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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

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ABSTRAKT

Emise kg CO_2 eq. vznikají v různých fázích životního cyklu výrobků a mají významný vliv na globální oteplování. Metoda určená k posouzení těchto negativních vlivů je analýza Life Cycle Assessment (LCA), která umožňuje určit uhlíkovou stopu a 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 využívá objemových vlastností výrobku a jeho strukturálních a materiálových 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 a LCA analýzou založenou na Oil Point Method (OPM). Nářadí bylo posuzováno ve 3 možných fázích konce životního cyklu (skládkování, spalování, 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 10 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

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 and energy requirements of materials production, manufacturing process, transport, use, and end of life (EoL). These analyses are time-consuming, costly to train, and require mass and material characterization of products.

The proposed VEME 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 and LCA analysis based on Oil Point Method (OPM). Tools were evaluated in 3 possible EoL phases (Landfilling, Combustion, 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, kg CO_2 emissions eq. (for 10 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

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.* Brno, 2021, 169 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 [24]. 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 [1, 10].

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 [4, 24]. 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]

Today's era requires meaningful management of raw materials, but also their reintegration into raw material resources for their further use. The requirements for the economic use of materials with the aim of reducing negative environmental impacts (eco-design) are embedded in the Kyoto Protocol and EU Directives 2009/125/EC, 2006/121/EC (REACH), the WEEE Directive [70] 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 the 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 the kg CO_2 eq. emissions in three End of Life stages (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/optimization, recycling and production optimization due to the increasing prices of emission allowances in the EU [64].

2 CURRENT STATE OF THE KNOWLEDGE

2.1 Using Eco-Design Tools in Industrial Design

[1] **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.

Results

The results present the role of industrial designers and design engineers in the product design process. Industrial design is described as user-centred as opposed to design engineers who have a technological orientation. According to eco-design theory, an industrial designer should have the same knowledge as a structural engineer. Figure (Fig. 2-1) shows the skills and differences between these professions.

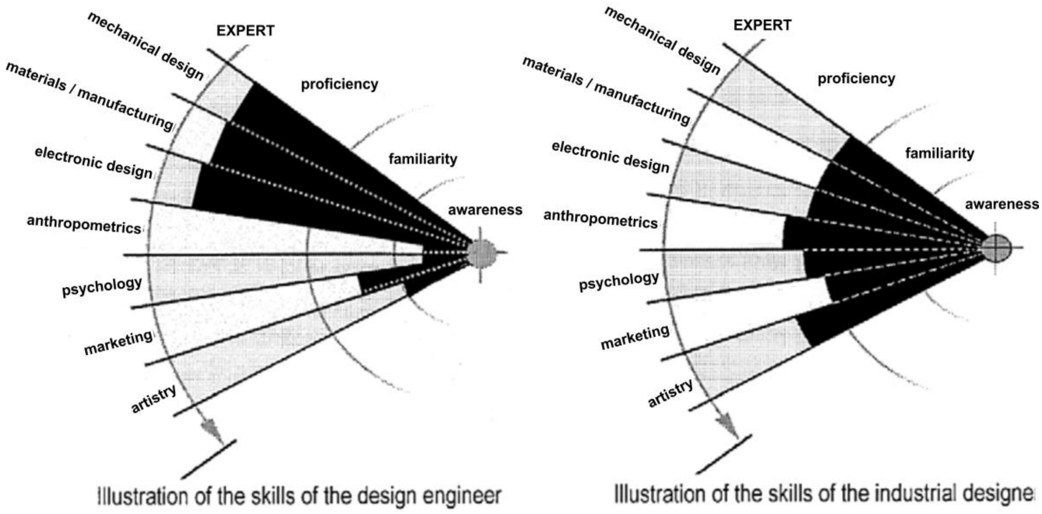


Fig. 2-1 Skills of an industrial designer and design engineer [1].

Requirements of industrial designers focused on eco-design:

- Design trends,
- appropriate application of materials,
- details on new types of joining elements,
- description of how the product works and its requirements,
- details of material properties and distribution,
- assembly descriptions,
- transportation and storage of products,
- where and how the product was made,
- where the product will be sold.

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.

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

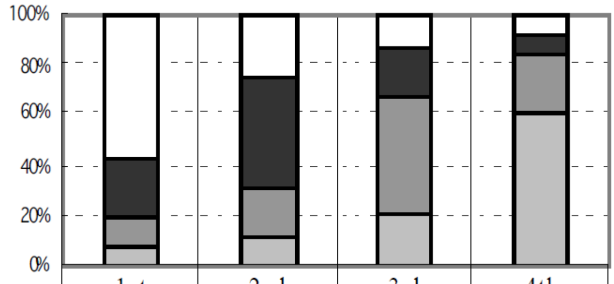
Results

The definition of eco-design was carried out with the help of experts from the EU. The questions were sent to 19 large companies in Japan, where 197 designers worked, and another 70 independent designers.

Research questions:

- Designer attitudes towards environmental issues,
- what are the principles of eco-design, can they be characterised,
- how the process should be characterised from the designers' point of view,
- do you integrate eco-design into products, have you encountered a barrier in design.

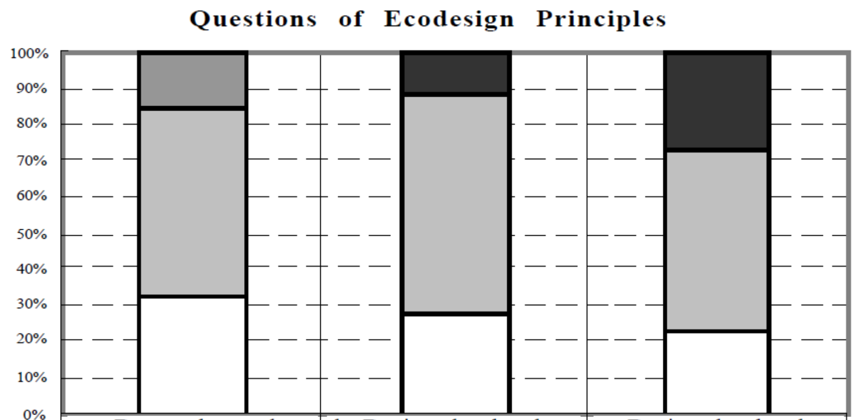
a. What do you consider the most important factors for solution of present environmental problems?



	1st	2nd	3rd	4th
1. Socio-cultural	14%	6%	3%	2%
2. Economic	6%	12%	5%	2%
3. Technology	3%	5%	11%	6%
4. Conserve the Nature	2%	3%	5%	15%

Fig. 2-2 Points of interest for industrial designers [10].

The results show a lack of knowledge of the basic tools of eco-design: in 72% ISO 14001 (regulation of recycling of electrical and electronic equipment) and a significant LCA methodology in 77%, see (Fig. 2-3). The 23 designers out of 197 interviewed worked in the field of eco-design.



	a. Do you know the meaning of Sustainable Development?	b. During the develop. stage of product do you use the ISO 14001?	c. During the develop. stage of product do you use the LCA?
Not answer	16%	0%	0%
I don't know	0%	11%	27%
No	51%	61%	50%
Yes	33%	28%	23%

Fig. 2-3 Industrial designers and knowledge of eco-design principles [10].

Conclusions

The research presents the preferences and attitudes of designers towards eco-design. The socio-cultural principles are preferred over the technological aspect, see (Fig. 2-2). 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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[27] **SOVJÁK, Richard**. Studying Knowledge about Eco-design Tools at Department of Industrial Design, Brno University of Technology. *GRANT Journal,* 2017, vol. 5, no. 2, p. 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.

Results

The results of the research were recorded by year of study and also by study program.

Research questions with Yes/No answers:

Q1. Are you familiar with eco-design tools?

Q2. Do you use LCA (product/service life cycle analysis) tools?

Q3. Do you know what the ISO 14000 set of standards is used for?

Q4. Would you like to design products that comply with eco-design rules?

Q5. Do you know the difference between qualitative and quantitative approaches in product life cycle assessment?

Q6. Would you be able to create an LCI (inventory analysis) of a service or product?

Q7. Should an industrial designer have knowledge of LCA (product life cycle assessment)?

Q8. Would you like to gain knowledge of LCA while studying at the BUT IMID?

Q9. Would you like to know the environmental impacts (energy requirements for product production and carbon footprint of products) of your designs at an early stage of product design?

Q10. Are ecodesign requirements reflected in greendesign compliant products?

Free-response research questions with a maximum of three data points:

Q11. List three ways in which the environmental impacts of products and services can be reduced.

Q12. Name one LCA software tool.

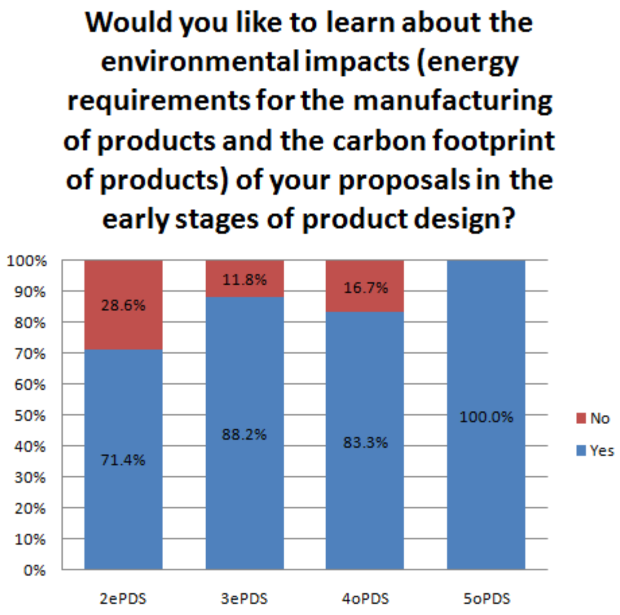

Fig. 2-4 Chart of LCA knowledge requirements for IMID students, Q9 [27].

According to the students' results of the answers of the students of each year to Question Q1 (Do you know eco-design tools?), the highest proportion of agreeing answers was recorded in the final years, around 18%. In question Q9 see (Fig. 2-4) that they would like to get information about the impacts of their products at an early stage of design. As the level of education increases, the interest in this information increases to 100%. According to the agreeing answers to Q7-Q9 questions, see (Fig. 2-5), it is possible to observe the overall interest in LCA issues and energy requirements for production including kg CO_2 eq.

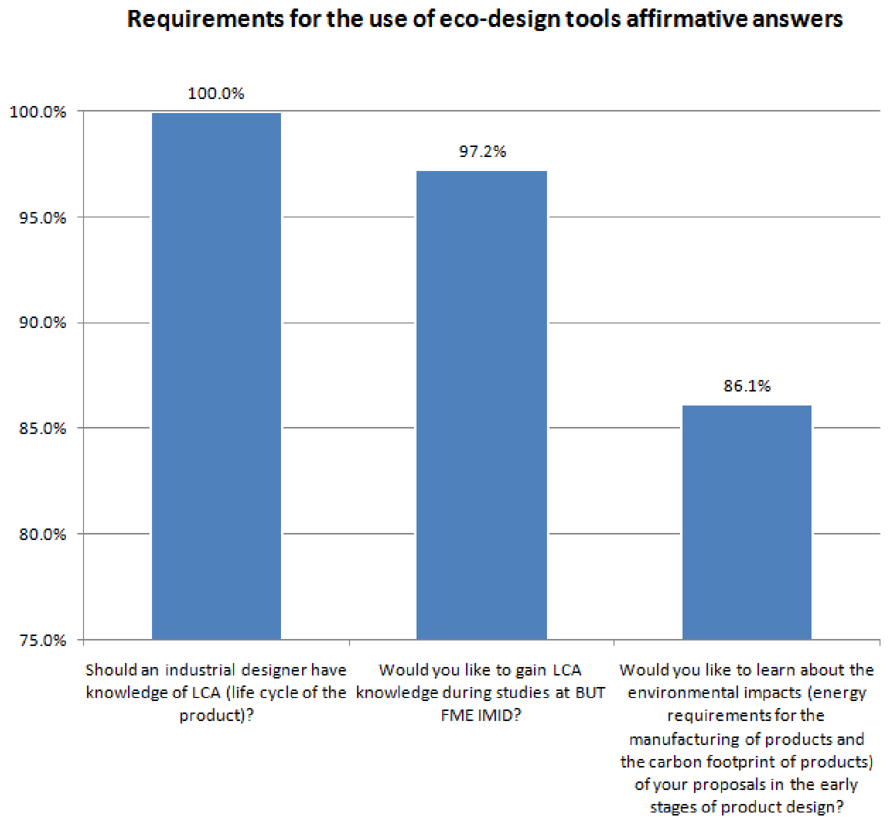

Fig. 2-5 Graph of student requirements for LCA, affirmative responses, Q7-Q9 [27].

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 [1] *"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.

Results

The work shows the results of long-term research and data collection, to which new designers and professionals in the fields of design and eco-design have contributed. A comprehensive eco-design tool must incorporate all the elements listed in the holistic framework; see (Fig. 2-6). This solution includes the LiDS Wheel, EcoWeb methodologies and the requirements of WEEE, RoHS, EuP, and Packaging and Packaging Waste regulations. A summary of all requirements has been incorporated into the web interface "Information/Inspiration" available at http://ecodesign.lboro.ac.uk/ to provide sufficient information for the application of eco-design by designers.

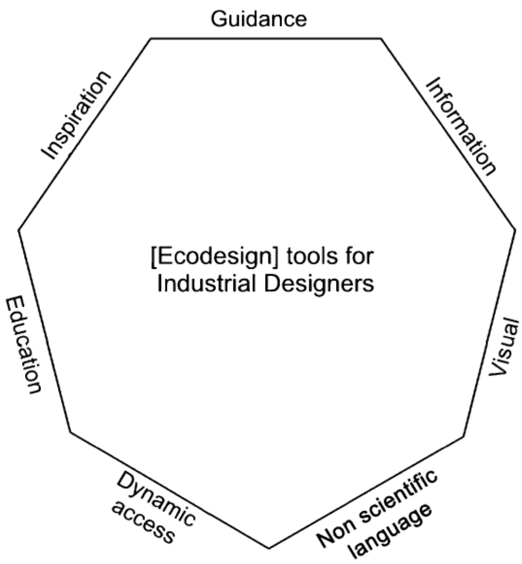

Fig. 2-6 A holistic framework of eco-design tools for industrial design [3].

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, see (Fig. 2-6), which are further detailed in the research.

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[14] **KOTA, Srinivas and Amaresh CHAKRABARTI**, 2011. ACLODS – A holistic framework for environmentally f riendly product lifecycle design. In: *Global Product Development*. Berlin, Heidelberg: Springer Berlin Heidelberg, s. 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, see (Fig. 2-7). Data are collected and compared in a percentage bar chart at each stage with the given factors.

Results

The result of the work is the development of an application framework that assesses 0% to 100% of environmental friendliness in existing eco-design tools. It aggregates the categories according to each attribute into framework groups, which are then used to create the ACLONDS application framework.

For the phases of the ACLONDS application framework, see (Fig. 2-7):

- Builder/designer activities (editing, selection, solution, etc.),
- criteria (quality, waste, recycling, weight, legislation, economics, etc.),
- life cycle (use, end of life, etc.),
- results (modification, rejection, acceptance),
- construction/design (conceptual design, purity of form, ...),
- structure (assembly, disassembly, parts, etc.).

