of the product itself.

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[8] ALLIONE, Cristina, Claudia DE GIORGI, Beatrice LERMA and Luca PETRUCCELLI. From ecodesign products guidelines to materials guidelines for a sustainable product. Qualitative and quantitative multicriteria environmental profile of a material. *Energy*. 2012, 39(1), 90-99. doi: 10.1016/j.energy.2011.08.055. ISSN 03605442. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0360544211005950

The authors dealt with the expansion of the MATto library, which contains more than 500 material items. Industrial designers use so-called material checklists (white: problem free materials, grey: problem uses, black: prohibited materials). However, the library is based directly on the LCA method, which looked at meeting material assumptions throughout the product life cycle or parts of it.

The result is a material MATto library containing sensory properties of materials, but also methodological guidelines for determining the appropriate durability of products/materials.

Conclusions

The article offers an innovative view of eco-design, using the existing MET methodology, which is extended with sensory perceptions (surface roughness, transparency, odour, etc.). These perceptions are not included in the LCA design methodology, nor do they contain them. Designers, who stand from the beginning of product development, have the opportunity to change the negative impact and improve the product life cycle not only with the help of the MATto library but also with the appropriate choice of material durability.

2.4 Comparison of Eco-Design Tools and Methods

[4] **KNIGHT, Paul and James O. JENKINS.** Adopting and applying eco-design techniques: a practitioners perspective. *Journal of Cleaner Production*. 2009, 17(5), 549-558. doi: 10.1016/j.jclepro.2008.10.002. ISSN 09596526. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0959652608002515

The article focuses on the possibility of introducing new eco-design techniques into the product design process. It compares the approach of three eco-design techniques that can be used according to the study. It also shows that a wide application is not possible due to the different nature of the different methods but that with appropriate application, economic and environmentally friendly production can be achieved.

Conclusions

The study provides us with a comparison and the capabilities of selected eco-design tools to reduce the impact of extraction, product production, use, and end of life of products. The implementation of these rules is driven by the willingness of companies to implement eco-design tools or the use of the "10 Rules of Ecodesign", which lack precision but operate based on common-sense rules. A convenient solution for assessing the life cycle of a product at each stage is the MET Matrix method (based on LCA), which contains more than 1,000 items of materials, pollution and works with 3D CAD systems.

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[11] **VALLET, Flore, Benoît EYNARD, Dominique MILLET, Stéphanie Glatard MAHUT, Benjamin TYL and Gwenola BERTOLUCI.** Using eco-design tools: An overview of experts' practices. *Design Studies*. 2013, 34(3), 345-377. doi: 10.1016/j.destud.2012.10.001. ISSN 0142694x. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0142694X12000634

The extensive work seeks answers to hypotheses related to the process of using eco-design tools and determining environmental burdens. The article focuses on the comparison of Ecofaire, Ecodesign Pilot, Information/Inspiration [3] and SimaPro 7.0 (LCA methodology). For comparison, hypotheses were presented and eco-design strategies compared.

Conclusions

The paper describes in detail the advantages of eco-design tools, and determines their suitability for certain phases of the product life cycle assessment. According to the findings, eco-design practitioners are not concerned with the design itself. The research found that some of the modifications made in the context of optimisation of eco-design may have little environmental impact. The results are based on answering hypotheses H1 and H2 and present a suitable tool for life cycle assessment, which is SimaPro that uses LCA.

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[5] **BEY, Niki.** Environmental assessment - Gotten across to industrial designers. In: *Proceeding of the 7th International Design Conference, Design 2002, May 14-17, 2002, Cavtat - Dubrovnik - Croatia*. Zagreb, Croatia: Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, p. 1293-1298. ISBN 9536313456. Available on: https://www.designsociety.org/publication/29732/environmental_assessmentgotten_across_to_industrial_designers

The purpose of this thesis is to find a solution to the problem and context within the work of an industrial designer. Finding the basic indicators in the early stage of product design. Due to the convenience of applying OPM (Oil Point Method), the methodology is quantified according to volume, weight, or consumption in kWh. The work shows the ability to use OPM in an informative and time-saving way in industrial design.

Conclusions

The results of the study show us the positive capabilities of OPM. When the procedure was followed, good results were achieved, which can replace the complex LCA methodology. The simple calculation model, the possibility of updating and adding input data of OPM are also advantages. This study facilitates the determination of environmental burdens for industrial designers.

[1] **BYGGETH, Sophie and Elisabeth HOCHSCHORNER.** Handling trade-offs in Ecodesign tools for sustainable product development and procurement. *Journal of Cleaner Production*. 2006, 14(15-16), 1420-1430. doi: 10.1016/j.jclepro.2005.03.024. ISSN 09596526. Available on: http://linkinghub.elsevier.com/retrieve/pii/S0959652605000946

The paper compares 15 eco-design tools and describes their characteristics. The tools that were the subject of the research provide a different nature of the output according to their focus, but also according to the scope and quality of the input data. It also indicates whether the tool itself includes an output evaluation.

Conclusions

Eco-design tools are designed according to the way they are used. They provide a qualitative, quantitative, or semiquantitative output that needs to be interpreted correctly. In the case of tools without self-assessment, correct interpretation of the results is very important.

3 ANALYSIS AND CONCLUSION OF LITERATURE REVIEW

3.1 Interpretation and Evaluation of Knowledge

The determination of the environmental impact is very problematic, especially emissions of kg CO_2 eq., which are closely linked to the production site and especially in the use phase. For the determination of energy requirements for the production of products and the determination of kg CO_2 eq. emissions, the use of tools based on the LCA methodology is the most suitable solution in terms of variability, precision, extension, and number of published articles and dissertations [1, 4, 5, 8, 9, 10, 11, 12, 17, 19, 27]. This method provides quantified output and these advantages are exploited by tools such as MET Matrix, MECO matrix and others. The LCA method is used for the entire life cycle of a product or at each stage from mining, manufacturing of the product, use, end of life, or reintroduction into the production chain [4, 11, 24].

Tools, whose output is qualitative data, are suitable for environmental impact assessment in industrial design. Unfortunately, this approach only evaluates the design based on the empirical experience of the assessor without the possibility of a quantified output with a clear indicator of the environmental impacts of the designs. These tools include SpiderWeb, Checklists, LiDS Wheel [4, 11, 14, 15, 16] and the "Information/Inspiration" interface [5], which is supported by the LiDS Wheel methodology, EcoWeb and the WEEE, RoHS, EuP and Packaging and Packaging Waste regulations [3, 15]. The extension of the methodology of the MET matrix to include sensory input of materials has resulted in the MATto tool, which takes into account the TQM known as ISO 9000/2000, EMS and the ISO 14000 set of standards, ISO 14020 (Type I-III Ecolabeling) labelling of products/products according to the energy intensity of their operation [4] and the emerging ISO 14024:2018 standard.

Secondary raw materials that are produced from waste materials that are reintroduced into the production chain significantly change the resulting environmental burden. The use of residual or waste materials can reduce Greenhouse Gases (GHG) emissions for low-use products by up to 50% compared to new products [6, 17]. The volume of distribution of the primary product on the market has a significant influence on the amount of emissions kg CO_2 eq., where there is a 50% increase in the emissions kg CO_2 eq. to the volume of distribution of the previous product, assuming an improvement in the characteristics of the original product.

It is found that up to 80% of the impact of pollution is due to the design and production of the product itself in the case of the low use phase. The distribution and pollution of a single product are predictable and therefore well quantifiable [7].

3.2 Knowledge Analysis

By summarizing articles and published dissertations, we can analyse the fundamental problems of the current state of knowledge:

- Students of Industrial Design and Active Designers are not aware of the use of eco-design and do not know the appropriate tools [10, 11, 22, 25],
- eco-design tools should be visually elaborate and time-saving [3],
- emerging industrial designers want to know the environmental impacts of their designs, including knowledge of LCA [25],
- the implementation of eco-design tools is costly and time-consuming to train [10],
- eco-design tools are usually based on the LCA methodology [1, 11, 12, 17, 18, 19, 26, 27],
- quantitative tools cannot be applied at an early stage of product design [1, 4, 5, 6, 7, 8, 11, 12, 17, 18, 19, 20, 21, 24],
- qualitative tools in product or service assessment depend on the capabilities of the evaluator of the system under assessment [3, 4, 15, 16],
- 80% of the pollution is due to the actual production of the product with a low use phase [7],
- when a new product is distributed on the market relative to the previous product, there is a 50% increase in kg CO_2 eq. [7].

The articles presented focus on the determination of pollution, energy requirements using checklists [4], input-output economic analysis of input materials and output materials [21], complete or simplified LCA, and analyses incorporated into other eco-design tools [1, 11, 17, 18, 19]. The knowledge gained from the research underlines the relevance of the objective of the dissertation, namely determining kg CO_2 eq. and the energy to produce them from the volumetric properties of the products. The work is novel with an unconventional approach and opens an unexplored area in the possibility of determining the amount of environmental pollution at a very early stage of product design without quantitative data for a full LCA calculations.

4 AIM OF THESIS

The essence of the dissertation is the development of a new method for determining the environmental impact in an early stage of product design in industrial design. Design, functional parameters, product application, material processing and size are known for electric power tools. Therefore, it is possible to predict quantifiable environmental impacts in their early design stage without the knowledge of complex LCA tools.

4.1 Definition of the Aim of the Thesis

The aim of the dissertation thesis is to develop a method for quantifying the emission of kg CO_2 eq. and energy inputs at a very early design stage using statistical processing of data from an LCA-based tool from defined product categories using their volume and material composition.

4.1.1 Partial Aims of the Dissertation Thesis

The fulfilment of the aim of the dissertation presupposes the development of subobjectives:

- Determination of the most suitable tool for determining kg CO_2 eq. emissions according to the analysis of the articles and dissertation (Information/Inspiration, LCA, OPM, Ecodesig Pilot, Ecofair, MATto, MET Matrix, MECO matrix) [1, 3, 4, 5, 8, 10, 11, 12, 14, 15, 17, 18, 19, 20, 27, 28],
- creation of basic categories for classifying power tools according to volume and characteristic features,
- identifying a group of products to be categorised and selected by the selected eco-design tool according to articles [1, 3, 4, 5, 8, 10, 11, 14, 15, 17, 18, 19, 20],
- creation of an inventory analysis LCI of the internal organisation of the selected product groups,
- perform a series of model situations using the selected eco-design tool according to articles [1, 3, 4, 5, 8, 10, 11, 12, 14, 15, 17, 18, 19, 20],
- introduce an environmental impact matrix [7] (fragmentation of the different phases of the product life cycle) in the evaluation,
- volume simulation for individual product groups,
- data processing and designing unit quantities of kg CO_2 eq. according to the actual volume for each product group,
- determination of the volume dependence on energy requirements and kg CO_2 eq. emissions,

- determining the amount of energy to produce during the product life cycle in terms of recycling, landfilling, and incineration of individual materials,
- due to the differences in kg CO_2 eq. emissions over the product life cycle, use energy mix emissions to determine the g CO_2 eq./kWh pollution of each country or economy (EU),
- create a web interface to calculate kg CO_2 eq. and energy to produce power tools and simulate savings in the amount of product distribution to the market.

4.2 Scientific Question and Research Hypothesis

How does the size and type of product affect environmental pollution? Can the amount of emissions kg CO_2 eq. and energy consumption for production be based only on the volume and nature of the product?

4.2.1 Research Hypotheses

- It is assumed that the environmental pollution, more precisely the amount of released kg CO_2 eq. released during the product life cycle, depends on the volume and nature characteristics of the product (e.g., angle grinder vs. hammer drill). Based on the principle of maintaining the functionality and proportionality of the product's internal layout, it is possible to determine the energy requirements for the production of the product and the amount of kg CO_2 eq. emissions according to the volume of the product at an early design stage.
- It is assumed that the achievement of the specified objective using the SimaPro LCA tool provides more accurate and reliable data than tools such as Checklists, Information/Inspiration, OPM, Ecodesig Pilot, Ecofair, MATto, MET Matrix, KEPI, MECO matrix, but it is possible to take advantage of the individual advantages of the mentioned methods. [1, 3, 4, 5, 8, 10, 11, 12, 14, 15, 17, 18, 19, 20]
- Emissions kg CO_2 eq. can be personalised according to the location of production and use of energy indicators according to the OPM methodology [5, 12] and determined from the emissions of the energy mixes of each country or economy. [30, 31, 32, 33]
- In the solution, it is possible to achieve a maximum deviation of 25% by determining the proposed volumetric methodology from the values determined using the OPM method and LCA (openLCA tool) with sufficient data processing with product type specification. [13]

4.3 Solution Method and Used Methods

In order to solve the established working hypothesis, a classification analysis will first be performed to sort the products into different categories. Then, empirical evidence will be conducted according to the set conditions of the experiment in each class. The data sets obtained from the applied eco-design tools for each class will be statistically processed and the dependencies of the volumetric pollution kg CO_2 eq. and energy requirements for their production for each class. By deduction, it will be possible to answer the scientific question.

4.3.1 Solutions and Issues

Possible problems that arise in solving the working hypothesis:

- Inappropriate classification analysis (inappropriate product categorisation),
- large dispersion of values and failure to find a valid kg CO_2 eq.,
- large dispersion of values and failure to find a valid energy coefficient,
- problems in processing and evaluating large amounts of data,
- incomplete inclusion of all parameters in the LCA methodology,
- poorly determined product volume.

4.3.2 Methodical Procedure

The procedure involves chronologically ordered stages for the determination of kg CO_2 eq. and energy requirements for the production of one type of product:

- Data categorisation - using a classification method to build up product categories (e.g., angle grinders, jig saws, circular saws, etc.),
- product category selection - compile detailed internal product composition, LCI analysis and determine volume proportions using a 3D scanner or camera (e.g., for angle grinders),
- Phase 1 - using the OPM tool, determine the energy requirements for production and recycling, as well as the energy requirements for the overall life cycle of the selected product with a given material composition and volume proportions (from raw material sources to recycling, landfilling or incineration),
- Phase 2 - through the emissions of the individual energy mixes, determine the pollution value kg CO_2 eq. of the selected product with a given material composition and volume proportions (for recycling, landfilling, or combustion),
- result - the values from the OPM (LCA) methodology (Phase 1 and Phase 2) are evaluated proportionally and the values obtained are compared,
- evaluation.