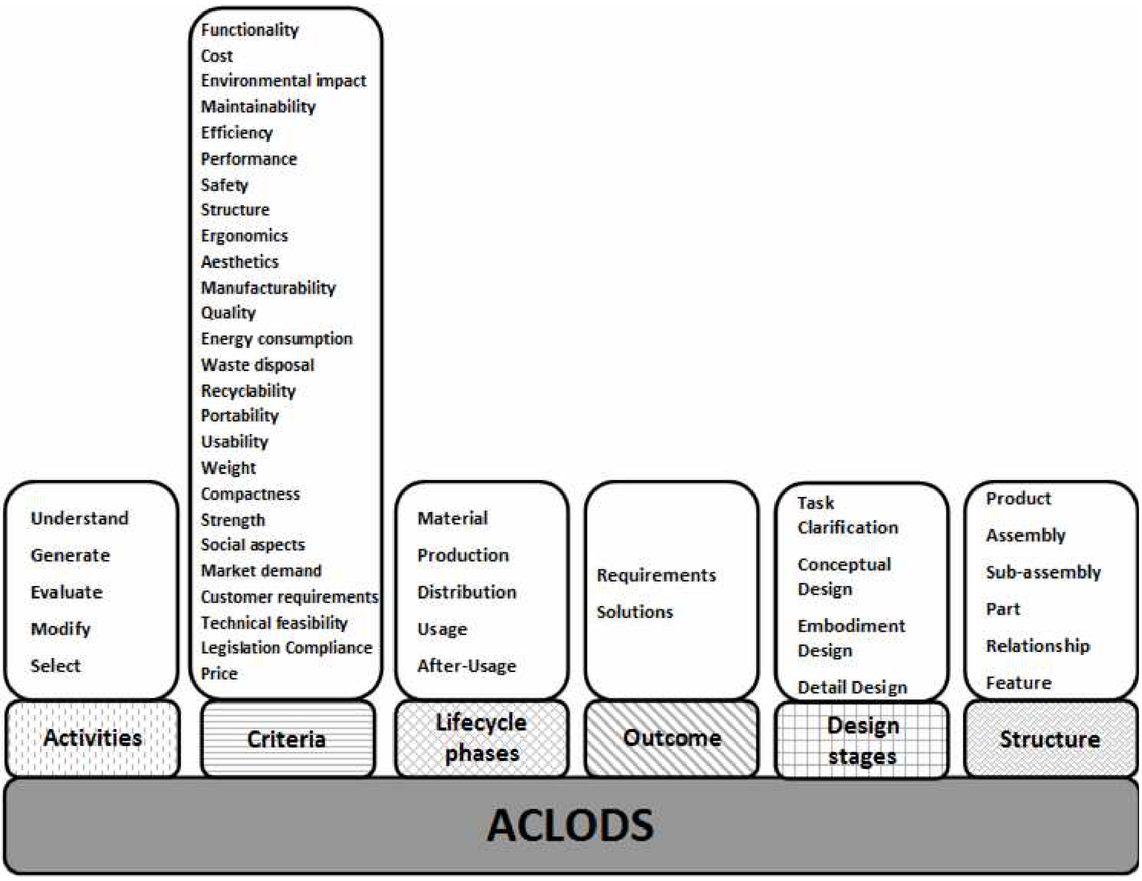

Fig. 2-7 Diagram of the ACLODS application framework [14].

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.

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[15] **IAN, Thomas**, 2016. 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 LCA analysis. The visualised LiDS Wheel eco-design tool see (Fig. 2-8) is based on a qualitative approach to environmental issues and provides concrete solutions.

Results

The information summarised in the learning interface is used to help students understand environmental management. It summarises the basic principles of clean production and focuses on the sustainable development of raw material resources. One of the methodologies featured is the LiDS Wheel method, which allows the comparison of the life cycle of both old and new products with impact intensity indicated through eight parameters that correspond to the intensity on each axis of the diagram.

For the breakdown of the different groups in the LiDS Wheel method, see (Fig. 2-8):

0-new development concept,

1-low impact,

2-reduction of material consumption,

3-optimisation of production techniques, 4-optimisation of the distribution system,

5-reducing the impact of the user phase,

6-optimization of initial lifetime,

7-optimization of end of life.

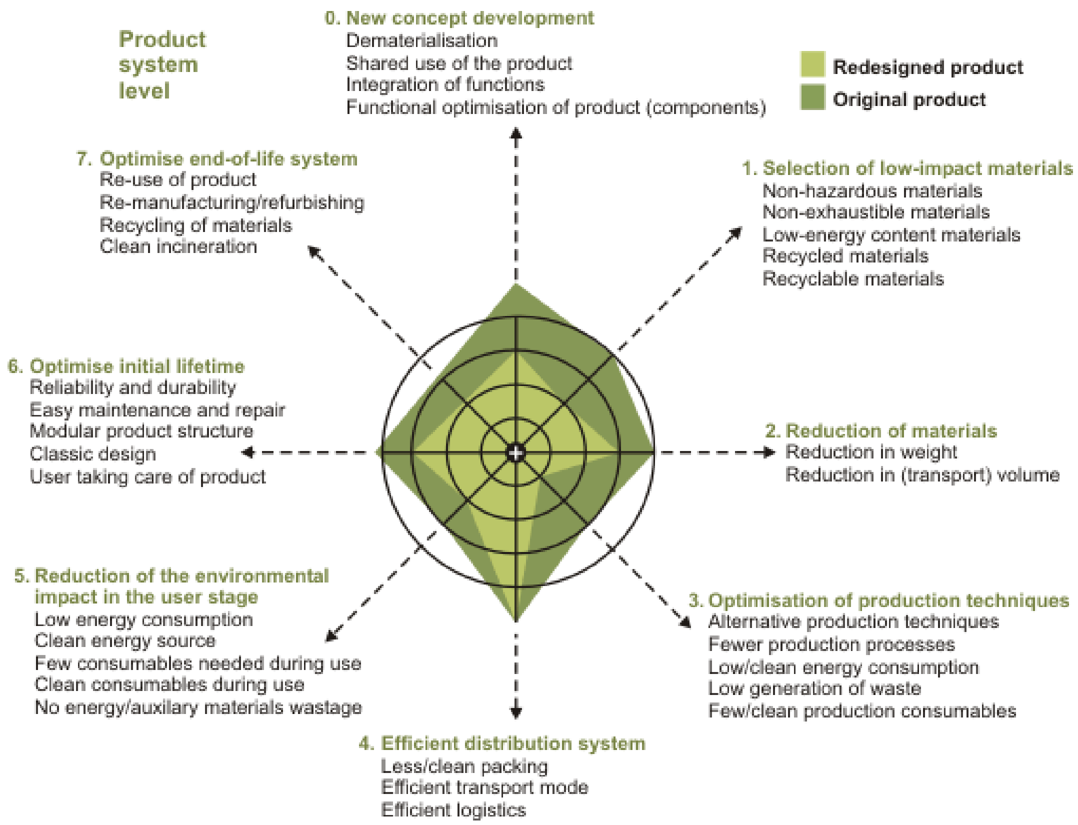

Fig. 2-8 LiDS Wheel [15].

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.

[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.

Results

The tool was developed to facilitate the implementation of sustainable product development (eco-design rules) in a multidisciplinary professional environment. The methodology combines many regulations into a coherent solution that can be applied in a corporate environment such as Bombardier. The tool includes the "10 golden rules of eco-design" see (Fig. 2-9), which is used at an early stage of design or to compare existing products. The output is qualitative information that can be used to make specific changes in the product life cycle.

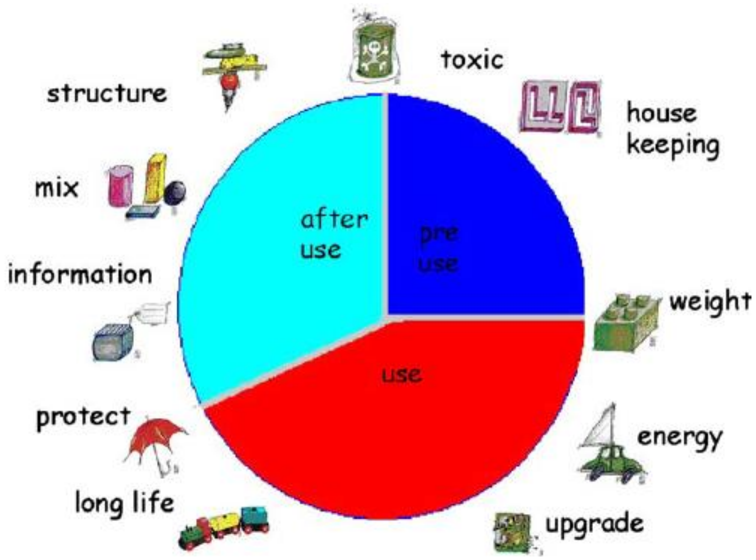

Fig. 2-9 Pie chart of the 10 Golden Rules [16].

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.

Results

The result of the work is the establishment of a procedure for a successful solution for the production of electrical equipment. The methodology was verified on a product study of a compressor for aquariums, see (Fig. 2-10).

Compilation of the methodology into basic phases:

- Descriptive - defines the problem and seeks a solution using DfA (Design for Assembly), DfM (Design for Maintenance) to increase durability, and DfD (Design for Disassembly) for assembly;
- Development - Analyses ergonomics, structure, function, morphology, marketing, technical solutions, productivity, transport, packaging and historical development;
- Design - once the design and technical solution is resolved, analysis of the impact on the ecosystem;
- Communication - report development and visual support.

The proposed method is able to optimize the number of assembly components in the range of different materials used, the limitations of production systems, and disassembly operations. As a result, the absence of bolted joints, the rectification of internal components using shaped protrusions and the limitation of their quantity and the types of materials used for each component are possible (Fig. 2-11).

Fig. 2-10 Internal design of compressors for aquariums [9].

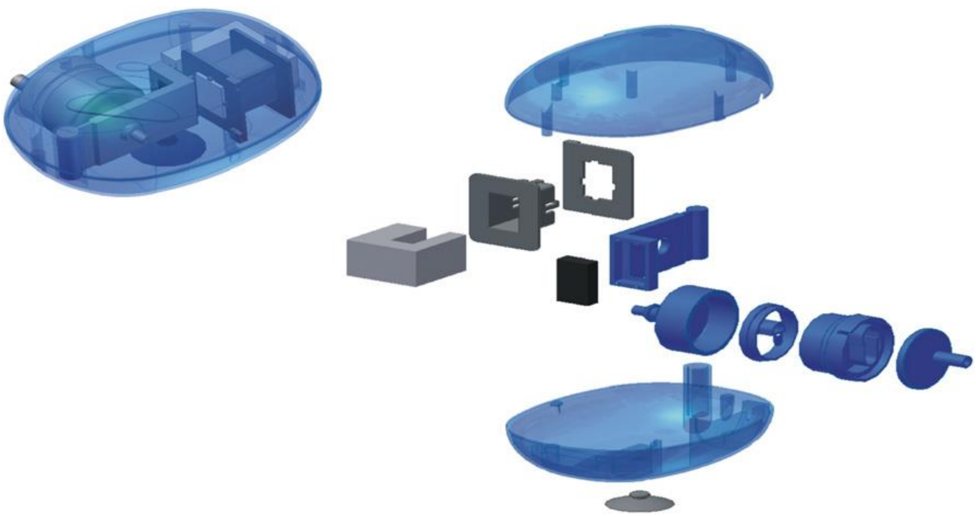

Fig. 2-11 Optimised internal compressor to the aquarium [9].

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

[26] *ISO 14044:2006: Environmental management -- Life cycle assessment -- Requirements and guidelines*, 2006. Switzerland: 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.

Results

LCA provides the most comprehensive and systematic assessment of the impact of a product, service, or system on the environment or on other areas of human interest. The assessment takes into account all stages of the life cycle, from the extraction of raw materials to the disposal of waste back into the ground "from cradle to grave", see (Figure 2-12). In the case of an LCA without the use of an environmental impact assessment, we speak after that of an LCI life cycle inventory analysis. Developing an LCI requires knowledge of manufacturing operations, environmental impacts, material compositions, types of energy input, product usage, recycling scenarios and all affected transportation. [28, 29, 30]

The standard provides guidance and requirements for the assessment of LCA and LCI as follows:

- The objective and scope of the LCA definition,
- Life Cycle Inventory analysis (LCI),
- Life Cycle Impact Analysis (LCIA),
- interpretation of life cycle phases,
- reporting and critical review of the LCA,
- establishing the limitations of LCA,
- the relationship between the different phases of the LCA,
- conditions for the use of values and optional values.

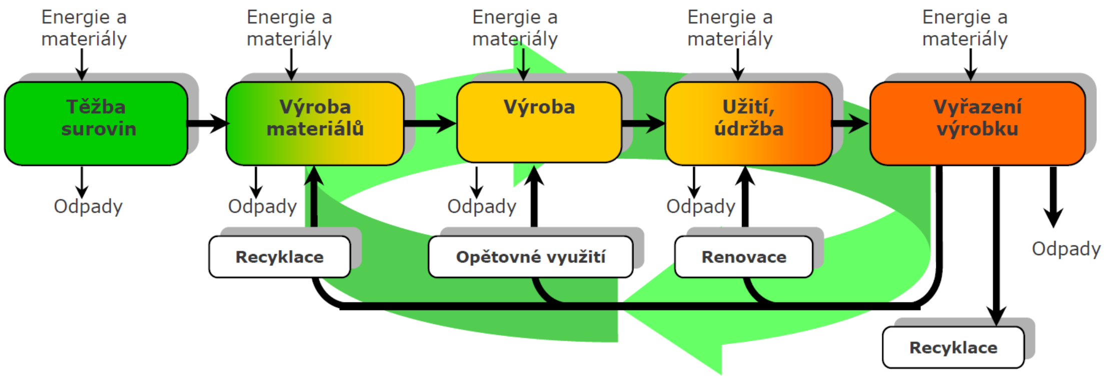

Fig. 2-12 LCA product life cycle diagram [28].

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, Nicki**, 2000. *The Oil Point Method: A tool for indicative environmental evaluation in material and process selection* [online]. Lyngby [cit. 2018-06-09]. Available on: http://polynet.dk/lenau/niki_bey_phd_thesis.pdf. Dissertation thesis. Technical University of Denmark.

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.

Results

OPM relies on the LCA methodology, which uses the combustion of fossil fuels (crude oil, coal, etc.) and gives a comprehensive picture of the environmental impact.

$$1 \textit{ Oil Point (OP)} = \textit{Energy of } 1 \textit{ kg crude oil} = 45 \textit{ MJ}$$

Oil Points are defined according to the methodology for:

- Materials,
- energy (primary energy and processes),
- production processes,
- transport,
- user part,
- end of life (EoL).

The construction of the method followed a three-by-three step approach, namely:

- "Focus" - comparing and assembling the system and functional units,
- "Evaluate" - constructing the life cycle, finding OP indicators, calculation and results,
- "Interpret" - checking the results in context.

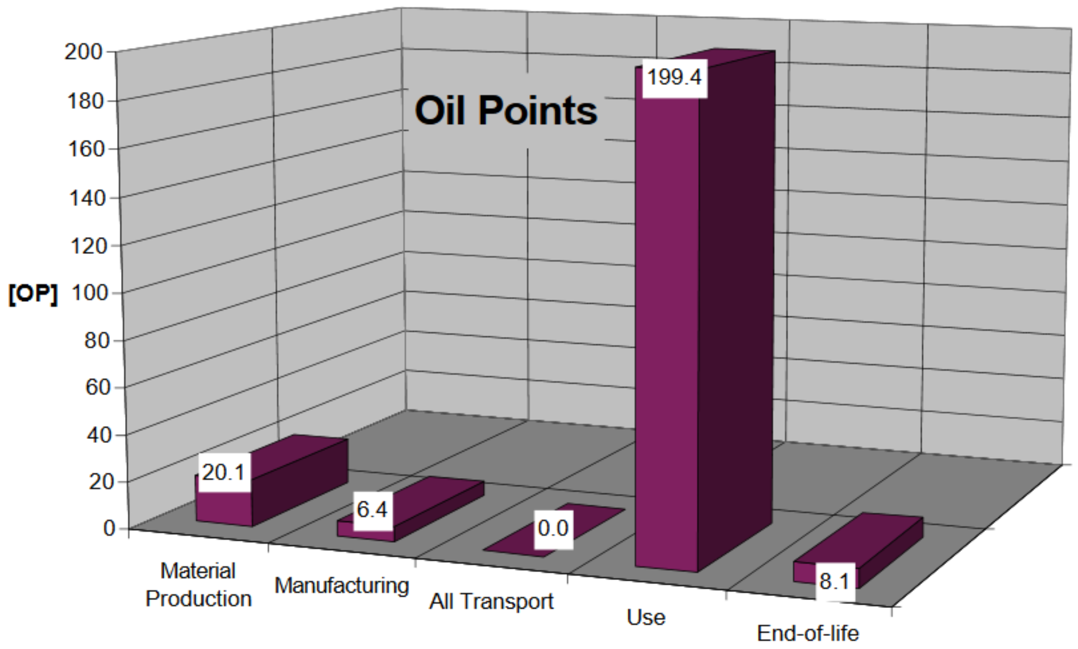

Fig. 2-13 Life cycle according to OP for an electric vacuum cleaner [123].

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, see (Fig. 2-13) 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.

Results

The result of the work is a full life cycle assessment in a military environment with eco-design requirements. Articles published related to the MECO tool were selected from the dissertation. The MECO tool belongs to a simplified LCA with a semi-quantitative approach (part of the results are both quantitative and qualitative due to the quantitative input data). The MECO matrix, see (Tab. 2-1) can be used at any stage of the product life cycle. Materials and energy are included in resource consumption, and environmental impacts are included in the toxicity category. The analysis provides more positive information on toxic substances and other impacts than LCA.

Tab. 2-1 Structure of MECO matrix [18].