4.3.3 Materials and Methods to Achieve the Aim

- Spreadsheet, which will be used for basic classification analysis (creation of product categories), processing of the data obtained from the experiment and subsequent evaluation,
- 3D scanner or camera for photogrammetry - subsequent determination of volume using the software,
- OPM methodology see source [12] will process the data (Phase 1),
- spreadsheet to determine kg CO_2 eq. from the energy mix values kg CO_2 eq./kWh from Phase 1 [30, 32, 33, 34].

5 MATERIALS AND METHODS

The chapter describes the range of power tool samples analysed and the tools and methods used. The methodological procedure describes details of the steps for obtaining data for subsequent LCA calculations, including Monte Carlo simulations with emission and energy equations. Power tools samples were provided by the recycling centre, and material analysis was carried out in the BUT laboratory.

5.1 Range of Examined Samples

The research was carried out on electric power tools, which were obtained in cooperation with the ENVIROPOL s. r. o. (Jihlava, Czech Republic) recycling centre. The selection was carried out without focusing on the type of tools, but taking into account the completeness of the tools. A total of 134 tools were analysed and subsequently categorised into 10 groups according to their type.

Categorised power tools into the groups:

- Random Orbital Sanders (6 pcs.),
- Sheet Sanders (16 pcs.),
- Electric Planers (9 pcs.),
- Handle Jigsaws (24 pcs.),
- Belt Sanders (7 pcs.),
- Percussion Drills (17 pcs.),
- Circular Saws (7 pcs.),
- Angle Grinders (26 pcs.),
- Electric Chainsaws (16 pcs.),
- Reciprocating Saws (6 pcs.).

5.2 Methodological Approach

The flowchart describes the detailed solution procedure in four basic steps to obtain the desired output in the form of energy and emission equations. The methodological approach is applied to each tool sample in the Data Preparation and LCA steps. The other steps are applied to the corresponding categorised power tools product groups (Fig. 5-1).

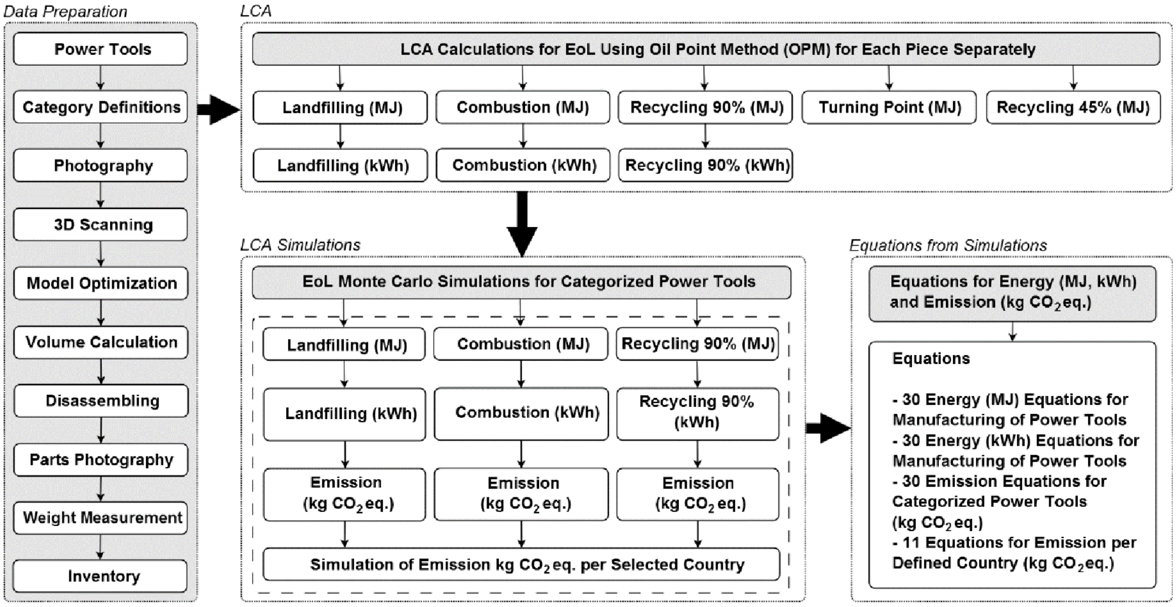

Fig. 5-1 Flowchart of the new volumetric method VEME.

A methodological procedure has been established: without cable for connection, no refills that are consumed during the use of the tools (lubricants), without tools and bars, possible missing parts, but always as little damage to the housing as possible, ignoring wear and tear on internal components, only a complete 360° 3D scan of the tools, disassembly into the smallest possible parts and components, always get half the windings from the stators, assigning materials and colours to each type of part, calculating welds and including surface finishes on parts, the energy required to assemble the products (0.007 kWh/min) was not calculated [37], recycling percentage linear on all parts, no service interventions or repairs to the products during the use phase.

5.3 Used Tools and Software

To achieve the aim of the dissertation, it was necessary to provide the necessary equipment (scale device SARTORIUS PMA7500 - 000C, EinScan HD Pro handheld 3D scanner, PC, measuring instruments, hand tools and power tools, software Rhinoceros 7, ExScan Pro, MS Excel and digital camera).

5.4 Data Preparation

Power Tools & Category Definitions

The tools for the analysis were selected with the greatest complexity and the least amount of damage to the covers in mind. The product was categorised and assigned to continuously emerging groups corresponding to the product types.

Photography & 3D Scanning

Before 3D scanning, the tool sample was first photographed for archiving. The sample was completed with a sufficient amount of marking points and scanned with a 3D scanner in its entirety in handheld rapid scan mode. Accuracy up to 0.045 mm in HD mode [36].

3D Model Optimization & Volume Calculation

The scanned 3D model is directly imported in STL format into Rhinoceros 7 software (Fig. 5-2, right and left part). This 3D model contains many surfaces that are unnecessary for the determination of the sample volume.

Fig. 5-2 Rhinoceros 7, imported STL Angle Grinder – narex EBU 13; (left) imported model; (right) cleared model.

5.4.1 Disassembling & Parts Photography

Disassembly was carried out using hand tools and power tools. First, the covers were removed, and the individual internal components were disassembled. In the case of merged parts, disassembly was performed where possible.

Materials and Structural Analysis

All parts have been materially identified (plastics, metals, glass, composites, non-metals, etc.) and allocated to the relevant manufacturing processes (injection moulding, hot rolling, cold rolling, welding, anodising, painting, etc.) see Appendix A.

Stators and Rotors Analysis

The stators of the power tools were disassembled into three basic materials: Copper (windings), Steel (armature) and Plastic. Due to the impossibility of separating the rotor parts into individual components, it was necessary to mathematically derive them from the sample (dimensional data from the rotors). The material composition of the rotor was divided into 4 material groups: Steel (armature and shaft), Copper (windings, commutator), Resin (winding protection and commutator) and Plastics (shaft protection).

5.4.2 Measurement & Invetory

After photographing the disassembled parts, measurements were taken of the weight, weld length, and surface finish (painting and anodising) of each part. In case it was not possible to weigh the individual parts from the set of parts, it was necessary to determine the weight of the individual parts (by finding the catalogue weight of the part or calculating it). The weighing capacity of the scale device is 7,500 g (permissible tolerance 0.1 g) [35]. Before processing to the LCA calculations, each type of part was inventoried by material group, manufacturing method and surface finish [38].

5.5 LCA Method

Life cycle calculations was performed using the OPM method (*"The Oil Point Method: A tool for indicative environmental evaluation in material and process selection"*) [12]. This method was selected on the basis of the current state of knowledge and provides a sufficient amount of materials, processes, and possible EoLs. The advantages are clarity, speed and easy implementation in MS Excel.

The OPM method was used to assess the product life cycle in the following basic phases:

- Materials Production, Manufacturing Processes, Transport, Use, End of Life (EoL).

The life cycle calculation also included the following: Packaging Analysis, Finding Turning Point, Demand for Recycling 45% (EU). Recycling requirements are now at 45% (2016) for selected countries, including CZ [39, 40]. The determinations of the location of 45% recycling were derived from a linear dependence of the recycling rate from 0% to 100%.

The end of life of the products was calculated in three variants EoL (Landfilling, Combustion, and Recycling 90%).

5.5.1 OPM Data Calculations

Power tools contains many components using different materials. The OPM method has a wide range of Materials Production and Manufacturing Processes, but some could not be found. For simple materials, information was found in databases and other methods. Groups of merged materials could only be calculated, in more complex cases complicated. For completeness of the calculation using the OPM method, the missing values of OP/kg were found by the calculations.

Recalculated Materials and Processes

The determination of the material properties of TPE was derived from the assumption of a ratio of PB and PP material (75% PB and 25% PP [41, 42]). Composite materials containing GF (Glass Fibres) were calculated as a mixture of the main material and the percentage of GF (calculated for Recycling and Combustion). The aluminium alloy "Dural" were calculated by the relative percentages of each component in the OPM method [43].

The painting process (Compressed Air, 3 bar at 250 l/min [44]) corresponds to a value of 0.042 kWh and will be calculated with a value of 0.01 OP/m^2. The paint materials (1 coat of paint per 1 m^2) were set at 1/10 of the OP values for the Epoxies material [45]. The energy to produce the product by Low Pressure Die Casting was set at 0.5 OP/kg [46, 47].

Calculated Components and Processes

The more complex products that are part of the power tools were calculated from individual OPM indicators and externally available information: Capacitors (60% aluminium foil, 20% paper, and 20% PP cover [48]), PCB (combustion allows only 33% of the PCB parts, which are organic parts [49]) and V-Belts (It was found that 35% is PB and the rest is nylon fibres).

Other Database Materials

The POM material was determined from LCI characteristics in the Plastics Europe [50]. The ECOlizer 2.0 tool was used to determine the material properties of EPDM [51]. The energy requirement of Manufacturing Processes to produce 1 kg of steel using Hot Rolling technology is 4.3 MJ and was set to 0.1 OP/kg [52, 53, 54].

5.5.2 Transport Calculations

The transport conditions were the same for Landfilling, Combustion and Recycling 90%. Transport phases were carried out at intervals:

- min. transport - local production (truck = 300 km, truck = 1,700 km and van = 500 km),
- max. transport - global production (truck = 300 km, ship = 14,500 km "sea transport" [72], truck = 1,700 km and van = 500 km).

5.5.3 Use Phase Calculations

Use phases were calculated for 1,000 hours over 2 years of operation (standard warranty in CZ) and were the same for Landfilling, Combustion and Recycling 90%. The use phase was always calculated as the corresponding power input of the product.

5.5.4 Packaging Calculations

The packaging material of the product was calculated as cardboard B (200 g/m^2) and PE foil 0.1 mm to wrap the product. The size (65/50/45 mm) of the packaging was derived from the volume of the tool with an allowance around the tool itself, including an allowance for the inner horizontal and two vertical panels.

5.5.5 Turning Point

The Turning Points values for EoL impacts were determined from a linear dependence of the recycling rate from 0% to 100%. The Turning Point is where the amount of energy in Combustion is equal to the energy gained through recycling in the interval 0% to 100%.

5.6 LCA Simulation

Due to the time-consuming nature of the individual LCA calculations, a Monte Carlo simulation was performed. The simulation was performed for two output categories with three EoL options:

- Energy requirements in units MJ and kWh, emission of kg CO_2 eq.

The simulation was carried out on data obtained from the analysis of each tool category as a function of product volume and energy requirements for production. The input data for the simulation were subjected to linear regression and tested for normal distribution with *p*-value < 0.05. This simulation for *n* = 1,000 steps was applied to individual tool categories in the Landfilling, Combustion and Recycling 90% life stages.

Data from the input analysis from a normal distribution with the standard deviation of the base set were processed at a test level of alpha = 0.05. Subsequent analysis involved linear regression with linear equations obtained at 95% confidence with p-values < 0.05 (t-Test paired with a two-tailed distribution). [61, 62, 64, 65]

The kg CO_2 eq. emission analysis was applied to the countries CZ, PL, EE, SE, TR, BR, CN, IN, US and JP (according to ISO code 3166-1) [29] and the United Kingdom as UK. The values obtained from the simulation and the energy mixes of each country (valid as to June 2019) [55].

5.6.1 Calculation Coefficient of Determination

The resulting correlation coefficient, r_{xy}, was calculated with the help of the solver using a VBA script that contained n = 1,000 iterations to obtain its highest value. The calculation of the coefficient was performed on the tool categories for each EoL.

5.7 Equations from Simulations

The calculation relationships for determining energy requirements in MJ, kWh and emissions of kg CO_2 eq. are derived from Monte Carlo simulations. The equations are determined for the tool categories according to their EoL.

The resulting equations for the calculations:

- Energy production requirements in MJ (30 equations),
- energy requirements for production in kWh (30 equations),
- emissions kg CO_2 eq. by product type (30 equations),
- kg CO_2 eq. emissions by production location (11 equations).

The calculation equations given in kWh are derived from the MJ equations and recalculated by a conversion factor between MJ and kWh. These equations are then used in the calculation of kg CO_2 eq. The kg CO_2 eq. emissions for tools according to each variant of EoL (abbreviated *LF* = Landfilling, *CM* = Combustion, *RC* = Recycling) are calculated from the arithmetic average of all defined countries. In the case of kg CO_2 eq.

6 RESULTS

A total of 134 power tools that were manufactured between 1989 and 2018 were analysed. The total weight was 310 kg with more than 9,700 individual parts and material groups (copper and brass contacts). Before processing the LCA, the tool samples were sequentially photographed and scanned with a 3D scanner to determine the volume of the product (example of a power tool in categories, see Fig. 6-1.).

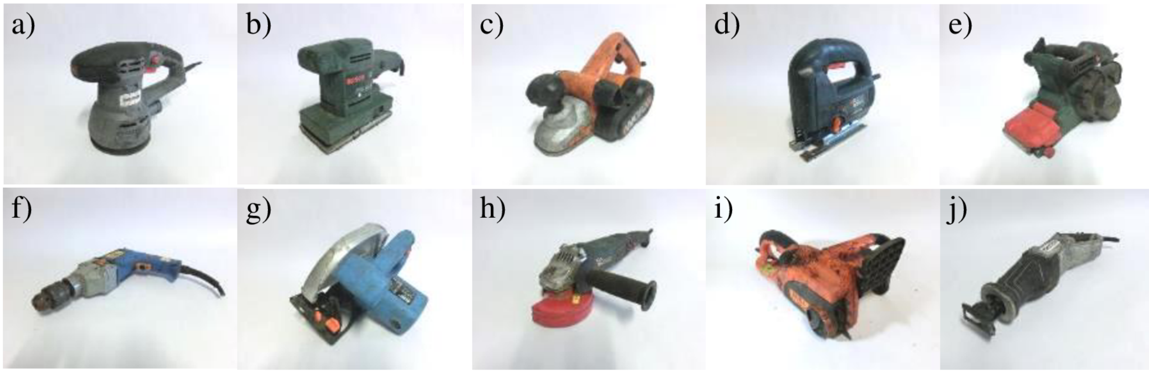

Fig. 6-1 Example of Power Tools; (a) Random Orbital Sander – OS5; (b) Sheet Sander – (SS8); (c) Electric Planer – (EP3); (d) Handle Jigsaw – HJ11; (e) Belt Sander – BS7; (f) Percussion Drill – PD2; (g) Circular Saw – CS7; (h) Angle Grinder – AG19; (i) Electric Chainsaw – EC13; (j) Reciprocating Saw – RS6.

6.1 Material Analysis

The tools were disassembled into individual parts and inventoried to prepare the data for the LCA calculations (Fig. 6-2). Manufacturing operations were assigned to the materials. Inventory analysis showed that in the early 1990s pure ABS was used to cover the products, while in later years it was PA6 and PA66 composites reinforced with GF from 30% to 50%. Balancer structures and bearing housings tend to be made of Zn alloy and aluminium alloy and steel. Flexible parts such as bearing seats are made of EPDM and PB. Brass and Bronze is used for plain bearings and contacts. A significant amount of steel is in electric motors such as stator plates and armature of rotors, copper in rotor windings, stator and wires.

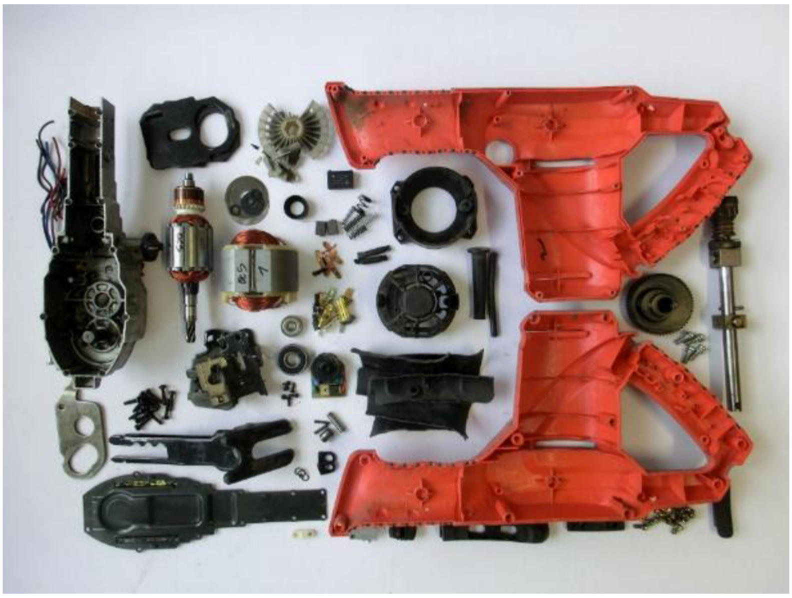

Fig. 6-2 Photography of decomposed Reciprocating Saw (RS1).

Stators and Rotors

The electric motor (consisting of a rotor and a stator) has a high share in the weight of the whole product (highest value 43.1% for Angle Grinders, smallest value for Belt Sanders 26.6%). The most significant percentage of copper parts and steel in electric motors is in smaller products.

6.1.1 Measured Properties of Power Tools

Volume and Weight

The volume characteristics of the product categories was determined by a 3D scanner and correspond to their characteristic properties and applications. The weight was determined for each part, which had the same material composition and method of manufacture (see Appendix B). The ranges of measured volumes and masses for the product categories are given in Appendix D.

Length and Diameters

The length values and diameters of the parts (rotors) were measured to calculate volumes and derive weights. Individual measurements are included in the MS Excel calculation file.

Depency of Weight and Volume

The values of the correlation coefficient range from 0.66–0.97. The average value is 0.84. The values represent a strong dependence [56]. The results show the dependence of the volume and weight characteristics of power tools on the potential for further uses.

6.2 LCA Calculations

The LCA calculations were processed from the inventory analysis for each tool sample. The scope of the data analysis included a total of 402 individual EoLs that were combined into product categories followed by linear regression. The alpha-value was set at 0.05 for all product categories. In 6 samples (20% of all samples) from 30 samples where the *p*-value is higher than the significance level alpha, we accept the hypothesis (Tab. 6-1).

Tab. 6-1 Correlation coefficient and *p*-value from LCA Calculations.

Power Tools	Landfilling	Combustion	Recycling 90%	Turning Point (not found) (%)
Random Orbital Sanders	*p*-value = 0.04 correlation = 0.83	*p*-value = 0.04 correlation = 0.83	*p*-value = 0.02 correlation = 0.88	33.3%
Sheet Sanders	*p*-value = 0.02 correlation = 0.57	*p*-value = **0.08** correlation = 0.45	*p*-value = 0.01 correlation = 0.62	81.2%
Electric Planers	*p*-value = **0.05** correlation = 0.66	*p*-value = **0.14** correlation = 0.53	*p*-value = 0.03 correlation = 0.72	11.1%
Handle Jigsaws	*p*-value = 0.00 correlation = 0.73	*p*-value = 0.00 correlation = 0.71	*p*-value = 0.00 correlation = 0.75	91.6%
Belt Sanders	*p*-value = 0.03 correlation = 0.81	*p*-value = 0.02 correlation = 0.84	*p*-value = **0.13** correlation = 0.62	42.8%
Percussion Drills	*p*-value = 0.00 correlation = 0.92	*p*-value = 0.00 correlation = 0.91	*p*-value = 0.00 correlation = 0.95	29.4%
Circular Saws	*p*-value = **0.27** correlation = 0.48	*p*-value = **0.34** correlation = 0.42	*p*-value = 0.01 correlation = 0.90	14.3%
Angle Grinders	*p*-value = 0.00 correlation = 0.96	*p*-value = 0.00 correlation = 0.96	*p*-value = 0.00 correlation = 0.98	0.0%
Electric Chainsaws	*p*-value = 0.00 correlation = 0.75	*p*-value = 0.00 correlation = 0.69	*p*-value = 0.00 correlation = 0.88	87.5%
Reciprocating Saws	*p*-value = 0.00 correlation = 0.98	*p*-value = 0.00 correlation = 0.98	*p*-value = 0.00 correlation = 0.99	0.0%

The samples of categories were statistically non-significant in 6.7% EoL Landfilling (2 samples), 10% Combustion (3 samples) and 3.3% Recycling 90% (1 sample). All samples over alpha-value = 0.05 come from the power tools categories with small amounts of samples. The correlation coefficient ranged from 42.5% to 98.7% (mean 77.8%). The use phase (1,000 h) comprised 90% to 99% of the entire life cycle. The position of each EoL curve was placed from the largest Landfilling, Combustion and Recycling 90% curves towards the origin (without overlapping them as in the Percussion Drills, Angle Grinders and Reciprocating Saws category).

In recycling, there is a backflow of materials into the system under evaluation. Because of recycling, materials are exposed to energy to be prepared for their return to the system. The product categories according to their design and ergonomic requirements contain a similar range of Material Production and Manufacturing Processes. The observed data are presented in Appendix C.

Packaging

The energy requirements for the packaging material are 8.537 MJ ± 0.270 MJ (Landfilling), -3.862 MJ ± 0.122 MJ (Combustion) and 11.374 MJ ± 0.359 MJ (Recycling 90%). The packaging energy is in a lower position relative to the transport when using materials that are suitable for recycling and do not require high energy to process, in particular aluminium alloy, copper, and steel. Smaller products such as Handle Jigsaws (and others) are at the upper end of the energy per Transport range in the Recycling 90% case. In the case of Sheet Sanders under EoL Recycling, the packaging energy requirements were above the upper limit and had up to twice the energy per Transport. These increased energy requirements are first evident in EoL Landfilling and indicate higher requirements in EoL Recycling 90% as well.

Use Phase

The use phase of 1,000 h ranged between 125 W (1,406 MJ = 391 kWh, the energy for production compared to the use phase is 7.5%) and 2,200 W (24,750 MJ = 6,875 kWh, the energy for production compared to the use phase is 2.4%).

6.2.1 Landfilling (LCA Calculations)

The EoL of Landfilling mode contained only zero values for all materials (OPM rules). An example for EoL (Landfilling) is the Reciprocating Saw tool (Fig. 6-3). Landfilling was found to be less energy intensive than Recycling 90% in 13 cases (from 0.3% to 6.2%). The reason for the increase in recycling is the use of the following plastics (PA6-GF30, PA66-GF35, PA6, PA66, TPE, HDPE and PP) and low amounts of steel, aluminium, copper, brass, bronze and zinc alloy.

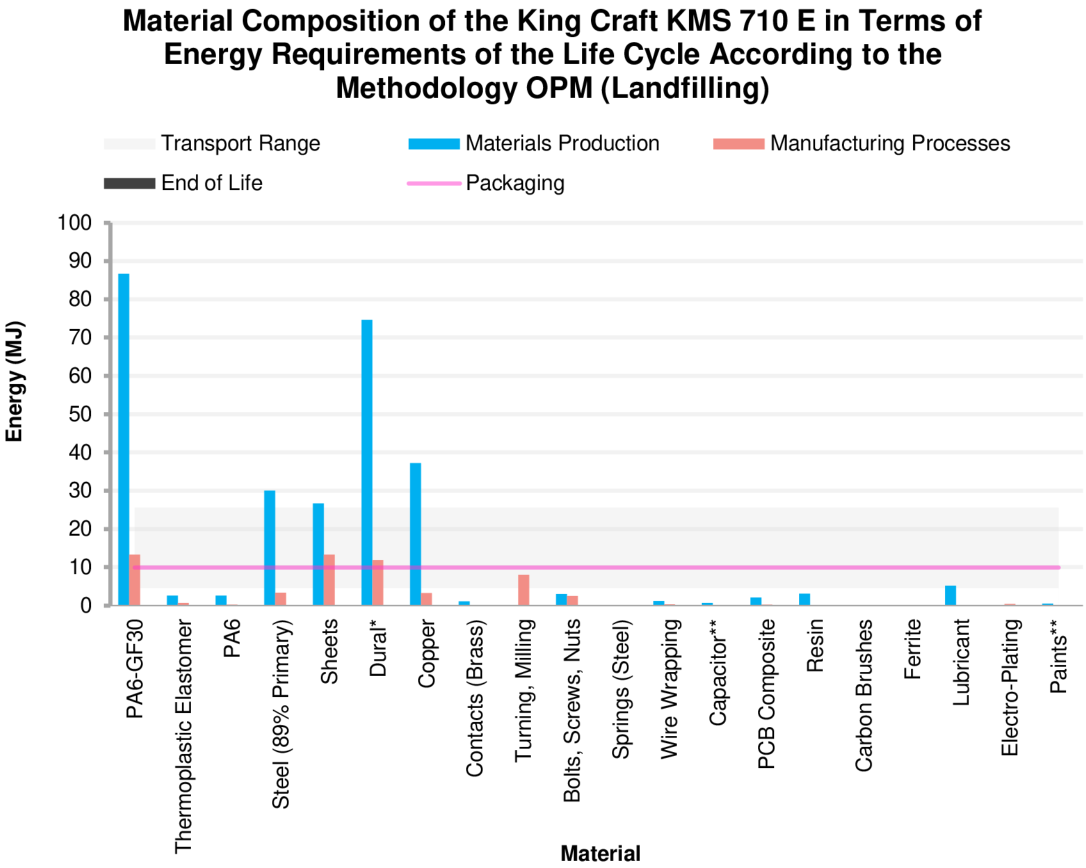

Fig. 6-3 Graph of Reciprocating Saw (Landfilling) – Example of LCA profile (RS1).

6.2.2 Combustion (LCA Calculations)

The combustion mode (Fig. 6-4) was only enabled for materials that contain Feedstock share indicators, such as ABS, PP, PMMA, PVC, etc. The composite materials PA6, PA66, PP, POM and PBT were only energetically recovered as a percentage without glass fibres reinforcement (GF). The plastic product covers and internal parts recovered the most energy. Energy recovery also occurred for Capacitors, Printed Circuit Boards (PCBs), V-Belts and Lubricants. In the case of incineration, the energy in the MJ is transferred to an independent system (electric or thermal energy). The combusted and non-combusted parts were landfilling. In total, in 61 cases (45.5%), the amount of energy for the EoL Combustion was below the Recycling 0% (Landfilling) to Recycling 100% interval. The energy of the Combustion was found in 73 cases (54.5%). The amount of manufacturing energy was on the recycling curve of 0% to 100% (Recycling 0% = Landfilling, Recycling 100% = complete recycling). The minimum value for Combustion was 10.6% (sample AG3) and the maximum was 99.6% (sample PD4 corresponding to almost 100% recycling) from the recycling interval of 0% to 100%. The average level of EoL Combustion corresponded to 39.2% ± 7% (interval Recycling 0% to Recycling 100%).