	Materials	Manufacture	Transport	Use	Disposal
MATERIALS	•Tree/ fibrous plants •White liquor		•Products (paper) • Transports		•Reuse/Upcycle Combine with other materials
ENERGY	•Machines to chipped and harvested	•Electricity for machines	•Energy for transports	•If use with machine like printer	•Recycle •Transport to landfill
CHEMICALS	•Sodiumsulfide •Caustic soda • Chlorine	•White liquor • Colour to dye the paper			•Recycle: mixture with chemicals
OTHERS	•Workers	•Workers			

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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[19] **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, s. 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.

Results

The KEPI method, see (Tab. 2-2) assesses the three life cycle factors of a product (production, distribution, and use) based on LCA results and evaluates them throughout their life cycle. Indicators that have a significant environmental impact are selected for evaluation. Product comparisons can be made, but assumptions must be met that the products are of the same type and the same technological design (e.g., PDA vs. PDA).

To ensure the effectiveness of the method:

- Provide clear results,
- require a limited amount of data,
- time-saving processing,
- data based on the physical and chemical properties of the product,
- impact assessment results without extrapolation.

Tab. 2-2 KEPI matrix [20].

Phase of the lifecycle	Manufacturing	Distribution	Use
Proposed indicators	• Gold quantity • Area of printed circuit borad x number of layer • Total area of dies (of integrated circuit) • Bromine quantity • LCD screen area • Quantity of solder paste • Copper quantity in charger and cables	• Number of components in the mobile phone	• Energy consumption in sleep mode

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.

[21] **NISSEN, Nils and Karsten SCHISCHKE, 2014**. Environmental evaluation methods: Toxic Potential Indicator (TPI). *Willkommen - Fraunhofer IZM* [online]. [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.

Results

The TPI is an indicator of the environmental impact of the toxic load and is aimed at the material composition of the product and is not intended for a cradle-to-grave product system. In addition, the tool is not intended to assess materials generated during ancillary processes, combustion waste, but the materials used and their aspects. Materials according to the MSDS are mapped with an indicator from 0 (worst) to 7 (best) and then multiplied by the weight of the substance and adjusted to a maximum value of 100. The resulting values are given in TPI/mg of the substance and express the weight over which the toxicity of the substance remains unchanged.

See (Fig. 2-14) for the input values for the calculation of the TPI:

- Maximum Occupational Concentration (MAK),
- carcinogenic classification (may exceed the workplace concentration),
- risk values according to the chemical regulation (R-values),
- Water Pollution Classes (WGK).

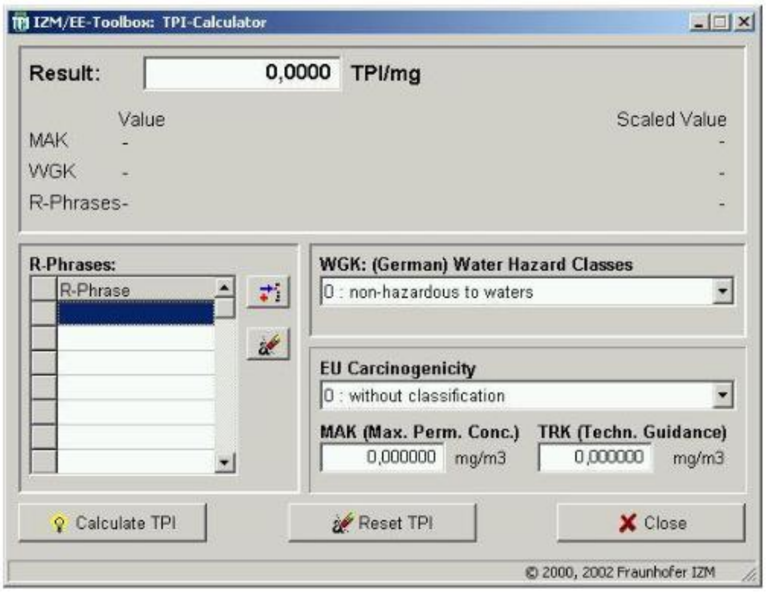

Fig. 2-14 Graphical interface of the assessment software TPI [21].

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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[20] **FROELICH, Daniel and Damien SULPICE**, 2013. ECO-DESIGN TOOLS - Indicators | Eco-3e. *Eco-3e* [online]. [cit. 2016-02-21]. Available on: http://eco3e.eu/wp-content/uploads/kalins-pdf/singles/indicators.pdf

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.

Results

The evaluation method is designed to provide a general assessment of the entire life cycle with qualitative and quantitative results. The MET Matrix tool consists of a matrix see (Tab. 2-3) that assesses the conservation of nature with respect to the life cycle of the product with emphasis on materials, energy and toxicity. The matrix can be used to address environmental issues at any stage of the life cycle, or to validate existing or plan new strategies. A broad knowledge of eco-design issues is required to achieve results, but the advantage is the speed and simplicity of this tool compared to performing an extensive LCA analysis.

Tab. 2-3 MET matrix diagram [22].

MET Matrix	VSTUPY		VÝSTUP
	(M) Materiály	**(E) Energie**	**(T) Toxické emise**
Suroviny & Výroba komponentů (těžba)	>Všechny potřebné materiály, díly a komponenty.	> Spotřeba energie pro získání surovin. > Energie použitá na vyčištění > Energie spotřebovaná na transport materiálů do továrny.	> Toxický odpad při těžbě a zušlechťování materiálu před výrobou.
Tovární výroba (včetně balení & odeslání)	> Pomocné materiály zakoupené (šrouby, elektrické položky atd.) > Další látky používané ve výrobním procesu (tj. předměty pro svařování, malování, atd.)	> Spotřeba energie v procesech používaných ve výrobním závodě.	> Toxický odpad produkovaný v továrně. > Zbytky materiálů: odřezky, zmetky, atd.
Distribuce & Dodavatelský řetězec	> Materiály používané pro balení výrobků. > Prvky obalů používaných pro přepravu a distribuci.	> Spotřeba energie v průběhu zabalování a balení (jsou-li > Doprava z továrny ke konečným distributorů.	> Odpad ze spalování během přepravy. > Odpad z balení.
Používání Používání (normální užívání) a servis (údržba a opravy)	> Spotřební materiál. > Odhadované náhradní díly.	> Energie spotřebovaná výrobkem po celou dobu jeho předpokládané životnosti.	> Odpady z spotřebního > Odpady z náhradních dílů.
End of Life - (EoL) Nakládání s odpady - využití a odstranění	> Spotřeba surovin a pomocných materiálů pro ukončení životnosti.	> Energie použitá ve EoL soustavě pro materiály nebo díly (spalování, recyklace, atd.) > Energie pro dopravu do EoL systémy.	> Toxický odpad vytvářený produkty v EoL. > Odpad ze spalování. > Recyklace & balení materiálů.

The article also considers eco-design from the perspective of disassembly, identifying the individual parts, the forces required for disassembly, the times for replacement, the number of parts, the tools required, etc. The aspects are evaluated and quantified.

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.

[23] **WEINZETTEL, Jan**, 2016. Input output analýza. *Úvod | Databáze vysokoškolských kvalifikačních prací zaměřených na LCA* [online]. [cit. 2016-01-10]. Available on: http://vskp.vsb.cz/oblast-ioa/

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 for each economic sector.

Results

IO analysis is based on the aggregation of input and output data within economic movements for products or services. LCI inventory analysis and LCA analysis are data intensive and focus directly on the product/service. For this reason, it is possible to use IOTs (input-output tables) that contain national pollution emissions. When using IOA in LCA, a Use Matrix and a Production Matrix are first constructed; see (Tab. 2-4). Product-specific rows and columns represent the economic sectors from which the indirect material and energy flows of products will be quantified in monetary units (determining the total energy and material flow requirements for a product during production in the economic sphere). After the defined mathematical adjustments and the substitution of the consumption vector for the product composition, we obtain the required information on pollution.

Meaning of sum vectors:

- t - consumption of the product, intermediate consumption and final consumption,
- q - total domestic production of products (consumption for the production of other products, intermediate products and final consumption),
- g - total output of each economic sector.

Tab. 2-4 Usage Matrix (top table) and Production Matrix (bottom table) [23].

Ekonomický sektor / Produkt	Ekonomický sektor 1	Ekonomický sektor 2	…	Ekonomický sektor n	Konečná spotřeba	Celková spotřeba
Produkt 1					y_1	t_1
Produkt 2			U matice		y_2	t_2
…					$y_{\dots}$	$t_{\dots}$
Produkt n					y_n	t_n

Ekonomický sektor / Produkt	Ekonomický sektor 1	Ekonomický sektor 2	…	Ekonomický sektor n	Celková domácí výroba
Produkt 1					$\sum$řádku = q_1
Produkt 2			M matice		$\sum$řádku = q_2
…					$\sum$řádku = $q_{\dots}$
Produkt n					$\sum$řádku = q_n
Celkové produkce ES	$\sum$ sloupce = g_1	$\sum$ sloupce = g_2	$\sum$ sloupce = $g_{..}$	$\sum$ sloupce = g_n	

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.

Results

The established methodology is compared with two studies: steel fabrication and polymer vacuum forming.

Waste reuse solutions in product design according to the designed phases:

- 1 - waste optimization (shape and value),
- 2 - unavoidable waste (what can be used and what cannot),
- 3 - design with waste (design and assessment of return to production).

The methodology for the recovery of waste elements in metal fabrication for the metal hinge (including caps, plugs, screws, and spacers) shows the positive use of phase two according to the methodology presented. It is possible to proceed to the final phase; see (Fig. 2-15). Recycling the waste to make the hinge will create less pollution than manufacturing in the traditional way (0.4 kg CO_2 eq. versus 0.7 kg CO_2 eq.).

Vacuum tube forming produces ABS waste (from turning) as well as tubes with defects. According to the Phase 1 assessment, the form of the waste and its geometry (chip and debris) are known. After the analysis of phase 2, the possibility of other uses in terms of function, dimension, physical, mechanical, sensory and potential properties (rejects and chips) is identified. From the perspective of the proposed methodology, it is possible to proceed with the reintroduction of waste into the production process.

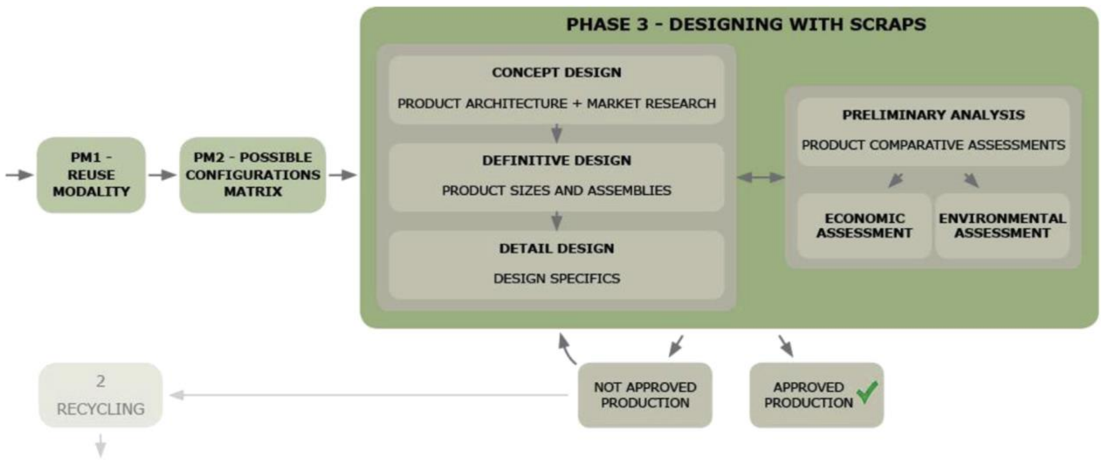

Fig. 2-15 Product design from waste [6].

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.

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[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.

Results

Up to 80% of the environmental impact of pollution has been found to be due to the production of the product. This rule applies to the production of a product without significant energy consumption (user phase). The distribution and pollution of a single product are predictable. When replacing an old product with a new one, there is a 50% increase in emissions assuming an improvement of the original product, see (Fig. 2-16).

The environmental impact matrix is given by the life cycle phases of the product (functions must be independent). The main diagonal of the matrix determines the load kg CO_2 eq.

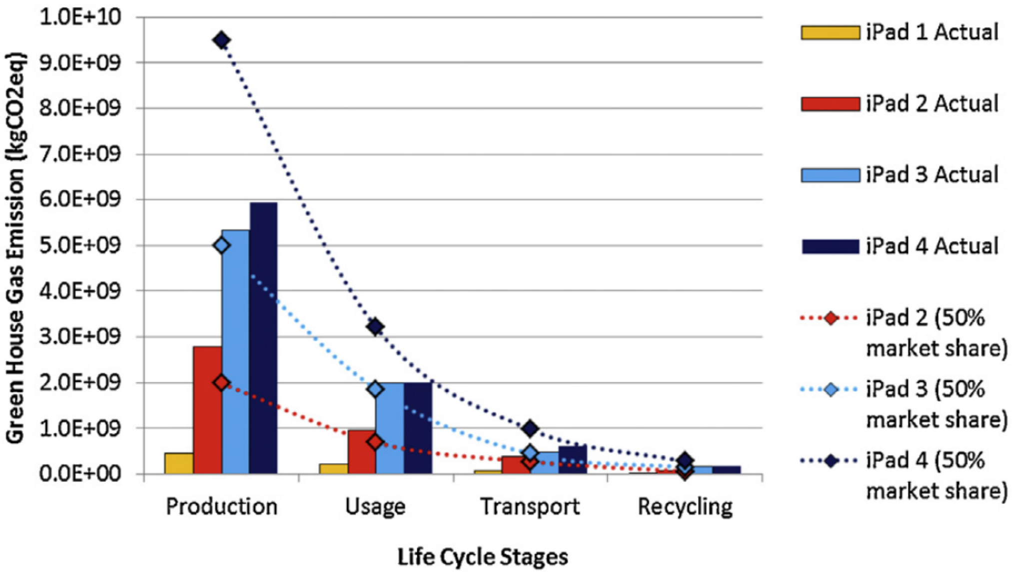

Fig. 2-16 Environmental impact for iPad products [7].

Construction of the environmental impact matrix (units are in emissions kg CO_2 eq.):

- - x_1 ... production (extraction, transport, manufacturing and packaging of the product),
- - x_2 ... use (electricity consumption of three years of intensive use),
- - x_3 ... transport (all transport to the distribution point, including packaging),
- - x_4 ... recycling (transport to collection point, shredding and sorting of material).

$$\text{Environmental impact}_{\text{Product or }FR} = \begin{bmatrix} x_1 & 0 & 0 & 0 \\ 0 & x_2 & 0 & 0 \\ 0 & 0 & x_3 & 0 \\ 0 & 0 & 0 & x_4 \end{bmatrix} \{\text{Production Usage Transport Recycling}\}$$

To predict the total environmental burden, "Environmental impact" was included in the matrix to calculate the total volume of products produced. The calculation was determined according to the SLF methodology, which simulates the growth of the product at time t in a market with an initial share. The market share parameter p, L is the natural limit and b are the scale and shape constants.

$$\text{Volume} = p(t) = \frac{L}{1 + ae^{-bt}}$$

Total environmental impact dependent on the volume of products produced and distributed.

$$\text{Total Environmental Impact(TE)} = PE \times p(t)$$

Conclusions

The research results open up new possibilities for determining the overall environmental impact of products using standard logistic functions (SLFs) 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.

Results

As a result, the MET Matrix is expanded to include the sensory properties of the materials, see (Fig. 2-18). The paper also discusses a methodological approach to identify the most important environmental properties of the material, see (Fig. 2-17). The methodology takes into account the TQM known as ISO 9000/2000, EMS, ISO 14000, ISO 14020 (Ecolabeling Type I-III) labeling of products according to energy performance.

Determination of the nature of the material according to ecological requirements:

- Selection of materials with low environmental impact,
- extending the lifetime of materials,
- ethics and compliance with regulations.

The methodology provides guidance for determining the durability of materials according to their intended use:

- short product lifetime,
- medium lifetime of the product,
- long life of the product.