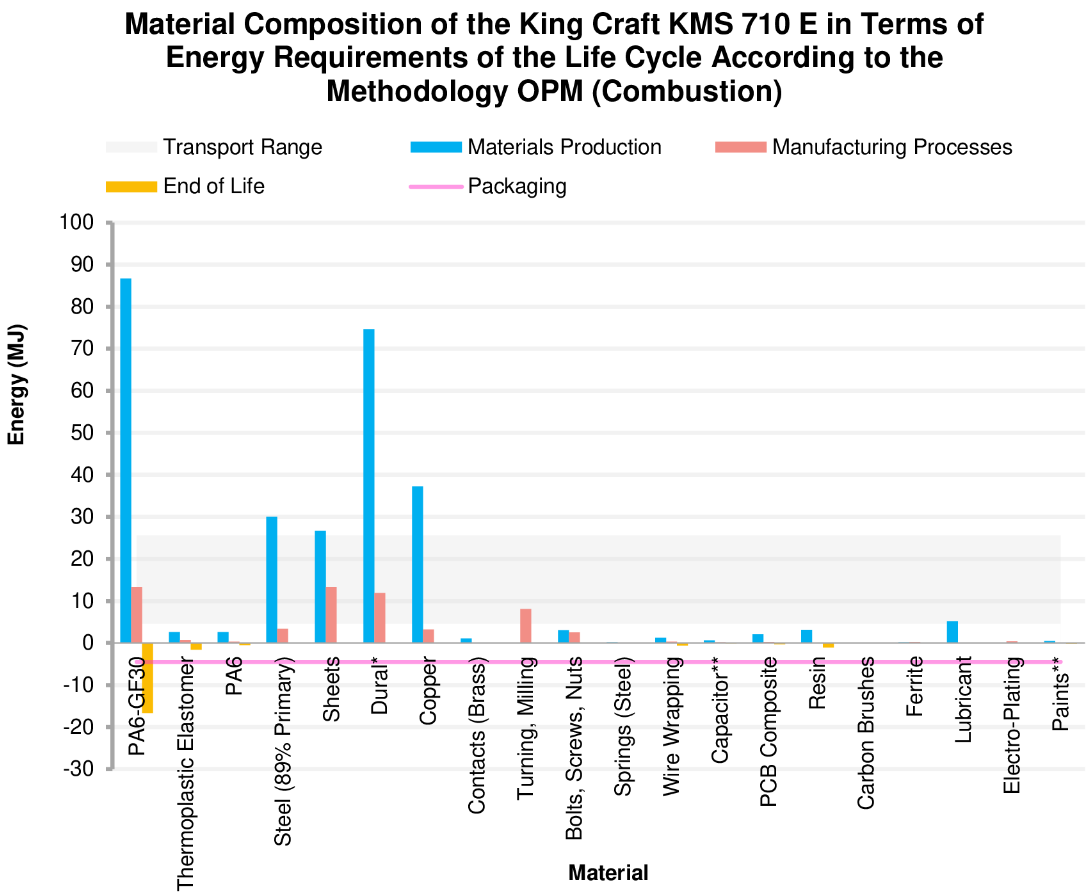

Fig. 6-4 Graph of Reciprocating Saw (Combustion) – Example of LCA profile (RS1).

6.2.3 Recycling 90% (LCA Calculations)

The return of some plastic material back into circulation is energy intensive because of the higher values for Recycling compared to Combustion and Landfilling. Recycling requires high amounts of energy for shredding, separation, and re-milling (Fig. 6-5). The average reduction in energy requirements for the manufacturing of recycling products relative to EoL Landfilling is 13.2% ± 1.6%. The increase in energy requirements for EoL (Recycling 90%) is only observed in 13 of 134 tools with an average value of 1.6% ± 0.8% (the maximum increase was 6.1%). From the analysis, it was found that there is an increase in energy requirements (straight-line directive positive) for recycling in 13 power tool samples.

This increase applies to 9.7% of all samples. The amount of aluminium alloys, steel, and copper relative to the plastics and composites used has a significant impact on the recycling contribution. For these reasons, the Turning Point where Combustion is below the Recycling 100%, and point could not be found and could not be determined.

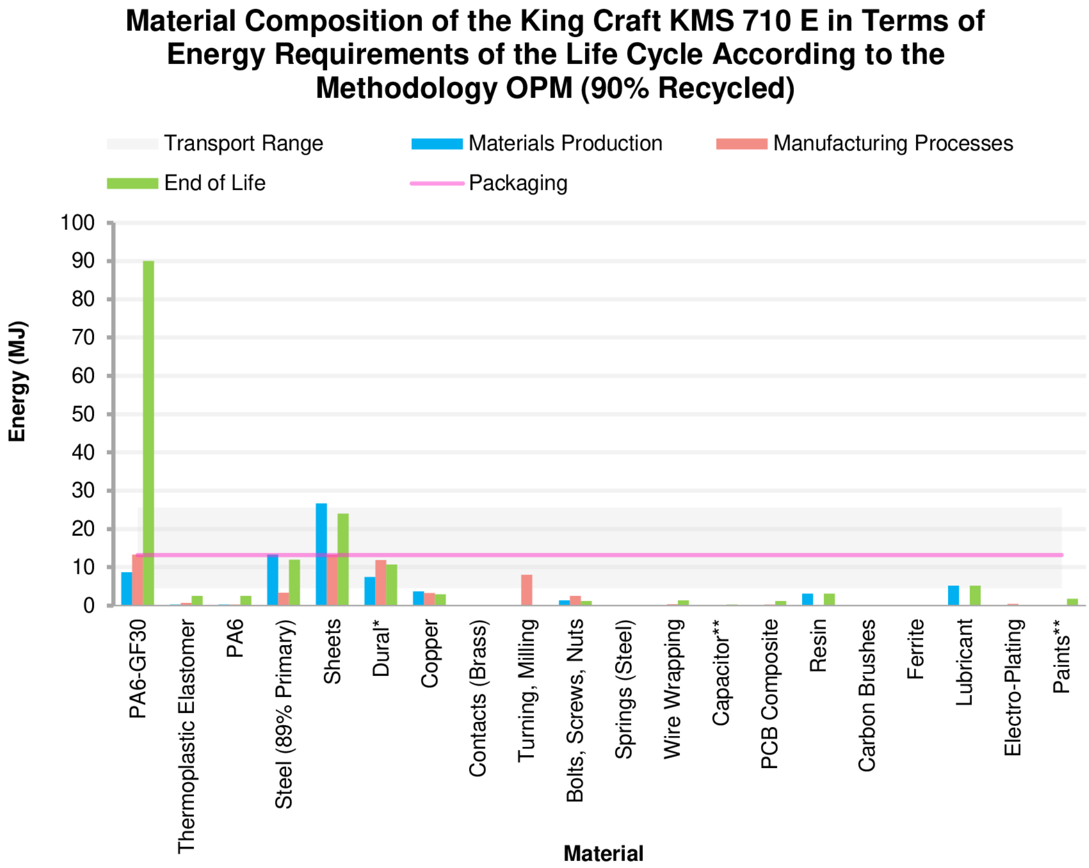

Fig. 6-5 Graph of Reciprocating Saw (Recycling 90%) – Example of LCA profile (RS1).

6.2.4 Turning Point (LCA Calculations)

The 134 tool samples were analysed in LCA for EoL impacts within the Landfilling, Combustion, Recycling 90% and with a recycling rate of 0% to 100%. Values were determined for a recycling rate of 45% as required by the EU and a Turning Point for the EoL variant of Combustion (the point where the amount of energy in incineration is equal to the energy calculated by recycling rate of 0% to 100%). For products with a high proportion of plastics used in the inner part and in the outer cover, it was possible to find a Turning Point on the whole recycling scale of 0% to 100% from a total amount of 54.5%. In the case of finding the Turning Point on the recycling line, it was possible to determine whether more energy is required to produce a product for the EoL Combustion than for Recycling 45%. (Fig. 6-6). In 47 cases, more energy is required in the EoL Combustion than in Recycling 45% (total 35% of samples). This energy for manufacturing products in the EoL Combustion is up to 12% higher compared to the Recycling 45%. Recycling 45% is up to 28% higher relative to Combustion. On average, there is a 4.1% increase due to recycling relative to combustion at alpha = 0.05. Detailed descriptions and values for each sample are given in Appendix C.

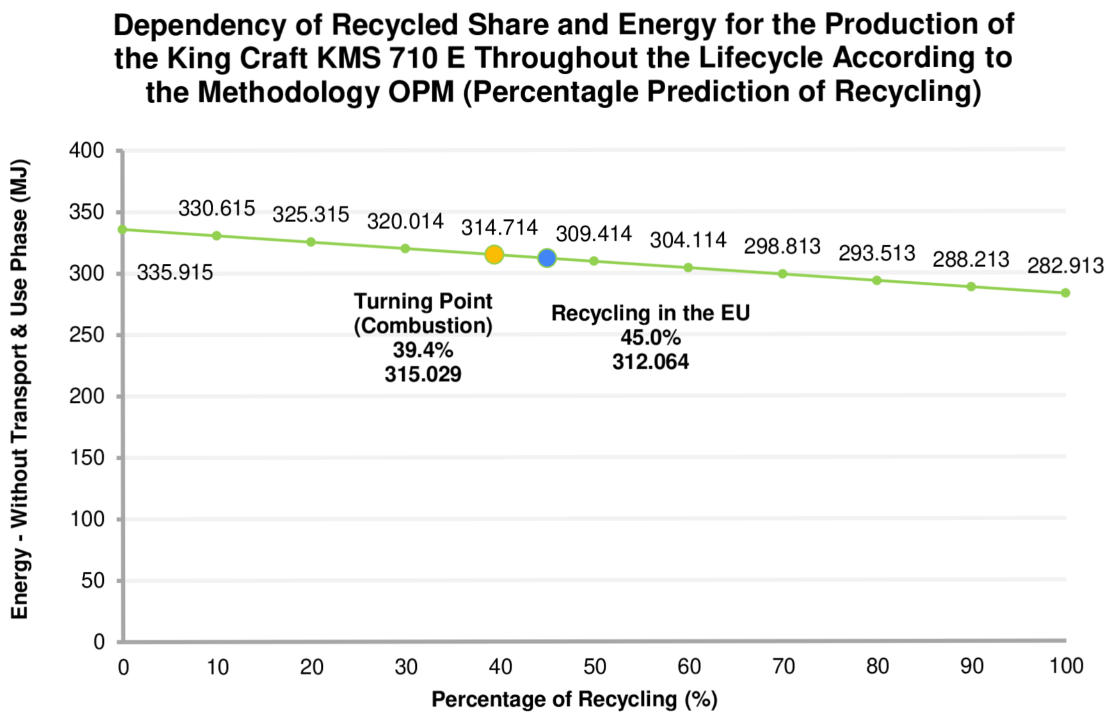

Fig. 6-6 Graph of Reciprocating Saw – Example of Turning Point and Recycling 45% (RS1).

6.3 Monte Carlo Simulation

The energy requirements for production in MJ and kWh were obtained by Monte Carlo simulation. From the LCA data analysed in Landfilling, Combustion and Recycling modes using normal distribution at 95% significance level, alpha = 0.05 for n = 1,000, the data was calculated with iteration step max. = 1,000 steps to find the highest correlation coefficient. The simulation was performed on the categorised groups in three life cycle steps. The data show the volume of the product and the energy dependencies for tool production. The resulting equations for determining the energy requirements for the production of power tools are presented in the following section.

With the use of Monte Carlo simulations (n = 1,000 and computational iterations), a more accurate prediction of the production energy was achieved. The linear regression from the simulations has a near-zero origin at the energy/volume coordinate points in 100% of the cases.

Average values of the correlation coefficient from the simulations for product categories (p-value = 0.05):

- Random Orbital Sanders (OS_{MJ} = 84.1% ± 0.6%),
- Sheet Sanders (SS_{MJ} = 65.7% ± 3.6%),

- Electric Planers (EP_{MJ} = 78.5% ± 3.8%),
- Handle Jigsaws (HJ_{MJ} = 76.7% ± 2.0%),
- Belt Sanders (BS_{MJ} = 81.2% ± 1.5%),
- Percussion Drills (PD_{MJ} = 84.4% ± 2.0%),
- Circular Saws (CS_{MJ} = 74.6% ± 6.5%),
- Angle Grinders (AG_{MJ} = 97.1% ± 0.2%),
- Electric Chainsaws (EC_{MJ} = 83.8% ± 2.4%),
- Reciprocating Saws (RS_{MJ} = 95.8% ± 0.5%) see Fig. 6-7.