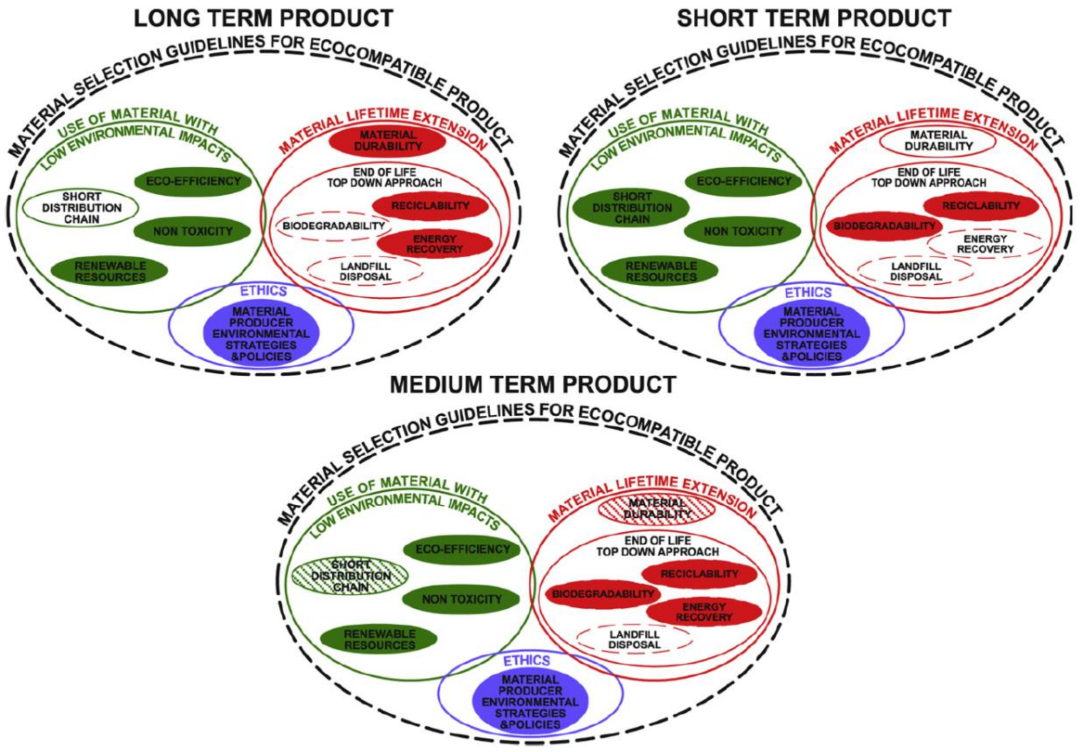

Fig. 2-17 Determining the choice of materials according to the nature of the product [8].

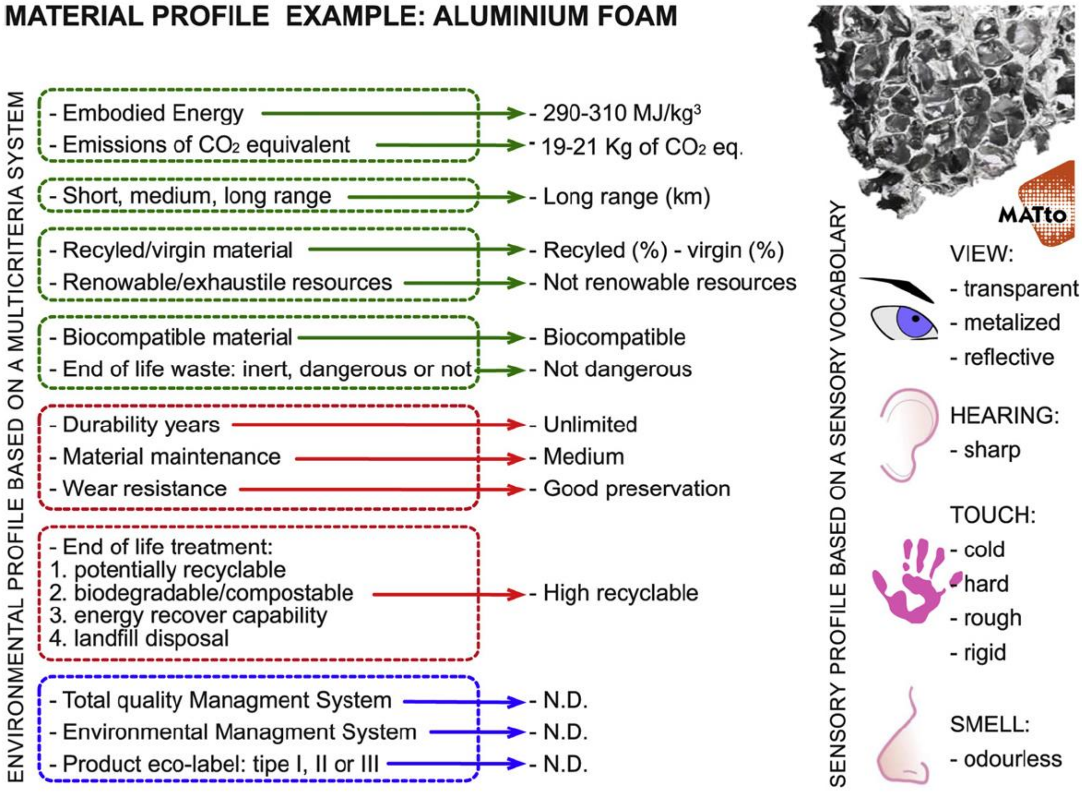

Fig. 2-18 Example of the MATto method with sensory input [8].

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.

Results

The paper analyses and compares the method of checklists "lists", which are widely used, easy to understand and serve as a first introduction to the subject. Solutions using ISO 14062 technical regulations that can be used immediately and, in particular, allow to address possible hazards that arise on the supply chain. The MET Matrix is used to summarize the environmental impact at each stage of the product life cycle. According to research, it is suitable for changes that are made during product design. It can be used with 3D CAD systems. According to this research, see (Fig. 2-19), the LCA methodology "Life Cycle Assessment" is ranked with 5 points on an 8 points scale with a worse user experience, but provides the most comprehensive results.

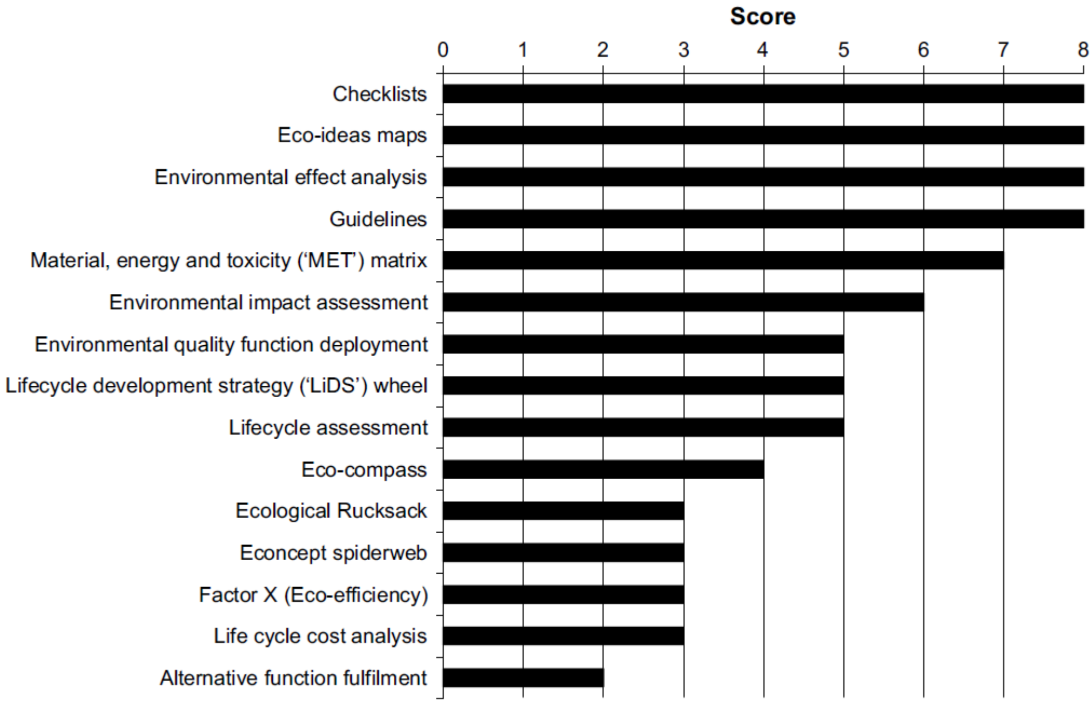

Fig. 2-19 Analysis of the use of eco-design tools [4].

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.

Results

Research hypotheses:

- H1 - does eco-design have a similar structure to traditional design,
- H2 - eco-design activities, finding solutions, and defining strategies are the most important.

According to the research, computer programs for environmental impact assessment are used 25% by consulting companies and 75% by researchers. Personal experience with the programs ranges from one year to fifteen years.

The capabilities of the eco-design tools have been tested on the software see (Tab. 2-5):

- Ecofaire,
- Ecodesign Pilot,
- Information/Inspiration,
- SimaPro 7.0 (LCA methodology).

The structure of eco-design is similar to the traditional designer's approach, as it has the same expert core, and thus hypothesis H1 is confirmed. The research result of hypothesis H2 provides solutions to eco-design problems in the initial or in its final phase with the SimaPro tool, which offers up to 20% more solutions found. Ecofair provides similar results, especially in the initial assessment. The Ecodesign Pilot tool is most suitable for identifying and defining a strategy for subsequent solutions.

Tab. 2-5 Characteristic features of eco-design tools [11].

Name of tool/author/ date published	*Category*	*Language*	*Addressed to*	*Objectives*
ECOFAIRE/SEM Pays de Loire/2008	Guideline	French	Engineering designers, Industrial designers, Research department, Marketing… Teachers, Students.	Introduction to eco-design Diagnosis/first environmental assessment Solution finding/evaluating solutions Communication
INFORMATION INSPIRATION/ Loughborough University/2005	Guideline	English	Industrial designers	Introduction to eco-design Environmental strategies Examples of eco-products
ECODESIGN PILOT/TU Wien/2001	Guideline	10 languages	Designers, Industrial designers, Manufacturers, Environment managers.	Introduction to eco-design Environmental strategies Tracks for environmental improvement
SimaPro 7.0/Pré Consultants	Analytic	English	Environmental experts	Environmental assessment

The subject spent 40% of their time assessing the product using the Ecodesign Pilot tool, up from 30% using Ecofair and 25% using SimaPro. The SimaPro tool achieved the most significant time savings in solution finding, saving up to twice the amount of time (Fig. 2-20).

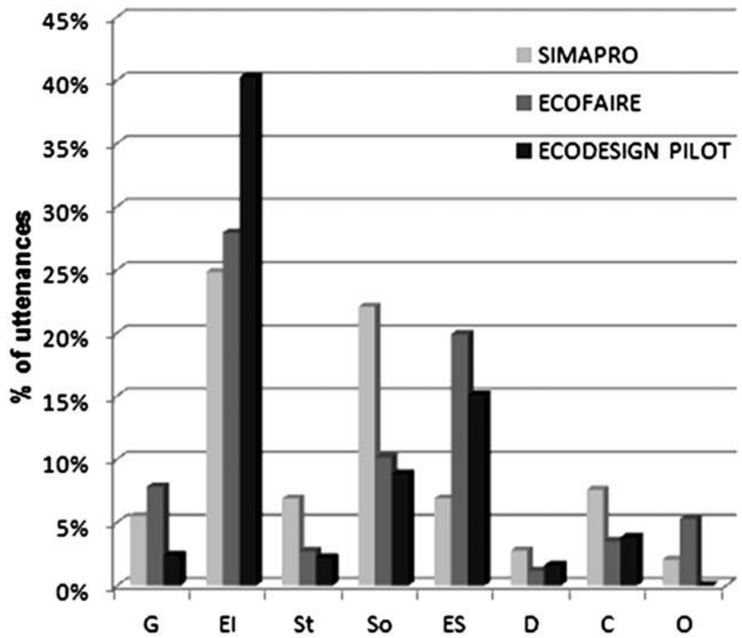

Fig. 2-20 Time distribution graph; G - Goal, EI - Initial assessment, St - Strategy, So - Solution, ES - Solution assessment, D - Decision, C - Control, O - Other [11].

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 optimization 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, Nicky**, Environmental assessment - Gotten across to industrial designers, *DESIGN 2002: Proceedings of the 7th International Design Conference*. 2002, Vols 1 and 2: 1293-1298. Available on: https://www.designsociety.org/publication/29732/environmental_assessment-gotten_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.

Results

The study focuses on the comparison of the environmental impacts of the production of a plastic window with steel reinforcement according to the following methods. LCA, Eco-Indicator 95 and OPM see (Fig. 2-21). To solve the problem, see dissertation source [12] "The Oil Point Method: A tool for indicative environmental evaluation in material and process selection" uses a new tool OPM which is based on LCA methodology.

To solve the problem of non-existing OPM indicators, they can be supplemented with the LCA methodology, the literature containing appropriate sources, or by interpolation of existing values (e.g., 50% aluminium recyclate is created by interpolating values). A description of more than 120 indicator values can be found at www.designisite.dk.

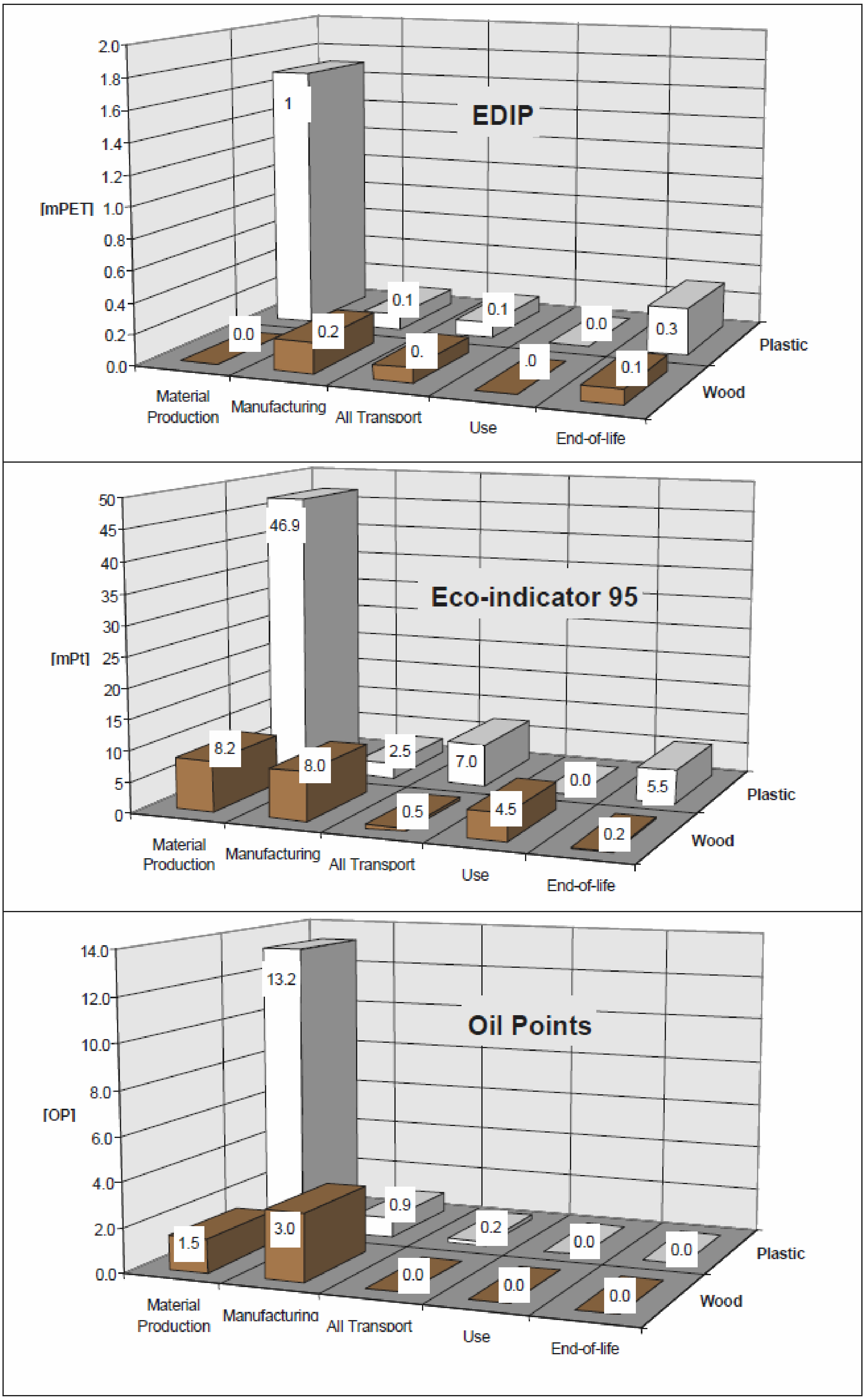

Fig. 2-21 Graphical comparison of different methods for the production of a plastic window [5].

Conclusions

The results of the study show us the positive capabilities of OPM. When the procedure was followed, good results were achieved (Fig. 2-21), 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.

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[24] **BYGGETH, Sophie and Elisabeth HOCHSCHORNER**, 2006. Handling trade-offs in Ecodesign tools for sustainable product development and procurement. *Journal of Cleaner Production*. 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.

Results

The result is an evaluation of 15 eco-design methods with a description of their 4 characteristics. Individual eco-design tools are described in terms of the purpose of their use and the structure of the output. The eco-design tool does not have to include an evaluation of the output of the analysis and for this reason it can be carried out by the user based on responsibility, experience, or considerations, see (Tab. 2-6). A very important aspect is the nature of the output (qualitative, quantitative, semiquantitative). A qualitative approach is able to identify a problem, e.g., with recycling or hazardous waste management.

Evaluation characteristics of 15 eco-design methods:

- Life Cycle Assessment,
- qualitative or quantitative approach,
- general or specific regulations.

Tab. 2-6 Table of eco-design tools and evaluation analysis [24].

Tool	No valuation in the tool	Valuation in the tool
Analysis tools		
ABC-Analysis		X
The Environmentally Responsible Product Assessment Matrix (ERPA)		X
MECO Method		X
MET-Matrix	X	
Comparing tools		
Philips Fast Five Awareness		X
Funktionkosten	X	
Dominance Matrix or Paired Comparison	X	
EcoDesign Checklist by Econcept		X
Econcept Spiderweb	X	
Environmental Objectives Deployment (EOD)	X	
LiDS-Wheel		X
The Morphological Box	X	
Prescribing tools		
Strategy List		X
Ten Golden Rules		X
Volvo's Black, Grey, and White Lists		X

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 the kg CO_2 eq. emissions, which are closely linked to the production site and especially in the user 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 [4, 5, 8, 9, 10, 11, 12, 17, 20, 24, 29]. 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, 26].

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) labeling 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 user 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 [1, 10, 11, 27],
- 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 [27],
- the implementation of eco-design tools is costly and time-consuming to train [10],
- eco-design tools are usually based on the LCA methodology [11, 12, 17, 19, 20, 24, 28, 29],
- quantitative tools cannot be applied at an early stage of product design [4, 5, 6, 7, 8, 11, 12, 17, 19, 20, 21, 22, 23, 24, 26],
- 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 user phase [7],
- when a new product is distributed on the market relative to the previous product, there is a 50% increase in the 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 [23], complete or simplified LCA, and analyses incorporated into other eco-design tools [11, 17, 19 20, 24]. The knowledge gained from the research underlines the relevance of the objective of the dissertation, namely determining the 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 analysis.

4 AIM OF THESIS

The essence of the dissertation is the development of a new method for determining the environmental load 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) [3, 4, 5, 8, 10, 11, 12, 14, 15, 17, 19, 20, 21, 24, 29, 30];
- 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 [3, 4, 5, 8, 10, 11, 14, 15, 17, 19, 20, 21, 24];
- 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 [3, 4, 5, 8, 10, 11, 12, 14, 15, 17, 19, 20, 21, 24];
- 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 [11] 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 [3, 4, 5, 8, 10, 11, 12, 14, 15, 17, 19, 20, 21, 24].
- 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 [32, 33, 35].
- 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.

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 categorization),
- 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, see (Fig. 5-1):

- Data categorization - 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 [32, 35, 36];

5 MATERIALS AND METHODS

The chapter describes the range of power tool samples analysed and the tools and methods used. The methodological procedure details the steps for obtaining data for subsequent LCA analysis, 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. The calculations are software processed exclusively in MS Excel and optimised using VBA code.

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) 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 Used Tools and Software

To achieve the aim of the dissertation, it was necessary to provide the necessary equipment. The equipment used was categorised into six groups:

- scale device,
- 3D scanner,

- PC,
- measuring instruments,
- hand tools and power tools,
- software,
- digital camera.

5.2.1 Scale Device

Measurement of single parts or a set of parts was performed with the SARTORIUS PMA7500 - 000C balance (Fig. 5-1). The resolution of the scale for the range of 0 g to 800 g is 0.05 g and 0.01 g for weights greater than 800 g. The weighing capacity of the scale device is 7,500 g (permissible tolerance 0.1 g). [37]

Fig. 5-1 Scale SARTORIUS PMA7500 – 00; (left) view of device; (right) product label.

5.2.2 3D Scanner

Power tool volume analysis was performed using an EinScan HD Pro handheld 3D scanner (SHINNING 3D) with LED structural light using hybrid alignment of the marking points and contour (Fig. 5-2). Scanning can be performed in handheld scan mode (3,000,000 points per second) or fixed mode (the same number of points in 0.5 s). Accuracy up to 0.045 mm in HD mode. The scanner can scan black and glossy surfaces. The scanner has the advantage of having a low weight of 1.13 kg. [38]

Fig. 5-2 3D scanner – EinScan Pro HD. [39]

5.2.3 Measuring Instruments

Measurements of parts and components of power tools for detailed calculations were performed with caliper SOMET measuring range of 0 mm to 160 mm graduation 0.05 mm (deviations according to DIN 862) with a flat depth rod [40]. A stainless steel ruler with a 300 mm graduation length of 0.5 mm was used to measure the orientation lengths.

5.2.4 Hand Tools nad Power Tools

The tools (Fig. 5-3) were used for disassembly of enclosures, internal components, as well as for disassembly of groups of mechanisms (gearboxes, motion mechanisms, connectors, switches, etc.) stators and power lines (wires).

Most commonly used tools:

- Bearing puller,
- screwdrivers,
- pliers (different types),
- impact wrench,
- bit set,
- circlip pliers,
- hammer,
- vice,
- lighter,
- saw.

Fig. 5-3 The tools for disassembly a power tools.

5.2.5 Software

Data collection, editing and processing was carried out using software focusing on three areas:

- Scanning of the model (ExScan Pro V3.4),
- editing of 3D model (Rhinoceros 7),
- inventory and calculation of data (MS Excel).

ExScan Pro V3.4

The ExScan Pro V3.4 software is designed for the EinScan HD Pro scanner. Calibration is performed as an initial step in the device setup. Scan resolution is possible in three modes (High, Medium, and Low Details). The acquired point cloud can then be processed as a mesh watertight or non-watertight model output with post-processing. The mesh can be saved as OBJ, STL, PLY, etc. [41].

Rhinoceros 7

The Rhinoceros 7 modeler works with NURBS curves, point clouds, polygon meshes and SubD. Polygon meshes can be edited in layers, fix holes in the model and closed in a watertight model. The Rhinoceros 7 software determines the centre of gravity volume and other physical properties of solids. Compatibility with a large number of 2D and 3D file types (STEP, STL, OBJ, DXF, etc.) for import into the Rhinoceros 7 modeler [42].

MS Excel

A widely used spreadsheet for processing data and creating simulations. Includes integrated tools for mathematical and statistical calculations. Visual output in the form of varied graphs for single or merged graphs, including optimization of data layers. Import of MS Office files, database files with possible updating of input data. Spreadsheet extensions can be achieved using individualised VBA macros.

5.2.6 Digital Camera

A compact digital camera for archiving power tools, CASIO EX-ZR1000 was used with a photo quality setting of 8 MP.

5.3 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 Analysis steps. The other steps are applied to the corresponding categorised power tools product groups (Fig. 5-4).

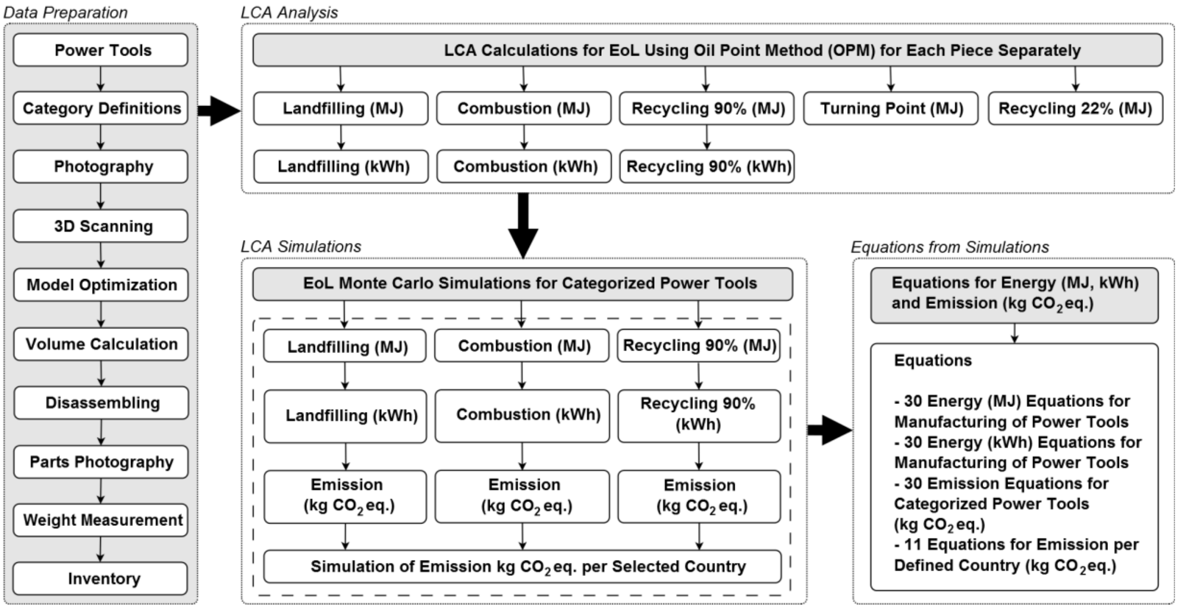


Fig. 5-4 Flowchart of the new volumetric method VEME.

Methodological guidelines:

- 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 [43],
- recycling percentage linear on all parts,
- no service interventions or repairs to the products during the user phase.

5.4 Data Preparation

5.4.1 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 manufacturer and model were determined for the selected sample and if not found, it was marked "_" or "_ _". The product was categorised and assigned to continuously emerging groups corresponding to the product types. Subsequently, the product groups were expanded and gradually added.

5.4.2 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 (the average amount of applied point on the power tool was about 50 pcs) and scanned with a 3D scanner in its entirety in handheld rapid scan mode (Fig. 5-5). The detail resolution was set to level Medium (0.7 mm accuracy) without the possibility of recording texture colour. In the 3D scanner software, the scanned sample was saved as a non-watertight model without post-processing. The 3D scan data were saved in STL and OBJ format.

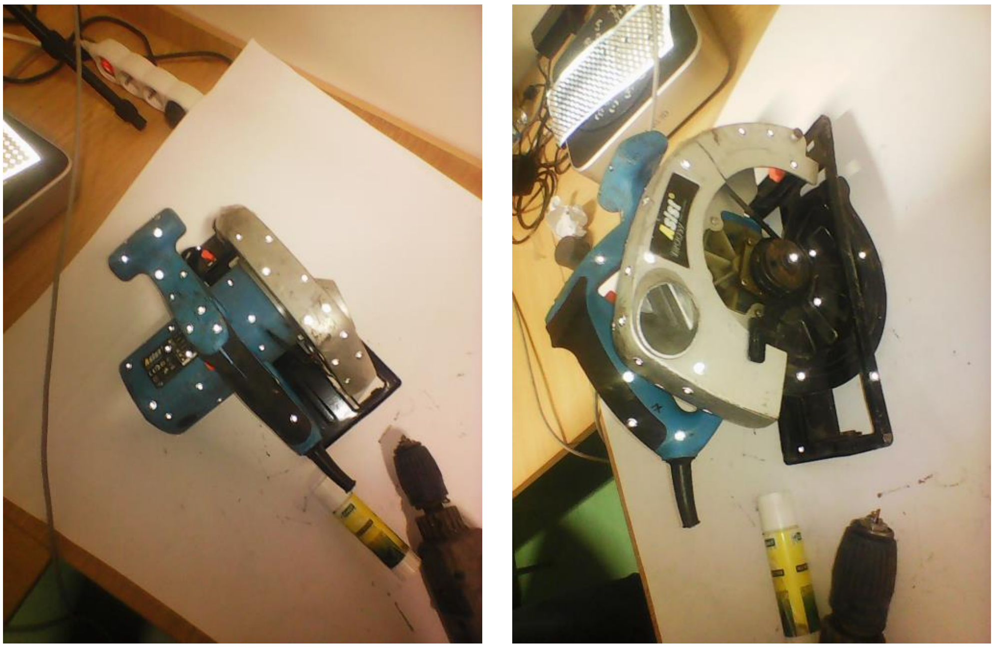


Fig. 5-5 Applied marking points for Circular Saw – Asist AE5KR120N; (left) marking points; (right) marking points.

5.4.3 3D Model Optimization & Volume Calculation

The scanned 3D model is directly imported in STL format into the Rhinoceros 7 software (Fig. 5-6, right part). This 3D model contains many surfaces that are unnecessary for the determination of the sample volume. The polygonal mesh editing tool removes these areas, and the sample is converted to a solid 3D model (Fig. 5-6, left part). The physical characteristics are analysed and the volume of the product in ml is determined (accuracy at 0.001 mm^3).

Fig. 5-6 Rhinoceros 7, imported STL Angle Grinder – narex EBU 13; (left) imported model; (right) cleared model.

5.4.4 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. All the parts from the analysed sample were arranged for photographing according to type, material type and method of manufacture.

Materials and Structural Analysis

The bearings were removed with a bearing puller when they could be removed. Connectors were disassembled into their individual material types. Vaseline was removed from the gears and motion mechanisms. Lubricants that were added by the user during the user phase were sliced off and not included.

Rubber parts with no clear identification were identified by their ignition and sensory determination of smoke odour (PVC, PB, and EPDM). Plastic parts of ambiguous origin (samples from the 1990s) were classified according to the usual materials of the epoch (mainly ABS).

The type of metal contact parts was determined by scratch test (plating or solid material). The materials were verified by magnetic test and thus the zinc and aluminium alloys were determined. The aluminium parts were divided according to the type of part.

Stators and Rotors Analysis

The electric motors of power tools (stators and rotors) were analysed in two ways:

- partial disassembly (stators),
- derivation of properties from the section (rotors).

The stators of the power tools were disassembled into three basic material and functional parts. One winding and plastic protection were removed from the stators for subsequent weighing (Fig. 5-7). The total winding and total weight were calculated and subtracted from the stator weight. The rest were the stator steel armatures.

Fig. 5-7 Photography of stator with removed one winding.

Due to the impossibility of separating the rotor parts into individual components, it was necessary to mathematically derive them from the sample. From the dimensional data on the rotor sample section, the predicted masses of the individual materials were determined. Using MS Excel, the weights were calculated using the volume and bulk weight of the materials (Fig. 5-8). The material composition of the rotor was divided into 4 material groups:

- Steel (armature and shaft),
- Copper (windings, commutator),
- Resin (winding protection and commutator),
- Plastics (shaft protection).

Individual materials were entered separately in the LCA calculation according to the manufacturing processes.

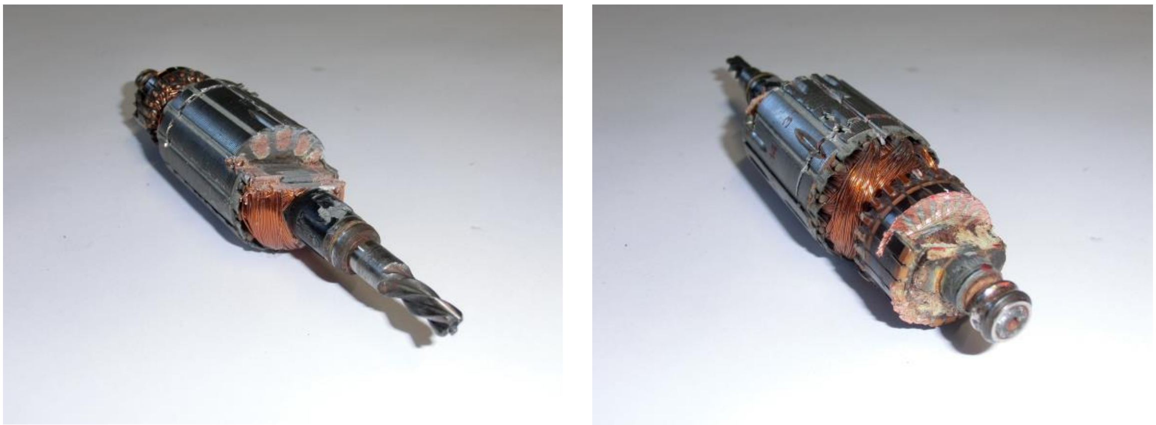


Fig. 5-8 Photography of rotor; (left) cut of armature; (right) cut of cummutator.

The rotors were measured, weighed and inventoried. If the rotor contained other parts such as bearings, plastic remnants and mechanisms, they were subtracted, inserted and inventoried. An inventory of the rotor dimensions for the calculations (Fig. 5-9).