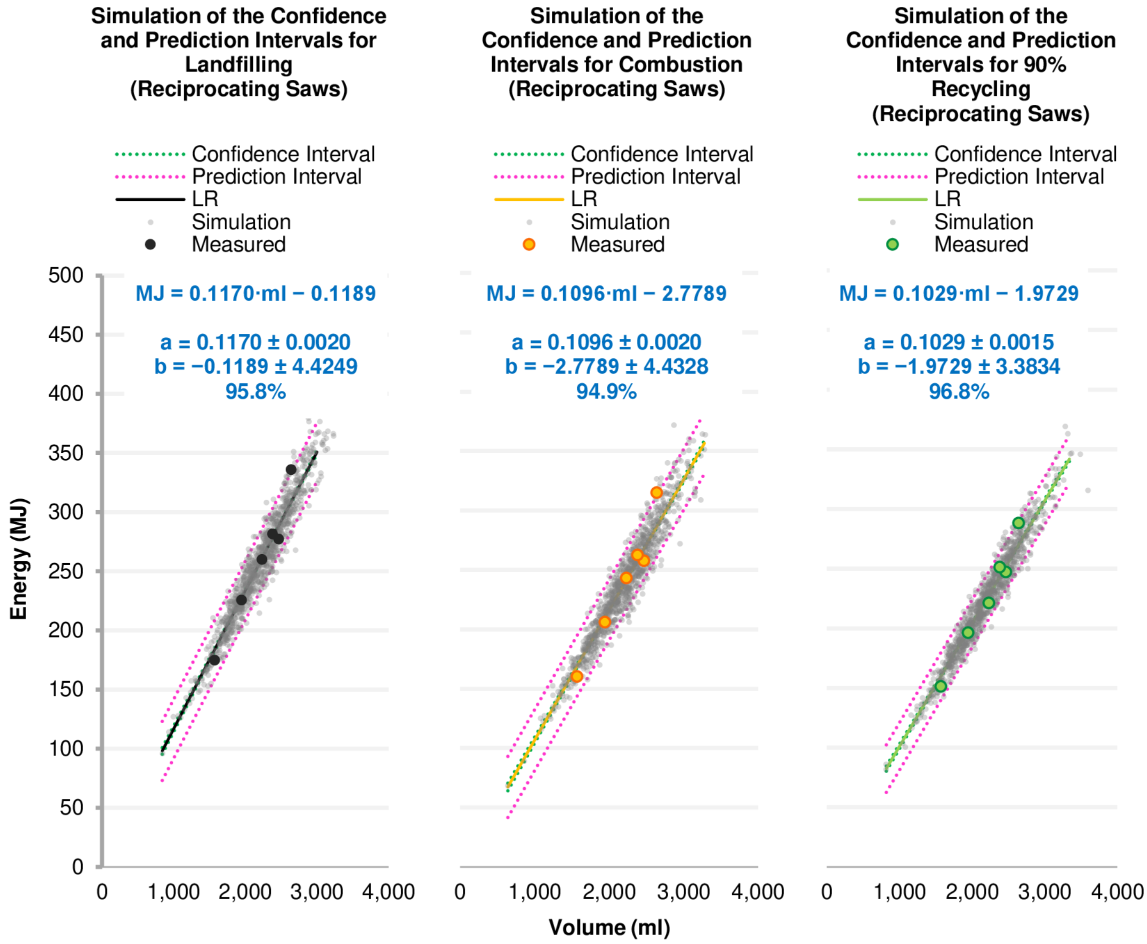

Fig. 6-7 Monte Carlo simulation for Reciprocating Saws (Landfilling, Combustion and Recycling 90%).

6.3.1 Energy for the Categories of Power Tools

The calculation of energy requirements for production was calculated by Monte Carlo simulation in units MJ and kWh. The graph of the relationship between Energy MJ and volume ml contains the different product categories in the three EoL variants (Fig. 6-8).

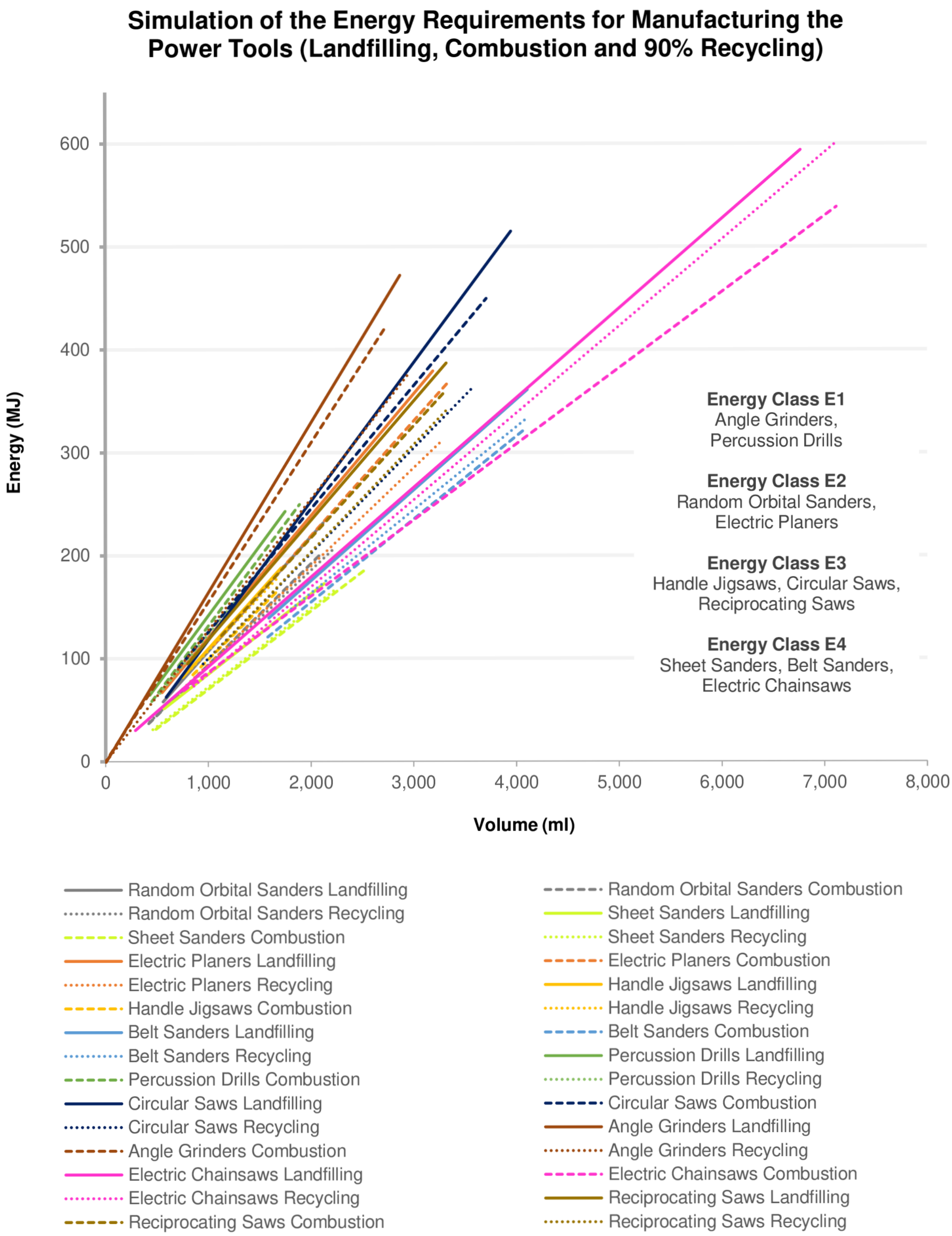

Fig. 6-8 Energy simulation of power tools category (Landfilling, Combustion & Recycling 90%).

The fan-shaped distribution of the power tool categories reflects their type, design, ergonomics and use. Power tools with low volume, high energy and high concentration of individual parts correspond to the higher steepness of the curve. The usual arrangement (from most energy per production to least) is Landfilling, Combustion and Recycling 90%. Electric Chainsaws have a higher energy requirements per production under EoL (Recycling 90%). The reason for this is the large amount of plastics (PP, PA6, PA66-with Glass Fibres, HDPE, PE and PVC) combined with the large amount of air and components used. The equations determined from the Monte Carlo simulation describe the dependence of the MJ energy and emission CO_2 on the ml volume of the product (Tab. 6-2). They describe the observed dependence with p-value = 0.05 (95% confidence level).

Tab. 6-2 Equations for calculating energy requirements for manufacturing power tools and their emission CO_2.

Category of Power Tools	End Of Life	Equation (MJ)	Equations (kg CO_2 eq.)	r_{xy} (%)
Random Orbital Sanders	Landfilling	MJ = 0.1130 ml - 6.3417	$kgCO_2$(LF)OS = 0.0157 ml - 0.5501	85.0
	Combustion	MJ = 0.0987 ml - 5.0446	$kgCO_2$(CM)OS = 0.0133 ml - 0.0458	83.1
	Recycling	MJ = 0.0923 ml + 0.3706	$kgCO_2$(RC)OS = 0.0135 ml - 0.6592	84.3
Sheet Sanders	Landfilling	MJ = 0.0858 ml - 1.8374	$kgCO_2$(LF)SS = 0.0122 ml - 0.7163	63.5
	Combustion	MJ = 0.0767 ml - 6.1391	$kgCO_2$(CM)SS = 0.0109 ml - 0.9540	60.8
	Recycling	MJ = 0.0802 ml - 7.3565	$kgCO_2$(RC)SS = 0.0104 ml + 0.0894	72.8
Electric Planers	Landfilling	MJ = 0.1244 ml - 12.4813	$kgCO_2$(LF)EP = 0.0180 ml - 2.4227	77.2
	Combustion	MJ = 0.1197 ml - 20.5420	$kgCO_2$(CM)EP = 0.0162 ml - 1.6797	72.6
	Recycling	MJ = 0.0962 ml - 2.5479	$kgCO_2$(RC)EP = 0.0140 ml - 1.2567	85.6
Handle Jigsaws	Landfilling	MJ = 0.1148 ml - 6.8751	$kgCO_2$(LF)HJ = 0.0159 ml - 0.7933	76.9
	Combustion	MJ = 0.1006 ml - 2.5794	$kgCO_2$(CM)HJ = 0.0144 ml - 0.7890	73.2
	Recycling	MJ = 0.1057 ml + 1.1723	$kgCO_2$(RC)HJ = 0.0150 ml - 0.0319	80.0
Belt Sanders	Landfilling	MJ = 0.0916 ml - 10.1117	$kgCO_2$(LF)BS = 0.0127 ml - 1.2017	83.1
	Combustion	MJ = 0.0789 ml - 1.5414	$kgCO_2$(CM)BS = 0.0112 ml - 0.3311	82.1
	Recycling	MJ = 0.0863 ml - 14.8796	$kgCO_2$(RC)BS = 0.0119 ml - 1.7030	78.3
Percussion Drills	Landfilling	MJ = 0.1464 ml - 4.6675	$kgCO_2$(LF)PD = 0.0210 ml - 1.2947	81.7
	Combustion	MJ = 0.1369 ml - 7.9260	$kgCO_2$(CM)PD = 0.0190 ml - 0.6383	83.0
	Recycling	MJ = 0.1253 ml - 2.8582	$kgCO_2$(RC)PD = 0.0175 ml - 0.3419	88.4
Circular Saws	Landfilling	MJ = 0.1398 ml - 26.7613	$kgCO_2$(LF)CS = 0.0191 ml - 2.8581	70.9
	Combustion	MJ = 0.1268 ml - 10.7441	$kgCO_2$(CM)CS = 0.0187 ml - 3.5570	65.6
	Recycling	MJ = 0.1016 ml - 0.3742	$kgCO_2$(RC)CS = 0.0141 ml + 0.0978	87.3
Angle Grinders	Landfilling	MJ = 0.1643 ml - 0.6158	$kgCO_2$(LF)AG = 0.0228 ml + 0.0182	97.0
	Combustion	MJ = 0.1543 ml - 0.3622	$kgCO_2$(CM)AG = 0.0218 ml - 0.0742	96.7
	Recycling	MJ = 0.1274 ml - 0.0324	$kgCO_2$(RC)AG = 0.0179 ml - 0.0955	97.5
Electric Chainsaws	Landfilling	MJ = 0.0914 ml - 12.6966	$kgCO_2$(LF)EC = 0.0131 ml - 2.1882	83.4
	Combustion	MJ = 0.0817 ml - 13.4431	$kgCO_2$(CM)EC = 0.0113 ml - 1.4077	79.8
	Recycling	MJ = 0.0854 ml - 2.9266	$kgCO_2$(RC)EC = 0.0120 ml - 0.7109	88.1
Reciprocating Saws	Landfilling	MJ = 0.1170 ml - 0.1189	$kgCO_2$(LF)RS = 0.0165 ml - 0.2223	95.8
	Combustion	MJ = 0.1096 ml - 2.7789	$kgCO_2$(CM)RS = 0.0155 ml - 0.5875	94.9
	Recycling	MJ = 0.1029 ml - 1.9729	$kgCO_2$(RC)RS = 0.0142 ml + 0.0105	96.8

6.3.2 Energy Density

Energy density represents how much energy is contained in a 1,000 ml volume of each category of products by different type of EoL. Products with a high value (average) represent products with high energy such as Angle Grinders (148.8 MJ per 1,000 ml), Percussion Drills (132.1 MJ per 1,000 ml), etc. Low values (average) on the other hand show more ambient air around components such as Sheet Sanders (75.5 MJ per 1,000 ml), Belt Sanders (81.5 MJ per 1,000 ml), and Electric Chainsaws (87.9 MJ per 1,000 ml). This is due to the safe grip of the power tool and the safety of guiding the power tool. High values show the dependence of air volume and all parts in covers.

6.4 Emission kg CO_2 eq. for the Categories of Power Tools

The simulation of kg CO_2 eq. emissions was performed on the data obtained from the LCA calculations. Energy production requirements in kWh (values were converted to kWh directly in the LCA calculations of the tool samples). The resulting kg CO_2 eq. emissions for each product category are recalculated from Monte Carlo simulations for kWh and graphically correspond to the energy requirements in MJ. The kg CO_2 eq. emissions for each country are the average energy requirements for the production of each tool category in all three EoL variants. The distribution of the product categories in the graph of kg CO_2 eq. emissions corresponds to the fan charts (Fig. 6-8) of the energy for production in MJ and kWh (converting 1 MJ = 0.2778 kWh). Calculation of emissions for categorised products in the three variants of EoL (Tab. 6-2).

6.5 Emission kg CO_2 eq. per Selected Country

The emissions of the selected countries kg CO_2 eq. per kWh are calculated as the average EoL values of the categorised products. The amount of emissions corresponds to their energy mixes and thus to their order (Fig. 6-9). The emission values range from 93 g CO_2 eq. per kWh for SE (Sweden) to 875 g CO_2 eq. per kWh for EE (Estonia) [55].