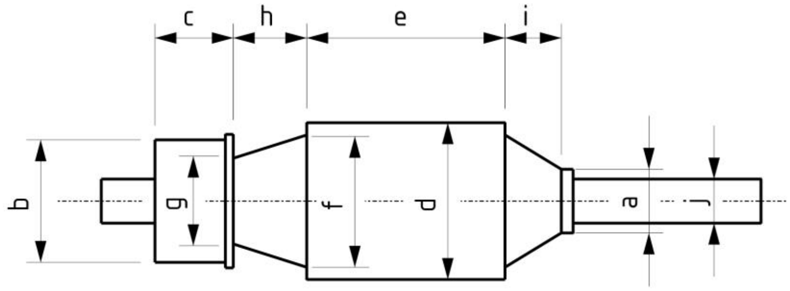


Fig. 5-9 Measured dimensions of rotors; (a) Rod with plastic protection, (b) Commutator d; (c) Commutator length; (d) Armature d; (e) Armature length; (f) Winding d max.; (g) Winding d min.; (h) Winding commutator length; (i) Winding length - free end; (j) Shaft (Rod) d.

The number of slotted copper winding in the armature was found to be 12, which were counted in the copper winding and simultaneously subtracted from the steel armature of the rotor. A detailed calculation is given in the MS Excel file analysing the power tools. The separation layer between the shaft, the commutator and the steel armature was separated by a layer thickness of 2 mm. The volume of the commutator and the steel armature is calculated without the volume of the shaft diameter cylinder with PA6 plastic protection.

5.4.5 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).

Before processing to the LCA analyses, each type of part was inventoried by material group, manufacturing method and surface finish. In the case of turning parts, 60.4% of the materials were found to be removed during manufacture [44]. Measured data and inventoried data are presented in an MS Excel spreadsheet and are the basis for LCA analysis.

5.5 LCA Analysis

Life cycle analysis 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 EoL. 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).

5.5.1 End of Life Calculation

Power Tools has been processed in three EoL phases for each product:

- Landfilling (100%),
- Combustion (materials that can be used for energy recovery),

- Recycling 90%.

Landfilling

The complete landfilling of the product was considered for the sake of further calculations in the recycling framework (recycling 0%), but also to compare the energy requirements for production with respect to different EoL. The landfilling scheme was calculated at 100% (1). EoL Processes for Landfilling [12]:

$$Landfilling = 0 \text{ OP/kg} \quad (1)$$

The values obtained are also valid for countries where there is no recycling, but only landfilling.

Combustion

Combustion was calculated for materials with energy Y = Feed stock share (2). Pure plastics and calculated and recalculated materials (lubricants, textiles, capacitors, PCBs, and plastics compounded with GF) were incinerated. Materials (metals) that could not be energy recovered (steel, aluminium, copper, glass fibres, ceramics, etc.) were landfilled. EoL Processes for Combustion [12]:

$$Combustion = \text{Y OP/kg} \quad (2)$$

The energy from combustion was not further calculated in the assessed system.

Recycling 90%

The 90% recycling value was chosen because of the 90% steel recycling in the OPM method. Recycling was calculated evenly for each material, without material recycling priority. It was calculated with energy X = Fuel share and according to the EoL scheme in OPM (Shredding, separation & re-milling) (3). EoL Processes for Recycling 90% [12]:

$$Recycling\ 90\% = (1 + X) \text{ OP/kg} \quad (3)$$

The OP input values in the Material Production life cycle have been reduced by 90%. Reductions could only occur if the material contained observed, calculated, or recalculated Fuel Share values. Recycling was calculated at a flat level on materials that allowed for recycling.

Recycling 45%

Until 2010, the WEEE recycling rate was approximately 23% in the EU [45]. Recycling requirements are now at 45% (2016) for selected countries, including CZ. The recycling rate is expected to be 65% by 2019 and 75% by 2030 [46, 47]. The determinations of the location of 45% recycling were derived from a linear dependence of the recycling rate from 0% to 100%. The 0% recycling value corresponded to EoL Landfilling and the values in the intervals 0% to 90% and 90% to 100% were calculated. 90% Recycling was calculated directly as Landfilling and Combustion.

5.5.2 OPM New 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. This ratio was set at 75% PB and 25% PP. The calculated values are similar to the EPDM material [48, 49]. Composite materials containing GF (Glass Fibres) were calculated as a mixture of the main material and the percentage of GF. This material enters its composition in the calculation for both Recycling and Combustion.

Materials containing a percentage of GF:

- PA6-GF35,
- PA6-GF30,
- PA6-GF33,
- PA66-GF35,
- PA66-GF30,
- PA66-GF50,
- PP-GF30,
- PBT-GF30,
- POM-GF30.

The OP/kg characteristics for the aluminium alloy Dural (composed of 95% copper, 4% aluminium and 1% magnesium) were calculated by the relative percentages of each component in the OPM method [50]. In the absence of finding the energy characteristics of Vaseline, a value of *1 OP* = 45 MJ (same as crude oil) was determined.

The manufacturing process using compressed air was included for painting surfaces. Compressed Air 3 bar (250 l/min) was calculated assuming 2.5 kWh to produce 283 l/min at 7 bar [51]. Painting a 1 m^2 part will require 1 min (14 motions of the painting nozzle in vertical and horizontal direction). The consumption to paint 1 m^2 of the surface with the engine running for 1 minute = 60 s is 150,000 J = 0.042 kWh. The painting process under the given conditions corresponds to a value of 0.004 OP/m^2 will be calculated with a value of 0.01 OP/m^2.

Wet painting has been considered. Paints for painting due to the large variety and small quantities were calculated as epoxies converted to 1 coat of paint per m2. This corresponds to a paint weight of 0.1 kg and therefore 1/10 of the OP values for the Epoxies material [52].

The energy to produce the product by Low Pressure Die Casting was determined to be 22.5 MJ/kg, which corresponds to 0.5 OP/kg. The value is around 17 MJ/kg, but was increased to take into account the value in the OPM methodology. [53, 54]

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. The energy properties of the components were considered in the EoL phases such as Combustion and Recycling. Components included:

- Capacitors,
- PCB (Printed Circuit Boards),
- V-Belt.

The weight ratio of the material composition of the foil capacitors was set to 60% aluminium foil, 20% paper, and 20% PP cover [55]. The calculation of the energy characteristics of the PCB components was based on energy recovery during their combustion.

Types of PCBs:

- Composite board,
- Ceramic board.

Combustion allows only 33% of the PCB parts, which are organic parts (epoxies). Composite PCB boards contain epoxies and oriented glass fibres (fibres will make up the remaining 33% of the total weight). Technical Ceramics and Aluminium is the remaining portion. The Feedstock Share for PCBs of 0.3 OP/kg is almost identical to the theoretical recalculated value of 0.26 OP/kg.

From the same principles, the Feedstock Share for ceramic board based circuits was determined. The calculation was based on the assumption that the content of epoxies was reduced to 6.1% of the total weight and the amount of technical ceramics was increased to 78.4% [56]. A detailed calculation is given in the appendices.

The calculation of V-Belt and the amount of PB and Nylon fibres was derived from the sample profile and belt section structure. It was found that 35% is PB and the rest is nylon fibres, the manufacturing process was defined as Rubber moulding. The resulting values were determined for Material Production and Manufacturing Processes.

Other Database Materials

The POM material was determined from LCI characteristics in the PlasticsEurope Fuel Share and Feedstock Energy databases [57]. The ECOlizer 2.0 tool was used to determine the material properties of EPDM. The PB and EPDM ratio of the ECOlizer 2.0 tool was determined and the relative ratio was determined. The energy to produce EPDM is 80% of the energy to produce PB. These values were converted to OP/kg [58]. The energy requirement of Manufacturing Processes to produce 1 kg of steel by Hot Rolling technology is 4.3 MJ (the theoretical value is 0.83 MJ/kg). The resulting indicator was set to 0.1 OP/kg considering the other OP indicators in Manufacturing Processes [59, 60, 61].

5.5.3 Transport Calculations

The transport conditions were the same for Landfilling, Combustion and Recycling 90% (the phases can be individually optimised in the XLS file). Transport life 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, truck = 1,700 km and van = 500 km).

The range was set for local transport of 2,500 km and for very long distance transport of 17,000 km (including sea transport). The energy requirements for transport under EoL Landfilling, Combustion and Recycling 90% are shown in the graphs as an interval band in grey. It illustrates the proportion represented by transport throughout the life cycle.

5.5.4 Use Phase Calculations

User phases (Tab. 5-1) were calculated for 1,000 hours over 2 years of operation (standard warranty in CZ) and were the same for Landfilling, Combustion and Recycling. Due to the different locations of consumption occurrence during the user phase of the tools, the calculation was not included in the overall calculations. The use phase was always calculated as the corresponding power input of the product.

Tab. 5-1 Calculation of the use phase range.

Entry Conditions	Time (hours), (days), (weeks)
Hours per Day	2
Days of the Week	5
Weeks a Year	50
Years	2
∑ Hours	1,000

5.5.5 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 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 (Tab. 5-2). The packaging material is shown as pink lines in the graphs and is included in the calculations in EoL Landfilling, Combustion, and Recycling. The detailed calculation is in the MS Excel file.

Tab. 5-2 Setting of packaging dimensions.

Description	Dimension (mm)
Summary of Cardboard Space - Size (x)	65
Summary of Cardboard Space - Size (y)	50
Summary of Cardboard Space - Size (z)	45
Thickness PE foil	0.1

5.5.6 Turning Point

The Turning Points values for EoL impacts were determined from a linear dependence of the recycling rate from 0% to 100%. Turning Point is on the same line as Recycling 45%. The values obtained from the Turning Point analysis for the EoL cycle of the sample show the potential to recycle materials. 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%.

The steepness of the linear curve of the recycling dependence 0% to 100%:

- Downward sloping curve (positive effect of recycling),
- rising curve (negative recycling).

A rising recycling curve 0% to 100% indicates that the energy cost of recycling itself is higher than the production from primary raw materials. The steepness indicates the significance of recycling (both negative and positive) within the observed sample.

5.6 LCA Simulation

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

- Energy requirements in units MJ,
- Energy requirements in units 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). [68, 69, 71, 72]

The kg CO_2 eq. emission analysis was applied to the countries CZ, PL, EE, SE, UK, TR, BR, CN, IN, US and JP (according to ISO code 3166-1). The values obtained from the simulation and the energy mixes of each country (kg CO_2 eq. per kWh values as of June 2019) were used to calculate the kg CO_2 eq. [62]

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. An example of the VBA script for calculating CO_2 emissions `"IncreaseTermCO2()"` and energy requirements in MJ `"IncreaseTermMJ()"` in the same way the energy requirements in kWh `"IncreaseTermkWh()"` is calculated. The calculation of the coefficient was performed on the tool categories for each EoL.

VBA code for the calculation of emission CO_2:

```
Sub IncreaseTermCO2()

Application.Calculation = xlManual

If MsgBox("Are you sure update data?", vbYesNo + vbExclamation + vbDefaultButton2, "Warning") = vbYes Then

Worksheets("Summary").Calculate
Worksheets("Input").Calculate
MsgBox "Update is OK"
End If

End Sub
```

VBA code for MJ calculation:

```
Sub IncreaseTermMJ()

Application.Calculation = xlManual
Dim myValue As Variant


If MsgBox("Are you sure continue for Goal Seeker and find the heighest R values?", vbYesNo + vbExclamation + vbDefaultButton2, "Warning") = vbYes Then

 myValue = InputBox("The Range of the Iteration", "Iteration Settings", 1000)
 Worksheets("Summary").Range("S7:S36").Value = ""

Dim arr() As Variant
Dim a As Integer
Dim sc As Integer
sc = Sheets.Count
```

```
    Dim z As Integer
    For z = 1 To 31


   If ((Sheets(z).Name)) <> "Summary" Then

            Dim i As Integer
            Dim s As Integer
            Dim x As Double

            For i = 1 To myValue
            Worksheets(Sheets(z).Name).Calculate
            If (Worksheets(Sheets(z).Name).Range("N11").Value2) > Worksheets(Sheets(z).Name).Range("N15").Value2 Then
            'MsgBox (z - 1) & "/" & (31 - 1) & vbCrLf & "Value for Sheet " & vbCrLf & Sheets(z).Name & vbCrLf & (Worksheets(Sheets(z).Name).Range("N11").Value2)
            Worksheets("Summary").Range("S" & (5 + z)).Value = "YES"
            Exit For
            Else
                If (i = myValue) Then
                'MsgBox (z - 1) & "/" & (31 - 1) & vbCrLf & "Value for Sheet" & vbCrLf & Sheets(z).Name & vbCrLf & "was not found"
                Worksheets("Summary").Range("S" & (5 + z)).Value = "NO"
                End If

            End If
            Next i

   End If

If (z = 31) Then
Worksheets("Summary").Calculate
MsgBox "Iteration is done"
End If

Next z

End If
End Sub
```

5.7 Equations from Simulations

The calculation relationships for determining energy requirements in MJ, kWh and kg CO_2 eq. emissions 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 the kg CO_2 eq. The kg CO_2 eq. emissions for tools according to each EoL (abbreviated *LF* = Landfilling, *CM* = Combustion, *RC* = Recycling) are calculated from the arithmetic average of all selected countries CZ, PL, EE, SE, UK, TR, BR, CN, IN, US, and JP (according to ISO code 3166-1) [31]. In the case of kg CO_2 eq. emissions per country, the input values of each tool category are arithmetically averaged, including the different EoL.

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 analysis, the tool samples were sequentially photographed (Fig. 6-1) and scanned with a 3D scanner to determine the volume of the product (Fig. 6-2). The volume of products ranged from 757 ml (Angle Grinder) to 5,530 ml (Electric Chainsaw).

Fig. 6-1 Photography of Reciprocating Saw (RS1).

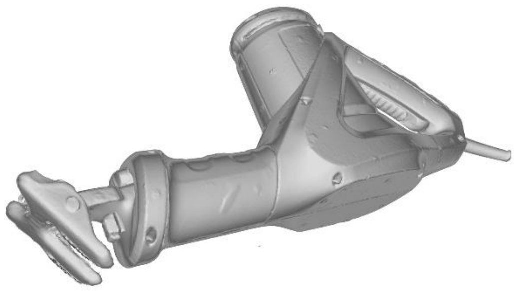


Fig. 6-2 3D Scan of Reciprocating Saw (RS1).

6.1 Material Analysis

The tools were disassembled into individual parts and inventoried to prepare the data for the LCA analysis (Fig. 6-3). 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.

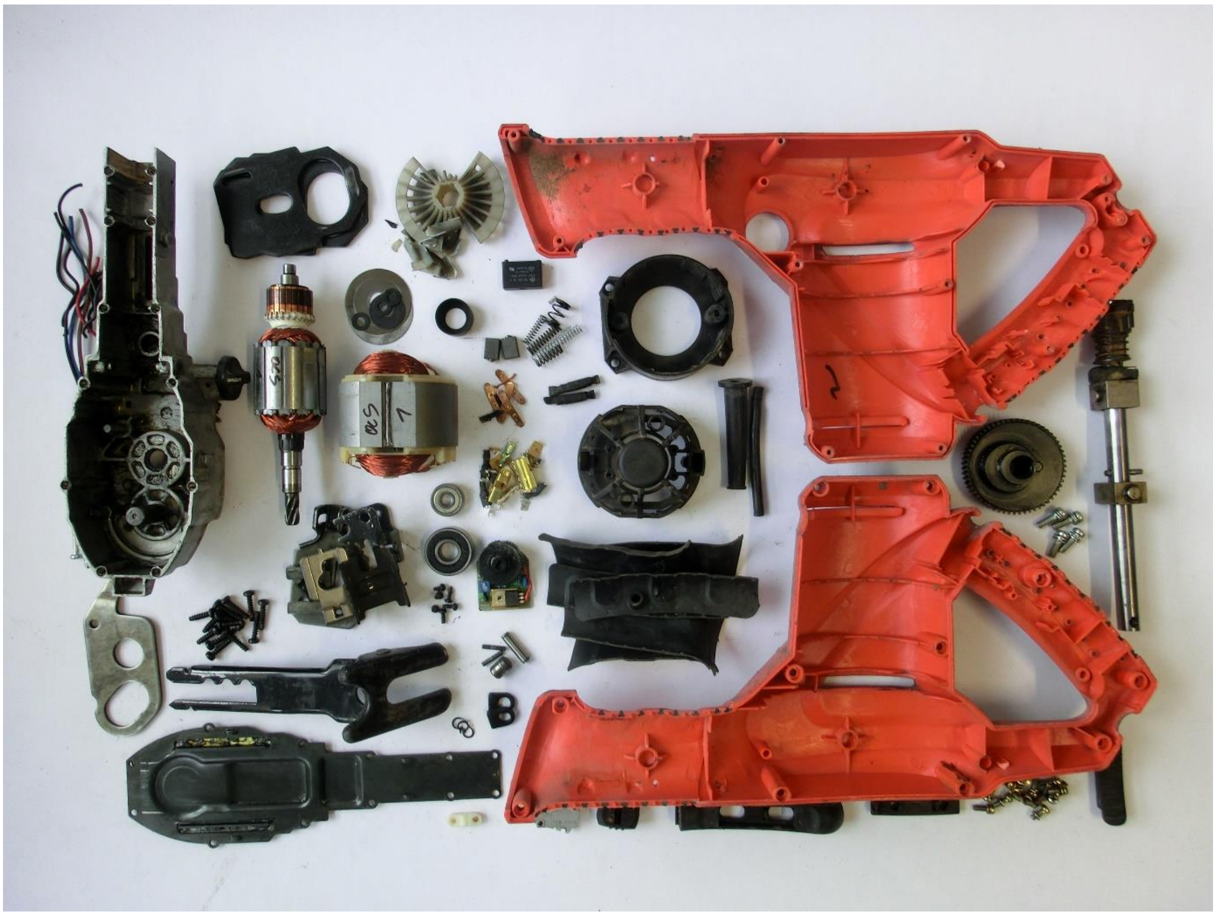


Fig. 6-3 Photography of Decomposed Reciprocating Saw (RS1).