Emission kg CO_2 eq. per Selected Country

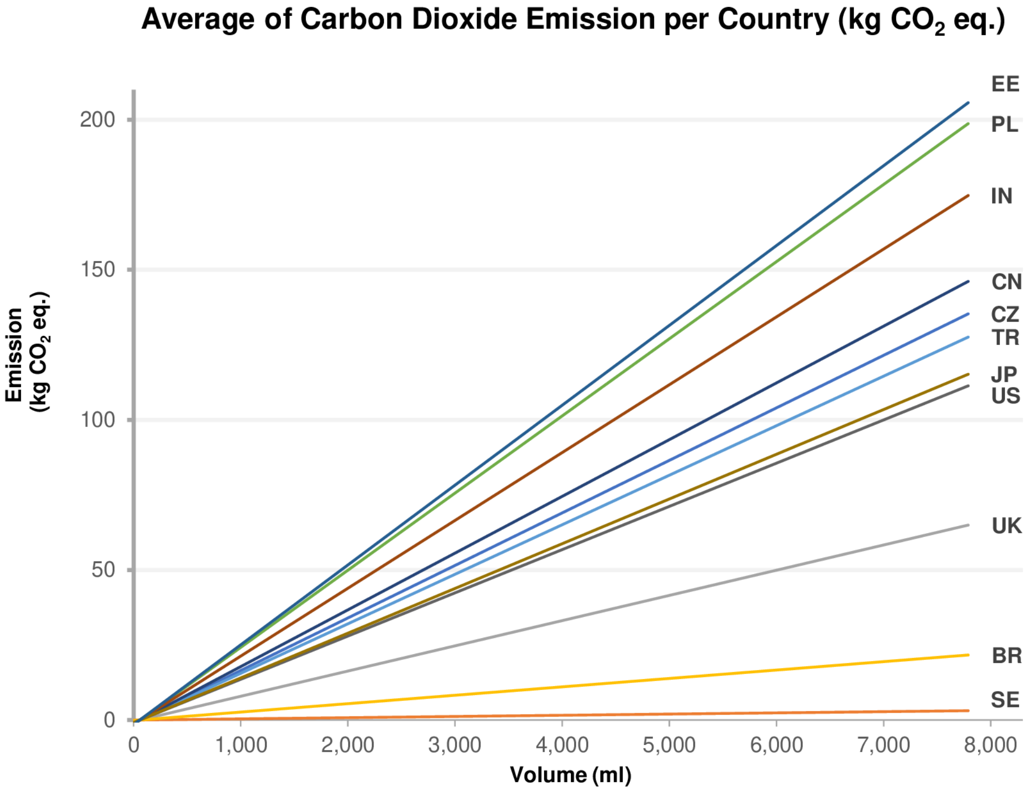

Fig. 6-9 Graph of simulation volume and emissions kg CO_2 eq. per country.

The emission equations for each country are mathematical formulations of kg CO_2 eq. emissions for the selected country. The values correspond to the energy mixes of each country. Equations are presented in the table below (Tab. 6-3).

Tab. 6-3 Equations for calculating emission kg CO_2 eq. per selected countries.

Country	Equations (kg CO_2 eq.)	max. (kg CO_2 eq.)
CZ	$kgCO_2$,CZ = 0.0175 ml - 1.0172	135.308
SE	$kgCO_2$,SE = 0.0004 ml - 0.0247	3.091
UK	$kgCO_2$,UK = 0.0084 ml - 0.4985	64.938
BR	$kgCO_2$,BR = 0.0028 ml - 0.1608	21.651
TR	$kgCO_2$,TR = 0.0165 ml - 0.9591	127.576
PL	$kgCO_2$,PL = 0.0257 ml - 1.5055	198.698
CN	$kgCO_2$,CN = 0.0189 ml - 1.1074	146.124
IN	$kgCO_2$,IN = 0.0226 ml - 1.3151	174.739
US	$kgCO_2$,US = 0.0144 ml - 0.8413	111.335
JP	$kgCO_2$,JP = 0.0149 ml - 0.8797	115.191
EE	$kgCO_2$,EE = 0.0266 ml - 1.5522	205.662

6.6 Application of Method VEME

The application of the proposed method was realised in designs by students of BUT IMID (Department of Industrial Design). The volumetric characteristics of the five Angle Grinders designs were the source for determining the energy requirements for the production and emissions of kg CO_2 eq. for three variants of the EoL – without use phase, transport and packaging. The results of the analysis show a percentage of energy usage and savings in the EoL Recycling 90% on their production compared to Landfilling. The design of a 1,099 ml angle grinder with 125 mm disc diameter shows energy savings of only 77.8% in Recycling 90% to produce the identical product and emission savings of 22.2%. The amount of released CO_2 emissions corresponds to the energy mix of the countries for the design concepts analysed (Fig. 6-10).

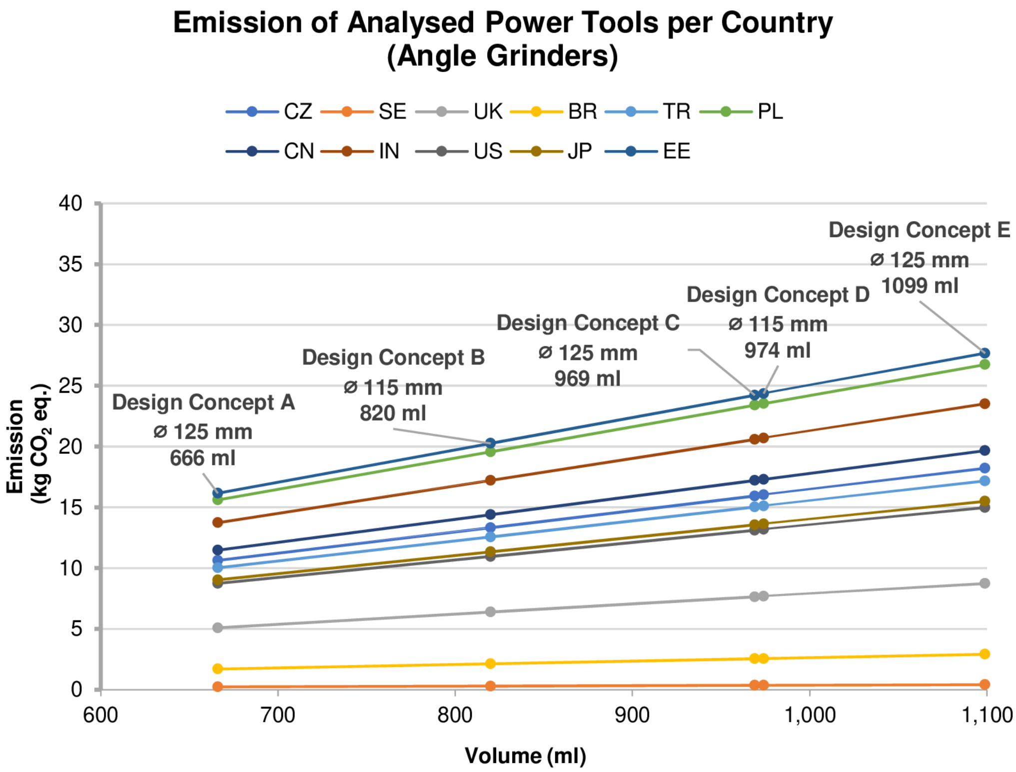

Fig. 6-10 Graph of designed angle grinders with dependency volume and emissions kg CO_2 eq. per selected countries.

The values obtained using the equations to determine the energy requirements MJ and emissions kg CO_2 eq. have p-value = 0.05. Correlation coefficients in the range of 96.7% to 97.5% for EoL indicate a correctly performed initial analysis and initial inventory analysis.

6.6.1 Economical & Environmental Benefits

The price of emission allowances is at 50 EUR per ton CO_2 eq. (August 2021) [57]. The value of emission allowances can cost up to 100 EUR per ton CO_2 eq. in 2030 [58]. The emissions kg CO_2 eq. per product production is negligible, but considering the large amount of power tool production, the location and recycling rate has a significant impact. An example of optimising the shape of an Angle Grinders product with a disc diameter of 115 mm and a volume 974 ml and 820 ml without using other emission reduction methods (high material recycling rate). Financial savings are 13,474 EUR (100,000 pcs.).

7 DISCUSSION

The proposed volumetric VEME (Volumetric Evaluating Method of Ecodesign) method focuses on the volumetric properties and type characteristics of power tools. The method allows to obtain energy requirements and kg CO_2 eq. emissions for production in three EoL variants. The power tools were subjected to material analysis and carefully inventoried. The samples obtained of 134 pcs. were produced over a period of almost 30 years and show the cross-sectional evolution of this product sector. The samples analysed contained different material and design solutions. As the samples were not composed only of products manufactured in the last 5 years, it was not possible to determine the current approach of the manufacturers to the environmental aspects of production. The proposed method includes a use phase (1,000 h), but is not included in the calculation equations (energy requirements and CO_2 emissions) to determine the energy requirements for tool production. The energy requirement of each power tool is determined by its power input and time of use, which determine the dominant part of the product life cycle. The method does not take into account maintenance costs and also service interventions on the products, due to the lack of data for a more detailed evaluation.

Categorisation of Power Tools

The number of samples in the categories and the resulting range of categories corresponded to the frequency of each sample (with respect to its useful life) in the e-waste recycling centre. A limiting factor for the inclusion of a sample for analysis was also the requirement of minimal damage to the tool sample. Some samples were very damaged and were rejected for further analysis. Due to the different nature of power tools (design, type of use), it was necessary to categorize them.

Material Analysis

For the LCA calculations, it was necessary to decompose the parts of the power tools into their individual materials and also to categorize them according to the production method. The problematic part of this material analysis was determining the type of plastic (marking from production for future recycling) used on power tools. The main indicator was the year of manufacture of the power tools themselves (the plastics used at the time). Plastics that could not be identified (PB, EPDM, TPE, and PVC parts) were flame tested. The optimal solution would be to crush and separate the different types of materials used. The problem with this calculation method is its inaccuracy in determining the volumes and subsequent weights of the individual parts. However, it is the most efficient solution with regard to the method of analysis and the locations where it is carried out.

3D Scanning and Digitisation

Digitising the samples with the 3D scanner was very accurate with the limitation of scanning deep holes such as screw holes and deep covering power tools. Analysis using accurate 3D scanning methods would have been inefficient and costly (CT or MRI). During 3D scanning, some samples were incomplete (missing drivers, cable protectors, and enclosures); however, during scanning, the volume was reduced to account for missing parts that had material and manufacturing characteristics (this missing part was not included in the LCA calculation).

OPM Calculations

The LCA calculations was processed at the three variants of EoL (Landfilling, Combustion, and Recycling 90%) with calculations for Use Phase, Transport and Packaging. The input data were based on the OPM method, which includes a wide range of Material Production, Manufacturing Processes, and other parts of the LCA. However, the power tools also contain parts that had to be calculated newly or recalculated.

The materials calculated directly from the existing OPM indicators were: Composite Materials with Glass Fibres, TPE, EPDM, Dural, V-Belts, Foil Capacitors, Liquid Colour, and Lubricants. These materials were obtained by direct calculation from sources of the OPM method and are determined with sufficient accuracy relative to existing data. The POM material was identified directly from the Plastics Europe Public LCI Database and compared with the OPM data.

Materials derived and compared with the OPM methodology as Printed Circuit Board (PCB) were calculated using the individual materials in OPM. The resulting calorific value generated during the combustion of the composite board was compared with the energy calculated by OPM. The calculated energy of the Feedstock share using OPM is 0.36 OP/kg and corresponds to the combustion value observed of 0.3 OP/kg from the publication and the theoretical value of 0.26 OP/kg [49]. The printed circuit board (technical ceramics) is calculated in the same way but with a reduction in Feedstock share.

The missing Manufacturing Processes (Turning, Milling, Hot Rolling, Low Pressure Die Casting, and Compressed Air) had to be found and integrated into the energy ranges according to the OPM method. Compressed Air was left at 7 bar and calculated to direct kWh consumption for a given air flow rate. The resulting value was compared to the typical energy cost of compressed air in industry [44, 59]. The energy directly for Hot Rolling was determined only for the process with parameters of 0.1 OP/kg and compared with Sheet Metal Forming 0.2 OP/kg and Metal Casting 0.26 OP/kg [12]. The energy requirements for Cold Rolling are greater than those for Hot Rolling [60]. The parameters for Hot Rolling are adequately specified for the OPM calculations.

LCA Calculations

LCA calculations have been implemented in the Materials Production and Manufacturing Processes areas with the maximum effort to correctly assign materials and manufacturing processes. In real practice, the level of recycling is very different within EU countries and the compliance with WEEE requirements are very different. The packaging energy requirements for EoL Landfilling were 8.5 MJ ± 1.1 MJ, this value corresponds to 5.5% of the total energy requirements for production. For Recycling 90%, the energy per packaging material was 11.4 MJ ± 1.3 MJ. The results are consistent with those found for carboard packaging with similar parameters [67]. It was found that the transport energy was 6.5% of the energy for the production of power tools.

Monte Carlo Simulation

The Monte Carlo simulation was used and calculated directly in MS Excel. The scope and calculation method were chosen because of the lack of measured data and the complexity of obtaining them. The most suitable for simulation purposes was a normal distribution (bell-shaped) with step n = 1,000. This step was found to be sufficient. When testing the larger n = 10,000 steps, the calculation was more challenging and was no longer beneficial.

Profit of Research

The VEME method allows the determination of energy requirements for production and emissions kg CO_2 eq. only on the volumetric characteristics of power tools. According to the current state of knowledge, there is no approach that provides quantitative data only on the volumetric characteristics of the product. Software solutions such as openLCA, GaBi, and SimaPro do not allow the calculation of both energy requirements for production knowing only the volume of the product. In these cases, it is necessary to know the detailed characteristics of the individual parts. The problem cannot be solved by IO Analysis, which approaches the solution using input and output consumption parameters during manufacturing. Qualitative assessment using environmental matrixes and the 10 Golden Rules, does not allow to achieve quantitative outputs from the nature of their methods. The VEME method analyses individual products and product categories in more detail. The intergroup association of product categories was found only on volume or weight, or volume and weight. Intergroup interferences in terms of weight and volume, product category dependencies were also found. Using the VEME method, it is possible to quantify energy savings from a production perspective, but also to take into account production location and transport. Calculating the properties of the product under consideration/proposal in a simple way using energy and emission equations. Using a recycling prediction in the range of 0% to 100%, it is possible to determine a Turning Point that identifies the incineration efficiency and it is possible to adjust the material profile of the product.

The LCA calculations are enormously time consuming and there is no approach that can instantly evaluate EoL just by specifying the volume of the product and the nature of the tooling. The VEME method is carefully calculated with the rules of the OPM method, but there is no data available to validate them. Power tool manufacturers have not provided these data for validation.

The energy savings for Recycling 90% goes towards zero recycling (complete landfilling) a maximum of 32.4% (average achievement is 13.3% ± 4.9%). The values correspond to the most represented materials, namely steel, aluminium, copper, and plastic. This reduction corresponds to a statistical reduction potential of up to 27.0% ± 9.0% (theoretical value) [68]. This level has been calculated with the linear recycling level of each material. The global values of the recycling potential by 2050 are calculated to be 64% steel, 94% aluminium, and 55% plastic, and the amount of energy to produce them decreases as the recycling percentage increases [69].

The energy intensity of production, including kg CO_2 eq. emissions, should motivate manufacturers to make production more environmentally friendly, but also to optimise material flows, including volume proportions, at an early stage of product design. This responsibility lies mainly with the industrial designers who design products [73]. An increase in the price of the emission allowances will logically lead to the optimisation of the production location and the reduction of energy requirements [71].

With the coming of Industry 4.0, there are demands for the integration of new materials and the optimization of product shapes. This responsibility of the industrial designer is aimed at sustainable production of products [73]. The design of new products should make targeted use of recycled materials to reduce the use of primary raw materials in high-volume production. Considering the worldwide sales of power tools, it is necessary to optimise products even at this early stage of design. Global sales of power tools are expected to reach USD 48 billion in the year 2027 (an increase of 4.8% in 2020) [74]. For these reasons, it is essential to focus on sustainable power tool production. Optimisation for a single product may seem insignificant, but for millions of tools produced, it already has a significant impact. The energy intensity for the production of raw materials and the price of materials are closely linked. [70]

Next Research

The proposed VEME method is based on the amount of power tools collected that have been analysed. To obtain more accurate results, it would be useful to extend the number of products in the product categories. There is also potential in the range of categories of tools analysed (now 10 categories). It would also be possible to integrate the calculations in the case of battery-operated power tools with respect to the change in the type of motor (change in the masses of the different parts copper, steel, plastic, and magnets). It is possible to further specify local and global transport requirements and use them for more precise calculations.

The EU percentage of post-consumer recycling of WEEE requirements are evolving and are updated with respect to location or prediction for the future.

In terms of kg CO_2 eq. emissions, examples of countries with a specific energy mix structure have been selected, but it is possible to expand the list and make further calculations. There is a great potential in the area of detailed calculations of kg CO_2 eq. emissions for categorised products focusing on their EoL with optimisation of energy costs for Transport.

By transforming the volumetric characteristics into mass characteristics, it is possible to determine the recycling potential of products in recycling centres.

Similar Approaches

Currently, no research has been conducted in the area of designing and assessing power tools based on the volume proportions of the product. This is a completely new approach that can be most closely compared to the method that has been used for a long time in the construction industry in the Czech Republic. The statistical method “price indices in the construction industry” is used for quick valuation of categorised types of buildings according to the “uniform classification of construction objects” (houses, bridges, etc.), using the external volume of the building [75]. Buildings are made up of basic materials and elements according to the same principle as power tools. In the construction industry, outputs are given in monetary units relative to their volume, and in the new VEME method (Volumetric Evaluating Method for Ecodesign), outputs are given in energy units also relative to their volume.

8 CONCLUSIONS

This dissertation thesis focuses on the development of a quantifiable method to assess environmental impacts based on the volume of a power tool product alone. It also brings together knowledge of the industrial designer's relationship with eco-design, eco-design methodologies, factors affecting the environmental impacts of product production and distribution. The wide-ranging issues of eco-design require knowledge covering international legislation, regulations and guidelines. The complexity of the application of eco-design tools itself is very problematic, especially LCA-based tools and the high costs of their cost and training (Gabi, SimaPro, etc.). In the research part of the dissertation thesis, it was found that there is no use of volumetric characteristics to determine the emissions of kg CO_2 eq. and energy requirements for the production of products in its entirety or in individual parts of the life cycle. The reason for the absence of this method is the highly problematic determination of quantifiable values at an early stage of product design, where only external shaping is used without the possibility of obtaining volumetric or weight data.

The volumetric characteristics of power tools and the energy requirements for their production are interdependent. The internal structure of the investigated power tools exhibits a common material composition and the proportion of materials used to the volume of the product. For this reason, the dependency studied is predictable. These characteristics of the product, such as design (ergonomics), economic production and structural design, interact and act in a self-regulating process (striving for an optimal product). This self-regulation is already considered in the standards and directives themselves, e.g., 2009/125/EC.

The environmental impacts of EoL for power tools, in particular, are affected by the type of tool, the material used, and the volume characteristics of the tool. According to the analysis carried out, the volume of the tool comprises a set of parts that must ultimately meet the economic, structural, and ergonomic requirements of the product while maintaining their elementary functional characteristics. From the material analysis, it was found that on average 35% of the total weight of the product are electric motors (11.2% copper and 23.8% steel). The highest percentage was in the Angle Grinders category at 43.1% and the lowest was in Belt Sanders at 26.6%.

LCA calculations were performed that contained 402 individual End of Life (EoL) values for 134 samples. From the analysis, it was found that large amounts of plastics (PA, PA66, epoxies, PU, PC, PET film, and PMMA) with a high Fuel share content worsen the recycling efficiency. Tools with a high proportion of these plastics (Electric Chainsaws and Handle Jigsaws), including GF-reinforced plastics, have the same or worse results in Recycling 90% as in Landfilling (only 13 samples of 134) with an average value of 1.6% ± 0.8% (the maximum increase was 6.1%). From the analysis, it was found that there is an increase in energy requirements (straight line directive positive) for 13 power tool samples during recycling. This increase applies to 9.7% of all samples.

The energy for packaging material (carboard and PE foils) accounts on average for 5.5% of the manufacturing energy for products. On average, 6.5% of the production energy is for the energy consumption of transporting the goods according to the defined transport range.

In 6 samples from 30 groups of categories the *p*-value is higher than the significance level alpha. All samples over alpha-value = 0.05 come from power tools category with small amount of samples.

The correlation coefficient of the analysed samples ranged from 42.5% to 98.7% (mean 77.8%). The average reduction in energy requirements for product recycling relative to the EoL Landfilling is 13.2% ± 1.6%. EU (WEEE) recycling requirements are set at 45%. In 47 cases, more energy is required in the EoL Combustion than in Recycling 45% (total 35% of samples). This energy for manufacturing products in the EoL Combustion is up to 12% higher compared to the Recycling 45%. Recycling 45% is up to 28% more efficient relative to Combustion. The energy requirements for transporting a power tool can be twice the energy required to produce its packaging.

Due to the time-consuming nature of determining the LCA for each power tool product, Monte Carlo simulation was applied to the LCA data obtained. The simulation was set at alpha = 0.05; the data will lie with a 95% probability in calculation n = 1,000. An iteration solver (up to 1,000 steps) was used in MS Excel for the calculation using a VBA script. The values of the correlation coefficient after simulation were found to be in the range of 60.8% to 97.5% energy MJ and 63.3% to 98.0% energy kWh for the tool categories (describes the dependence of volume and energy requirements on production). The results corresponded to a strong to perfect positive association.

The higher percentage values of the correlation coefficient are due to the smaller air volume inside the tool and a very similar material composition (the cover envelops tightly around the internal components both in the grip area and in the gear area).

From the volumetric and material properties, it is possible to derive their carbon footprint according to the location of manufacture and the subsequent use phase. The calculation of emissions has the same characteristics as the energy requirements for the production of the tool categories, as they are based on this and recalculated (recalculation from MJ to kWh and then emissions kg CO_2 eq.). It is evident from the results that kg CO_2 eq. emissions depend on the energy mix of the countries where they are produced. Among the selected countries, SE (Sweden) is the best and EE (Estonia) the worst in terms of carbon footprint. The method for power tool analysis is based on OPM without knowledge of LCA software, which requires expensive training of the solver and is easily integrated into MS Excel. The ability to use it can be seen in the application of the VEME method on volumetric designs of products in the Angle Grinders category.

The VEME method provides a simplified analysis of the volumetric characteristics of the tooling product only. Using the defined equations, the energy requirements for their production can be quickly determined. The equations of the overall analysis are classified into 10 main groups according to the type of tool. These groups contain 60 energy equations (kWh and MJ) describing the product production requirements and 30 equations for determining emissions kg CO_2 eq. There are 11 equations for the determination of emissions kg CO_2 eq. by geographical location of production. A total of 60,000,000 simulation calculations were performed to establish the equations.

The newly proposed method provides an optimisation tool for the development, production of products and determination of kg CO_2 eq. emissions according to the energy mix of each country. From the point of view of a full life cycle assessment of a product, the largest emissions kg CO_2 eq. for electrical appliances are produced during their use phase (operation of the product). However, these emissions are closely related to the location of the use phase, but also according to the place of birth of the product. A weakness of this method is the determination of the parameters (kWh, MJ and kg CO_2 eq. emissions) from the equations at low product volumes in the three EoL studies.

The difference in energy requirements for product transport in the range of minimum and maximum transport is in the 0.08–0.47% range of the whole life cycle energy requirements (excluding packaging energy). The use phase (1,000 h) is 90–99% of the entire product life cycle and increases with motor power input. The potential of this research allows the extension of energy labelling for products (consumption) to include energy requirements for tool manufacturing, transportation, and packaging.

The benefits of this work are the ability to obtain quantitative output that can be applied at an early stage of product design based on the volume of the product without knowing the internal structure of the product. Determining environmental impacts based on the volumetric properties of designs can be applied not only in the field of industrial design, but also in the areas of marketing, production planning and optimisation, and potentially for recycling materials in recycling centres. The price of emission allowances will have a significant impact on the optimisation of the production and use phase. On the scale of a single product, savings in terms of product modifications or material recycling may seem negligible, but with millions of units produced, thousands of tonnes of greenhouse gases can be saved.

The hypothesis that it is possible to determine the energy requirements for the production of power tools based on the volume characteristics in given product categories has been confirmed.

The advantage of the method is the high efficiency of work, without knowledge of LCA, and low requirements for input data (type and volume of product and place of production). The novelty of the method lies in linking a very early stage of product design with the LCA method, which has not been used before. Calculating the impact of EoL variants can be done with a single quantitative variable, namely, the volume of the product under evaluation. The calculation equations of the VEME method are included in the web interface available at **http://VEME.cz** (printscreen, see Appendix E).

9 LIST OF PUBLICATIONS

Journals

SOVJÁK, Richard, Marie TICHÁ and Eva FRIDRICHOVÁ. The Volumetric Method Describing the Life Cycle of Power Tools during Their Production with Different Ends of Life. *Sustainability*. 2022, **14**(3). ISSN 2071-1050. Available on: doi:10.3390/su14031498

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SOVJÁK, Richard. Studying Knowledge about Eco-design Tools at Department of Industrial Design, Brno University of Technology. *GRANT Journal.* 2017, **5**(1), 72-75. ISSN 1805-0638.

Conference Abstracts

SOVJÁK, Richard. Volumetric Methodology for the Determination of CO_2 Emissions and Energy Requirements for the Production of Products at the Early Stage of Product Design. In: *NORDSCI Social, Sciences Conference July 17 – 19 2018*. Helsinki, 2018.

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11 LIST OF SYMBOLS AND ABBREVIATIONS

11.1 List of Used Abbreviations

3D	3 Dimension
AB	Aktiebolag
ABS	Acrylonitrile Butadiene Styrene
ACLONDS	Activities Criteria Lifecycle phases Outcome Design Strategies Structure
AG	Angle Grinder
alpha-value	Significance level
BR	Brazil
BS	Belt Sander
BUT	Brno University of Technology
CAD	Computer Aided Design
CM	Combustion
CN	China
CO_2	Carbon Dioxide
CS	Circular Saw
CT	Computed Tomography
CZ	Czechia (Czech Republic)
EC	Electric Chainsaw
EE	Estonia
EIA	Environmental Impact Assessment
EMS	Environmental Management System
EoL	End of Life
EP	Electric Planer

EPDM	Ethylene-Propylene-Diene Monomer Rubber
ERPA	Environmentally Responsible Product Assessment
etc.	et citera
EU	European Union
EuP	Energy Using Products
EUR	National Currency of the EU
GF	Glass Fibres
HD	High Definition
HDPE	High-Density Polyethylene
HJ	Handle Jigsaw
IMID	Institute of Machine and Industrial Design
IN	India
IO	Input Output
IOA	Input Output Analysis
ISO	International Organization for Standardization
JP	Japan
KEPI	Key Indicators of Environmental Performance
KHT	Kungliga Tekniska Högskolan
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LF	Landfilling
LiDS	Lifecycle Design Strategies
max.	maximum
MECO	Materials Energy Chemistry Others
MET	Material Energy Toxicity

min.	minimum
MRI	Magnetic Resonance Imaging
MS	Microsoft
OPM	Oil Point Method
OS	Random Orbital Sander
PA6	Polyamid 6
PA66	Polyamid 66
PB	Polybutadiene
PBT	Polybutylene Terephthalate
PC	Personal Computer
PCB	Printed Circuit Board
pcs.	pieces
PD	Percussion Drill
PDA	Personal Digital Assistant
PE	Polyethylene
PET	Polyethylene Terephthalate
PL	Poland
PMMA	Polymethyl Methacrylate
POM	Polyoxymethylene/Polyacetals
PP	Polypropylene
PU	Polyurethane
p-value	Probability Value
PVC	Polyvinyl Chloride
R^2	Correlation Between the Two Variables
RC	Recycling
RS	Reciprocating Saw

R-lists	Risk lists
RMIT	Royal Melbourne Institute of Technology
RoHS	Restriction of the use of Hazardous Substances
r_{xy}	Correlation Coefficient
SE	Sweden
SLF	Standard Logistic Function
SS	Sheet Sander
STL	Stereolithography
TPE	Thermoplastics Elastomer
TPI	Toxic Potential Indicator
TQM	Total Quality Management
TR	Turkey
t-Test	Student's t-test (Statistical Test)
UK	United Kingdom of Great Britain and Northern Ireland
US	United States of America
USD	United States Dollar
VBA	Visual Basic for Applications
VEME	Volumetric Evaluating Method for Ecodesign
WEEE	Waste Electrical and Electronic Equipment

11.2 List of Used Units

bar	metric unit of measurement for pressure
g	gram
$g\ CO_2\ eq.$	carbon dioxide emission equivalent in gram
$g\ CO_2\ eq./kWh$	carbon dioxide emission equivalent in gram per kilowatt
g/m^2	grams per square metre

h	hour
J	Joule
kg	kilogram
kg CO_2 *eq.*	carbon dioxide emission equivalent in kilogram
kg CO_2 *eq./kWh*	carbon dioxide emission equivalent in gram per kilowatt
km	kilometre
kWh	kilowatt hour
l/min	litre per minute
mg	milligram
MJ	megajoule
ml	millilitre
mm	millimetre
OP	Oil Point
OP/kg	Oil Point per kg
OP/m^2	Oil Point per square metre
ton CO_2 *eq.*	carbon dioxide emission equivalent in ton (1,000 kilogram)
W	Watt

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13 LIST OF TABLES

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Appendix B (Summary of power tools parts) 289 p.