6.1.1 Stators and Rotors

The electric motor (consisting of a rotor and a stator) has a high share in the weight of the whole product. The most significant percentage of copper parts and steel in electric motors is in smaller products. In larger products, such as Electric Chainsaws and Reciprocating Saws, the weight of the covering is almost equal. The percentages of copper and steel to the total product weight for the product groups are shown below the table (Tab. 6-1). Measured rotor part diameters and lengths and stator weights are provided in Parts-of-Tools-27012021.xlsx. An example of the rotor and stator file (Fig. 6-4 and Fig. 6-5).

Tab. 6-1 Percentage of weight of electric motor materials to total weight of product groups.

Power Tools	**Copper** (%)	**Steel** (%)	**Average** (%)
Random Orbital Sanders	12.6	27.5	40.1
Sheet Sanders	13.3	27.6	40.9
Electric Planers	9.6	20	29.6
Handle Jigsaws	11	24.3	35.4
Belt Sanders	8.6	18	26.6
Percussion Drills	10.8	22.8	33.6
Circular Saws	10.7	22.4	33
Angle Grinders	14	29.1	43.1
Electric Chainsaws	12.1	27.3	39.4
Reciprocating Saws	8.9	19.3	28.2
All Groups	11.2	23.8	35.0

The weights of the rotor and stator parts were measured and calculated. The weights of the measured stators correspond to the following:

- Total stator weight (range 214 g to 1,317.1 g),
- copper (interval 30.4 g to 360.4 g),
- steel (162.2 g to 1,008.7 g).

The min. and max. weights for copper and steel are paired. Rotor weights were in the 174.4 g to 1,012.6 g interval.

Fig. 6-4 Photography of rotors.

Fig. 6-5 Photography of stators and rotors.

6.1.2 Mesured Properties of Power Tools

The values that were determined by measurement:

- the measured volume of the product,
- measurements of the weights of the individual components,
- the weight sum of the components in one product,
- diameters and lengths of components.

Volume

The volume of the single products (samples) was determined by a 3D scanner with an accuracy of 0.001 mm^3. The volume characteristics of the product categories correspond to their characteristic properties and applications (Fig. 6-6). Angle Grinders have a smaller volume due to their design and grip design. Reciprocating Saws and Electric Chainsaw require more power and a secure grip.

Measured volume ranges for product categories (Appendix D):

- Random Orbital Sanders (946 ml to 1,717 ml),
- Sheet Sanders (838 ml to 1,717 ml),
- Electric Planers (1,616 ml to 2,818 ml),
- Handle Jigsaws (963 ml to 1,612 ml),
- Belt Sanders (2,403 ml to 3,494 ml),
- Percussion Drills (944 ml to 1,654 ml),
- Circular Saws (1,469 ml to 2,869 ml),
- Angle Grinders (757 ml to 3,011 ml),
- Electric Chainsaws (2,027 ml to 5,530 ml),
- Reciprocating Saws (1,573 ml to 2,641 ml).

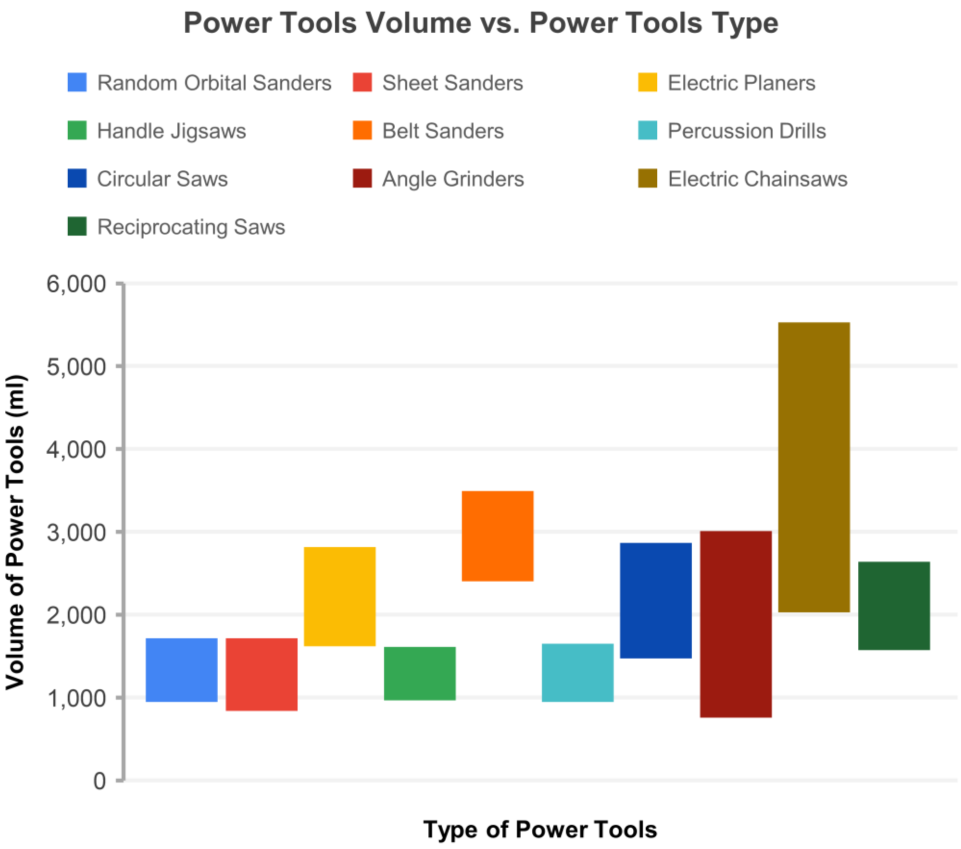


Fig. 6-6 Graph of volume versus power tools type.

Product volume measurement grouped product types into 4 classes:

- Volume Class V1 (Random Orbital Sanders, Sheet Sanders, Handle Jigsaws, Percussion Drills),
- Volume Class V2 (Electric Planers, Circular Saws, Angle Grinders, Reciprocating Saws),
- Volume Class V3 (Belt Sanders),
- Volume Class V4 (Electric Chainsaws).

Weight

The weight was determined for each part, which had the same material composition and method of manufacture (Fig. 6-7). Table (Tab. 6-2) shows an example of the composition of the Reciprocating Saw (RS1) product with a total component weight of 3.313 kg. A detailed inventory is provided in Appendix B.

Tab. 6-2 Example of materials composition and manufacturing processes of Reciprocating Saw (RS1).

Description	**Material**	**Weight** (g)	**Quantity** (kg), (m^2), (m)
PA6-GF30	PA6-GF30*	740.8	0.741
PA6-GF33	PA6-GF33*	0.0	0.000
PA6-GF35	PA6-GF35*	0.0	0.000
PA66-GF30	PA66-GF30*	0.0	0.000
PA66-GF35	PA66-GF35*	0.0	0.000
PA66-GF50	PA66-GF50*	0.0	0.000
PP-GF30	PP-GF30*	0.0	0.000
POM-GF30	POM-GF30*	0.0	0.000
PBT-GF30	PBT-GF30*	0.0	0.000
Thermoplastic Elastomer	TPE**	38.3	0.038
EPDM	EPDM**	0.0	0.000
Polymethylmethacrylate	PMMA	0.0	0.000
Polyoxymethylen	POM	0.0	0.000
PA6	PA6	16.4	0.016
PA66	PA66	0.0	0.000
Polyurethan	PUR	0.0	0.000
ABS	ABS	0.0	0.000
High-Density Polyethylene	HDPE	0.0	0.000
Polycarbonate	PC	0.0	0.000
Polyethylen	PE	0.0	0.000
Polypropylen	PP	0.0	0.000
Rubber	PB	0.0	0.000
Steel (89% Primary)	Steel	740.3	0.740
Sheets	Steel	1,481.4	1.481
Aluminium Parts	Aluminium	0.0	0.000
Dural*	Al+Cu+Mg	377.0	0.377
Copper	Copper	359.3	0.359
Contacts (Brass)	Brass	13.6	0.014
Nickel	Nickel	0.0	0.000
Bronze	Bronze	0.0	0.000
Zinc Alloys	Zn Alloy	0.0	0.000
Ceramics	Technical	0.0	0.000
Turning, Milling	Removed	447.1	0.447
Bolts, Screws, Nuts	Steel	74.6	0.075
Springs (Steel)	Steel	4.0	0.004
Wire Wrapping	PVC	18.0	0.018
Capacitor**	PP+Al+Paper	4.8	0.005
PCB Ceramic	Cermic Board**	0.0	0.000
PCB Composite	Composite Board**	17.3	0.017
Textile	Textile	0.0	0.000
Paper	Paper	0.0	0.000
Resin	Epoxies	21.0	0.021
Carbon Brushes	Carbon	2.4	0.002
Ferrite	Steel	6.0	0.006
V-Belt	PB+Nylon	0.0	0.000
Lubricant	Vaseline	115.1	0.115
∑		**4,030.4**	**4.030**

Description	Material	Area (mm^2)	Area (m^2)
Electro-Plating	Cr, Ni, Zn, Cu	10,800.0	0.01080
Anodising	Al	0.0	0.00000
Paints**	Liquid Paints	36,900.0	0.03690
∑		**47,700.0**	**0.048**

Description	Material	Length (mm)	Length (m)
Welding	Steel	0.0	0.000
∑		**0.0**	**0.000**

* Recalculated, ** Approximately Calculated

Measured weight ranges for product categories (Appendix D):

- Random Orbital Sanders (1,158 g to 2,005 g),
- Sheet Sanders (826 g to 1,686 g),
- Electric Planers (1,871 g to 3,147 g),
- Handle Jigsaws (1,181 g to 2,630 g),
- Belt Sanders (2,013 g to 3,173 g),
- Percussion Drills (1,530 g to 2,710 g),
- Circular Saws (2,880 g to 4,107 g),
- Angle Grinders (1,226 g to 5,170 g),
- Electric Chainsaws (2,032 g to 4,801 g),
- Reciprocating Saws (2,114 g to 4,030 g).

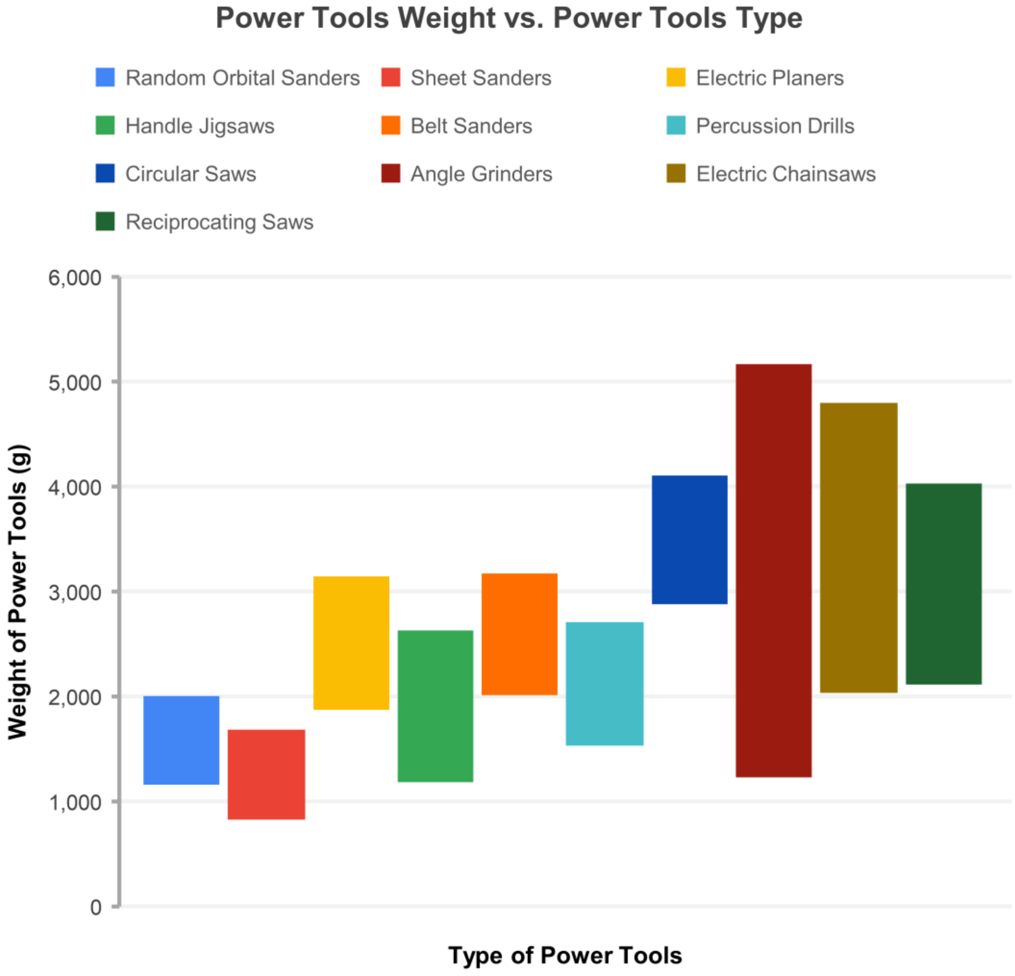


Fig. 6-7 Graph of weight versus power tools type.

Measurement of product weight grouped product types into 5 classes:

- Weight Class W1 (Random Orbital Sanders),
- Weight Class W2 (Sheet Sanders),
- Weight Class W3 (Electric Planers, Belt Sanders),
- Weight Class W4 (Handle Jigsaws, Percussion Drills),
- Weight Class W5 (Circular Saws, Electric Chainsaws, Angle Grinders, Reciprocating Saws).

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

From the data obtained, a weight vs. volume graph was constructed (Fig. 6-8). The values of the correlation coefficient range from 0.66–0.97. The average value is 0.84. The values represent a strong dependence. The quality of the described R^2 data can be seen in the graph.