Appendix C (Summary of LCA – Landfilling, Combustion, Recycling 90% & Turning Point) 441 p.

Appendix D (Summary of main properties of power tools) 3 p.

Appendix E (Web interface of VEME method) 1 p. “source of background image [66]”

APPENDIX D

#	Alias	Product	Model	Weight (g)	Volume (ml)	Power (W)
1	OS	BOSCH	PEX 270A	1,640.9	1,395	270
2	OS	ProStar	ESM 4201	2,005.5	1,602	420
3	OS	Makita	B05010	1,158.3	946	220
4	OS	PowerTec	_	1,857.4	1,717	420
5	OS	Pattfield	_	1,840.1	1,609	430
6	OS	BOSCH	PEX 115 A	1,338.0	1,262	190
1	SS	NOELI	E0007	1,023.7	1,453	135
2	SS	SKIL	660H1	1,450.9	1,711	150
3	SS	BOSCH	PSS 23	1,292.6	1,410	150
4	SS	_	PTSS 150	1,128.8	1,331	150
5	SS	Ferm	VM-150	1,224.0	1,518	150
6	SS	Einhell	BSS 150	1,175.1	1,602	150
7	SS	BOSCH	PSS 230	1,685.6	1,561	150
8	SS	BOSCH	PSS 23A	1,351.1	1,598	150
9	SS	PARKSIDE	PMFS 200 B2	1,220.9	1,216	200
10	SS	PARKSIDE	PSS 250 C3	1,426.2	1,615	250
11	SS	ProfiTools	_	1,142.8	1,527	135
12	SS	SKIL	7300 H1	1,350.6	1,717	150
13	SS	AEG	VS 230	1,626.3	1,648	150
14	SS	PARKSIDE	PHS 160 ES	882.5	982	160
15	SS	METERK	TS 002	825.6	838	125
16	SS	FLEX	MS 713	1,139.8	920	220
1	EP	AEG	H 500	2,498.2	2,818	500
2	EP	HOLZ-HER	2310	2,363.2	1,958	600
3	EP	WORX	WX623.1	3,146.7	2,805	950
4	EP	SKIL	2310	2,175.6	1,921	400
5	EP	hanseatic	H-HO 82-600	2,516.7	2,079	600
6	EP	SKIL	91H1	1,871.2	1,616	400
7	EP	Ferm	PPM1009	2,562.3	2,116	650
8	EP	T.I.P.	EH618	2,420.4	2,217	600
9	EP	CMI	C-HO 82-600	2,505.7	2,356	600
1	HJ	AEG	STS 380	1,747.0	1,205	380
2	HJ	BOSCH	PST 54 PE	1,907.3	1,333	380
3	HJ	KINZO	72179	1,181.0	963	350
4	HJ	Black & Decker	KS688E	1,747.7	1,434	500
5	HJ	BOSCH	PST 700 E	1,588.4	1,087	500
6	HJ	Kress	6250E	1,935.7	1,257	500
7	HJ	meister	BPS 750 L	2,166.8	1,377	750
8	HJ	hanseatic	H-ST 500E	1,823.8	1,216	500
9	HJ	Black & Decker	BD 547 E	1,902.0	1,431	480
10	HJ	Ferm	FJS-600N	2,063.0	1,612	600
11	HJ	Black & Decker	KS 656PE	1,670.0	1,519	450
12	HJ	TESCO	FC710J	2,073.7	1,474	710
13	HJ	PARKSIDE	PPHSS 730 SE - KH 3021	2,629.9	1,555	730

14	HJ	Bruder MANNESMANN	12884	1,939.1	1,288	710
15	HJ	Black & Decker	KS888E	1,701.4	1,361	500
16	HJ	CMI	C-ST 570P	1,868.7	1,294	570
17	HJ	UNIROPA	6260 E	1,885.0	1,124	400
18	HJ	BOSCH	PST 55-PE	1,893.0	1,335	380
19	HJ	SKIL	4275H1	1,817.4	1,201	450
20	HJ	Ferm	JSV-650P	1,882.1	1,269	570
21	HJ	SPARKY	TH 60 E	1,733.4	1,264	500
22	HJ	AEG	STEP 600 X FIXTEC	2,098.6	1,427	600
23	HJ	_	_	2,021.0	1,284	850
24	HJ	AEG	STSE 400 A	1,710.5	1,176	400
1	BS	King Craft	KCB 720	2,845.0	2,876	720
2	BS	Ferm	FBS-800	2,601.6	3,225	800
3	BS	narex	_	2,842.0	2,926	800
4	BS	_	_	3,163.8	3,297	800
5	BS	ETAtool	RBP 900	3,173.2	3,494	900
6	BS	Black & Decker	H1B	2,013.4	2,477	500
7	BS	PARKSIDE	PBSD 600 A1	2,199.8	2,403	600
1	PD	AEG	SB2E 13 RL	2,559.7	1,374	450
2	PD	narex	_	2,084.9	1,067	550
3	PD	BOSCH	CSB 650-2RE	2,280.1	1,254	650
4	PD	LFG	LF-6525K	1,583.8	946	500
5	PD	CM	C-39500P	1,539.5	1,008	500
6	PD	Black & Decker	KD664RE	1,529.8	951	500
7	PD	HILTI	TE 2-M	2,534.0	1,587	650
8	PD	Kress	SBLR 2365TC	1,738.0	1,122	650
9	PD	PARKSIDE	PSBM 500 C4	1,566.1	1,003	500
10	PD	AEG	SBE 630 R	1,572.9	971	630
11	PD	BOSCH	CSB 400-E	1,690.0	1,061	400
12	PD	_	_	1,781.6	1,035	500
13	PD	DeWALT	D250T3	2,277.9	1,269	650
14	PD	WURTH	H24-MLE	2,710.2	1,654	620
15	PD	BOSCH	PSB 500 RE	1,775.4	968	500
16	PD	Powerforce	Z1JE-KZ11-13B	2,046.5	1,372	1,050
17	PD	Tech power	GW 13	1,586.5	944	500
1	CS	Black & Decker	KS865N	3,308.6	2,755	1,300
2	CS	FERM	FKS-165	3,456.2	2,204	1,200
3	CS	Inspira	IN-1210	3,869.1	2,869	1,200
4	CS	hanseatic	PSC160D	3,200.4	2,110	1,200
5	CS	Black & Decker	DN57/D21	2,879.7	1,469	800
6	CS	O.K.	HKS 185	4,107.2	2,845	1,200
7	CS	Asist	AE5KR120N	3,028.5	2,487	1,200
1	AG	narex	EBU 13	1,956.6	1,002	800
2	AG	FLEX	L 3709/125	1,937.7	941	800
3	AG	_	_	5,170.4	2,366	2,000
4	AG	FERM	FAG-125N	2,294.3	1,082	880
5	AG	FERM	FAG-125/950	1,914.3	1,058	950
6	AG	_	_	1,927.6	943	750

7	AG	PRO Work	PWS 125/850-2	2,033.9	1,082	850
8	AG	BOSCH	PWS 720-115	1,550.5	915	720
9	AG	MATRIX	AG 1100	2,010.2	1,137	1,100
10	AG	Budget	BWS 1155	1,549.0	770	500
11	AG	Black & Decker	KG 10	1,814.6	842	650
12	AG	Kawasaki	K-AG 800-2	1,732.9	985	800
13	AG	Basictool	BWS 125/850-2	1,929.1	1,052	850
14	AG	DeWALT	DS81111-QS	2,029.1	964	850
15	AG	DeWALT	DS23132-Q	1,988.9	998	1,200
16	AG	KINZO	72193	1,226.5	757	500
17	AG	BOSCH	PWS 750-125	1,606.0	916	750
18	AG	Ferm	FAG-115N	1,782.9	943	710
19	AG	PARKSIDE	PWS 125 B2	2,497.2	1,291	1,200
20	AG	PARKSIDE	PWS 125 D3	2,159.9	1,335	1,200
21	AG	HITACHI	G 23ST	4,348.5	2,453	2,000
22	AG	NOELI	E0020	4,640.7	2,467	2,000
23	AG	Ferm	FAG-230/2000	4,055.7	2,355	2,000
24	AG	Ferm	AGM1029 - FDAG-2000	4,997.5	3,011	2,000
25	AG	narex	EBU 12	1,938.5	857	750
26	AG	Einhell	GWS 115-2	1,516.0	839	500
1	EC	McCULLOCH	Electramac 16E	3,109.1	2,414	1,600
2	EC	BOSCH	GKE 40 BC	3,673.8	3,791	1,600
3	EC	DOLMAR	ES 3	3,578.7	4,047	1,400
4	EC	Einhell	REK 2040 WK	3,962.1	4,840	2,000
5	EC	SACHS-DOLMAR	260	2,031.9	2,027	1,050
6	EC	STIHL	E 14	3,453.5	3,140	1,400
7	EC	DOLMAR	ES-33A	3,726.5	3,975	1,800
8	EC	McCULLOCH	Electramac 35ES	3,373.2	3,009	1,400
9	EC	DOLMAR	ES-38A	3,494.5	3,348	1,800
10	EC	ASGATEC	KS 1800	4,800.9	4,104	1,800
11	EC	PARTNER	ES2014	3,730.2	4,531	2,000
12	EC	florabest	FKS 2200 G4	4,244.0	4,930	2,200
13	EC	ATIKA	KS 2001/40	4,520.5	5,304	2,000
14	EC	ATIKA	KS 1800/35	3,686.1	4,292	1,800
15	EC	PARTNER	P 1640	3,565.1	4,755	1,650
16	EC	King Craft	KSI 2000	3,972.9	5,530	2,000
1	RS	King Craft	KMS 710 E	4,030.4	2,641	710
2	RS	ProStar	PMS6000	3,284.3	2,468	600
3	RS	King Craft	KMS 600 E	3,312.7	2,382	600
4	RS	BOSCH	PFZ 550 PE	2,990.4	2,234	550
5	RS	CMI	C-ESS-800	2,114.1	1,573	800
6	RS	Pattfield	_-850SA	2,468.8	1,947	850

APPENDIX E

VEME Volumetric Evaluating Method for Ecodesign

Input Data for Environmental Calculation
Power Tools Category

Volume of Power Tool	1000	ml (millilitres)
Emission Allowances	100	EUR (ton CO_2 eq. per kWh)
Pieces on the Market	1	pc./pcs.
Type of Power Tools	Random Orbital Sanders	
Optimalised Design	0% Volume Cut Off	
Location of Emissions	CZ	

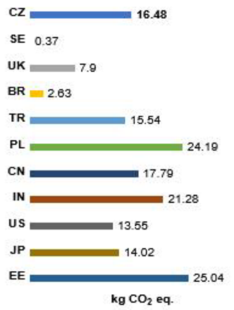
Energy for Production
(1 pc.)

Landfilling	Combustion	Recycling 90%
106.9 MJ / 29.8 kWh	93.8 MJ / 25.7 kWh	92.1 MJ / 25.3 kWh

Amount of Emissions for Production
(1 pc.)

Landfilling	Combustion	Recycling 90%
15.14 kg CO_2 eq.	13.25 kg CO_2 eq.	12.84 kg CO_2 eq.

Amount of Emissions per Country
(1 pc.)



Environmental Calculation
(1 pcs.)

Landfilling	Combustion	Recycling 90%
29.8 kWh	25.7 kWh	25.3 kWh
15.149 kg CO_2 eq.	13.254 kg CO_2 eq.	12.84 kg CO_2 eq.

Price of Emission Allowances
(1 pcs.)

Landfilling	Combustion	Recycling 90%
1.5 EUR	1.3 EUR	1.2 EUR
Δ0 EUR	Δ0.2 EUR	Δ0.3 EUR

Amount of Kilometres Driven by a Vehicle with the Same Emissions
0.1223 kg CO_2/km
(1 pcs.)

Landfilling	Combustion	Recycling 90%
123 km	108 km	104 km
Δ0 km / -0%	Δ15 km / -12%	Δ19 km / -16%

Results for Product Manufacturing in the CZ
(1 pcs.)

Power Tools Average
16.482 kg CO_2 eq.
1.6 EUR
134 km

Energy for Transport 17,000 km, 6.5% from Manufacturing Energy
(1 pcs.)

6 MJ / 1 kWh
0.1 kg Crude Oil
0.1 l Benzine
0.4 kg Coal

Energy for Packaging, 5.5% from Manufacturing Energy
(1 pcs.)

5 MJ / 1 kWh

VEME Method (Dissertation Thesis) for Evaluating Environmental Impacts of Power Tools was developed at the Brno University of Technology, Faculty of Mechanical Engineering, Institute of Machine and Industrial Design (2021)