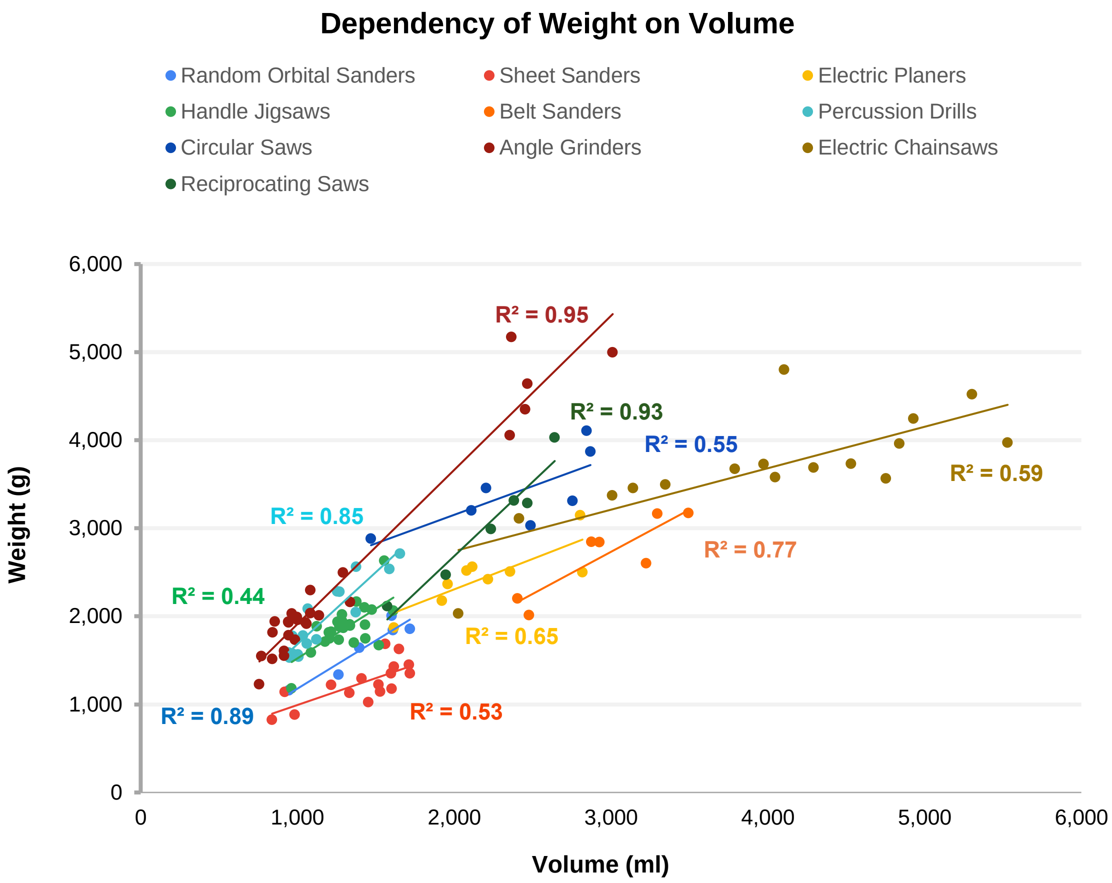


Fig. 6-8 Graph of power tools weight versus power tools volume.

6.2 LCA Analysis

The LCA analysis was processed from the inventory analysis for each tool sample (Fig. 6-9). The scope of the data analysis included a total of 402 individual EoL analyses that were combined into product categories followed by linear regression. The alpha-value was set at 0.05 (5% significance level) 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. The samples were statistically significant. In 6.7% EoL Landfilling (2 samples), 10% Combustion (3 samples) and 3.3% Recycling 90% (1 sample). All samples under *p*-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 user 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). According to OPM's methodology, the most energy intensive phases in Materials Production are Titanium Alloy, Metal Powders Composites (MMC), CFRP, Nickel, Technical Ceramics and Aluminium alloys. Of the Manufacturing Processes, the most Wave soldering, Textile manufacturing and Rubber moulding are the most energy intensive. Some of these phases contained tooling samples analysed. The energy requirements for manufacturing are identical for Landfilling and Combustion. 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.

Fig. 6-9 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. .

6.2.1 Random Orbital Sanders

The Random Orbital Sanders product category analysed had power ratings in the 190 W to 430 W range (Fig. 6-10). The difference between the maximum and minimum Transport requirements with respect to the entire life cycle (excluding power requirements for packaging) was in the 0.19% to 0.31% interval (mean = 0.24%). The *p*-values are less than alpha 0.05 (5%) and the correlation coefficient is greater than 0.8, a very strong association [63]. The R^2 index was in the 0.69–0.78 interval.

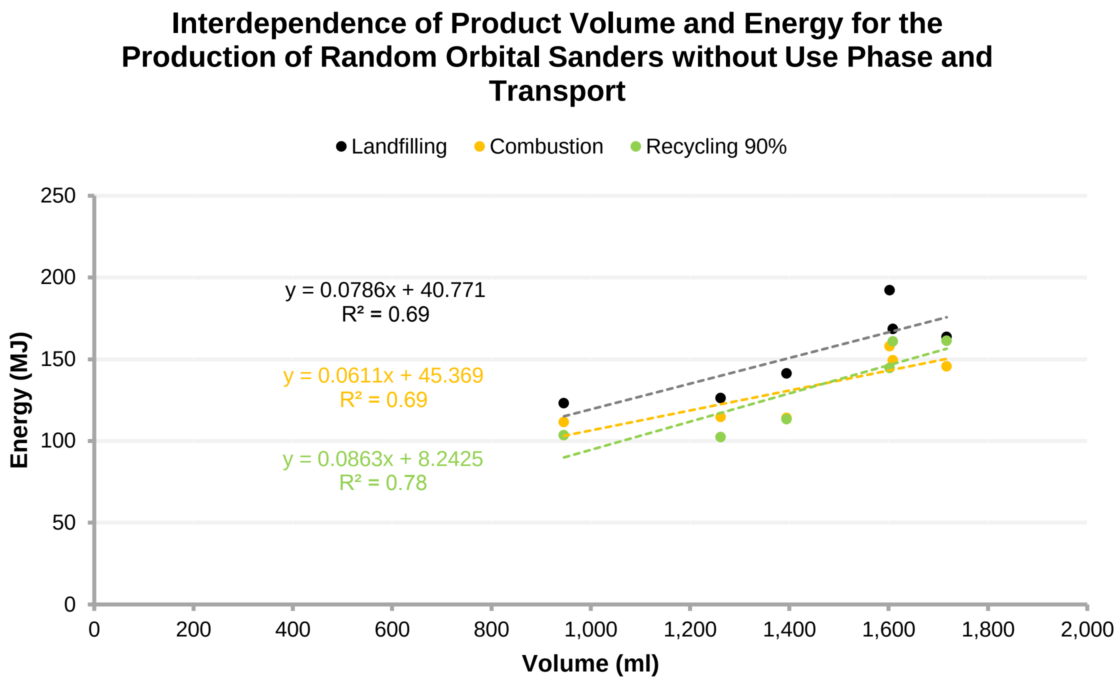


Fig. 6-10 Graph of Volume vs. Energy for Random Orbital Sanders.

Statistical analysis for the tools category (6 pcs.):

- Landfilling (*p*-value = 0.04 <= 0.05, correlation = 0.83),
- Combustion (*p*-value = 0.04 <= 0.05, correlation = 0.83),
- Recycling 90% (*p*-value = 0.02 <= 0.05, correlation = 0.88).

The results of the LCA analysis (Tab. 6-3) show a dependence on the volume of the product even for a small number of samples. The product recycling curve of all 100% samples had a decreasing energy characteristic with an increasing recycling percentage. No Turning Point was found on the recycling curve of 0% to 100% in 33.3% (4 samples). The trends of the individual curves (Fig. 6-10) had a Landfilling, Combustion and Recycling 90% arrangement with Combustion and Recycling 90% ordering at the observed volume of 946 ml to 1,717 ml.

Tab. 6-3 End of Life (EoL) Energy Analysis for Random Orbital Sanders.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	OS	BOSCH	PEX 270A	141.307	114.123	113.264
2	OS	ProStar	ESM 4201	192.114	157.991	144.673
3	OS	Makita	B05010	122.999	111.634	103.426
4	OS	PowerTec	_	163.709	145.585	161.283
5	OS	Pattfield	_	168.596	149.281	160.844
6	OS	BOSCH	PEX 115 A	126.188	114.621	102.379

6.2.2 Sheet Sanders

Tools in this category (Fig. 6-11 and Tab. 6-4) had power ratings of 125 W to 250 W. The difference in transport over the entire life cycle (excluding energy requirements for packaging) ranged from 0.23% to 0.47% (average 0.34%). The correlation coefficient was in the interval 0.45 to 0.60 (moderate dependence) in two cases and greater than 0.6 (strong dependence) in one case [63]. In the case of Combustion, the *p*-value was greater than 0.05 (alpha 0.05), and the hypothesis at the 5% confidence level was rejected. The R^2 was in the interval 0.20 to 0.38.

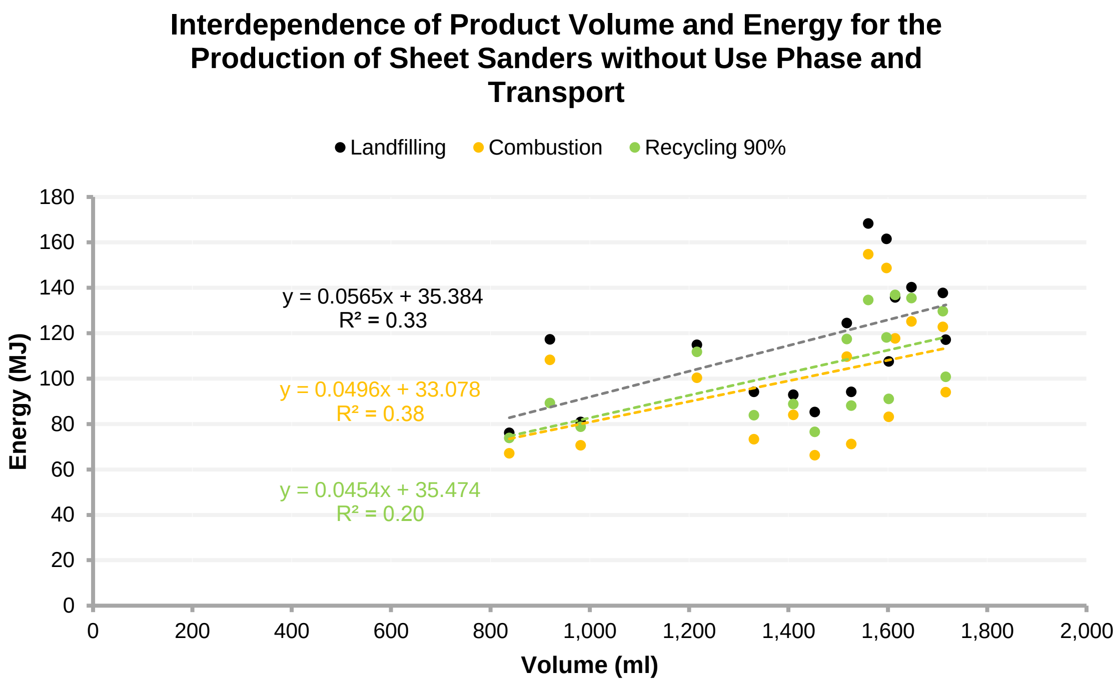


Fig. 6-11 Graph of Volume vs. Energy for Sheet Sanders.

Statistical analysis for the tools category (16 pcs.):

- Landfilling (*p*-value = 0.02 <= 0.05, correlation = 0.57),
- Combustion (*p*-value = **0.08 <≠ 0.05**, correlation = 0.45),
- Recycling 90% (*p*-value = 0.01 <= 0.05, correlation = 0.62).

The trend of the combustion curve is placed below the Recycling 90% level because of the lower use of energy in the combustion products. The volume of products was in the range of 838 ml to 1,717 ml. The combustion point was not located on the recycling 0% to 100% curve in 81.2% (13 samples). In the product category, this point was below the 100% recycled calculated.

Tab. 6-4 End of Life (EoL) Energy Analysis for Sheet Sanders.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	SS	NOELI	E0007	85.231	66.096	76.418
2	SS	SKIL	660H1	137.669	122.656	129.613
3	SS	BOSCH	PSS 23	92.753	83.918	88.758
4	SS	_	PTSS 150	94.021	73.232	83.765
5	SS	Ferm	VM-150	124.315	109.578	117.305
6	SS	Einhell	BSS 150	107.453	83.121	90.953
7	SS	BOSCH	PSS 230	168.216	154.657	134.472
8	SS	BOSCH	PSS 23A	161.396	148.592	118.020
9	SS	PARKSIDE	PMFS 200 B2	114.818	100.271	111.736
10	SS	PARKSIDE	PSS 250 C3	135.708	117.539	136.722
11	SS	ProfiTools	_	94.107	71.028	87.946
12	SS	SKIL	7300 H1	117.033	93.889	100.755
13	SS	AEG	VS 230	140.165	125.091	135.377
14	SS	PARKSIDE	PHS 160 ES	80.746	70.500	78.697
15	SS	METERK	TS 002	75.965	67.048	73.724
16	SS	FLEX	MS 713	117.206	108.100	89.199

6.2.3 Electric Planers

The power output of the analysed samples was 400 W to 900 W. The trend of the Landfilling, Combustion and Recycling 90% curves has a characteristic distribution with respect to the energy requirements for production (Fig. 6-12). The EoL (Combustion) significantly exceeded alpha = 0.05, *p*-value = 0.14 (rejecting the hypothesis). A moderate exceedance also occurred for Landfilling. The R^2 indicator was in the 0.29–0.53 interval. The correlation coefficient ranged from moderate to strong [63]. The difference in transport was in the 0.15% to 0.24% interval (mean 0.19%) throughout the life cycle (excluding the energy requirements for packaging).

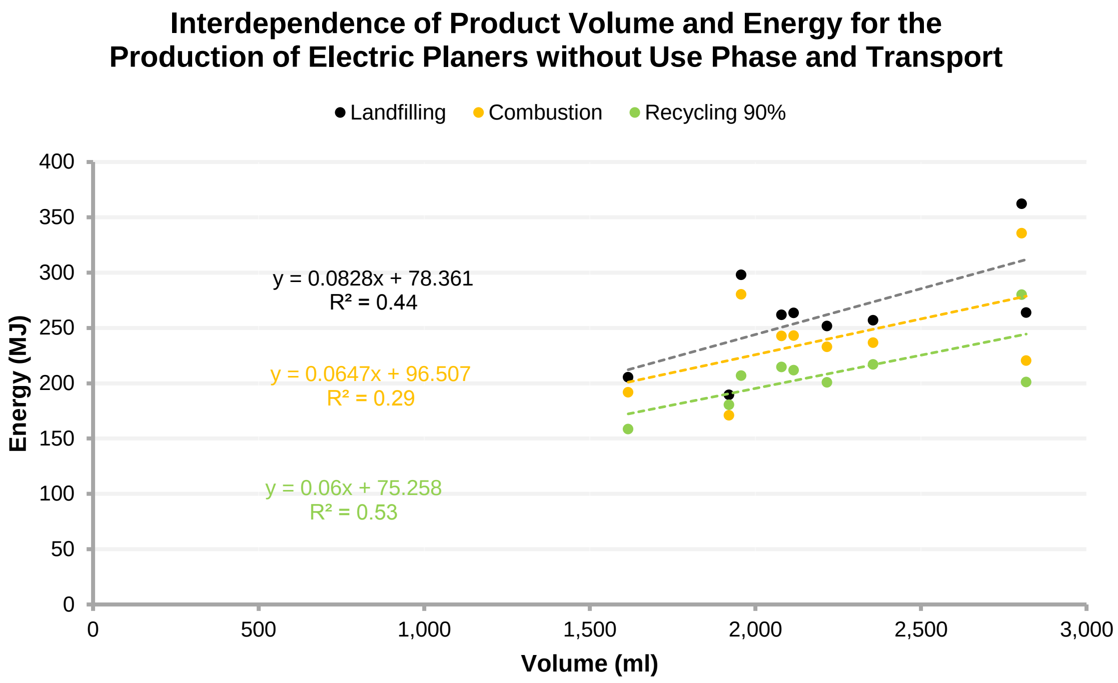


Fig. 6-12 Graph of Volume vs. Energy for Electric Planers.

Statistical analysis for the tools category (9 pcs.):

- Landfilling (*p*-value = **0.05 <= 0.05**, correlation = 0.66),
- Combustion (*p*-value = **0.14 <≠ 0.05**, correlation = 0.53),
- Recycling 90% (*p*-value = 0.03 <= 0.05, correlation = 0.72).

The distribution of the curve trend is Landfilling, Combustion and Recycling 90% from the highest energy requirements to the lower requirements. In only one case (11.1%) was the Combustion point lower than Recycling 100% (Tab. 6-5). The volume of the product ranged from 1.616 ml to 2.818 ml.

Tab. 6-5 End of Life (EoL) Energy Analysis for Electric Planers.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	EP	AEG	H 500	263.948	220.322	201.02
2	EP	HOLZ-HER	2310	298.029	280.422	206.943
3	EP	WORX	WX623.1	362.095	335.595	280.105
4	EP	SKIL	2310	189.31	170.99	180.536
5	EP	hanseatic	H-HO 82-600	261.767	242.667	214.483
6	EP	SKIL	91H1	205.499	191.732	158.531
7	EP	Ferm	PPM1009	263.606	242.999	211.842
8	EP	T.I.P.	EH618	251.52	232.893	200.749
9	EP	CMI	C-HO 82-600	256.862	236.634	217.02

6.2.4 Handle Jigsaws

The analysed Handle Jigs (Fig. 6-13) had power ratings in the range of 350 W to 850 W. Correlation values are higher than 0.6 and show a strong dependence of the volume and power requirements on production [63]. The *p*-value is close to 0.00 and confirms statistical significance in the category. The R^2 indicator was in the narrow interval of 0.51–0.57. The difference in transport was in the 0.11% to 0.22% interval (mean 0.16%) throughout the life cycle (excluding the energy requirements for packaging).

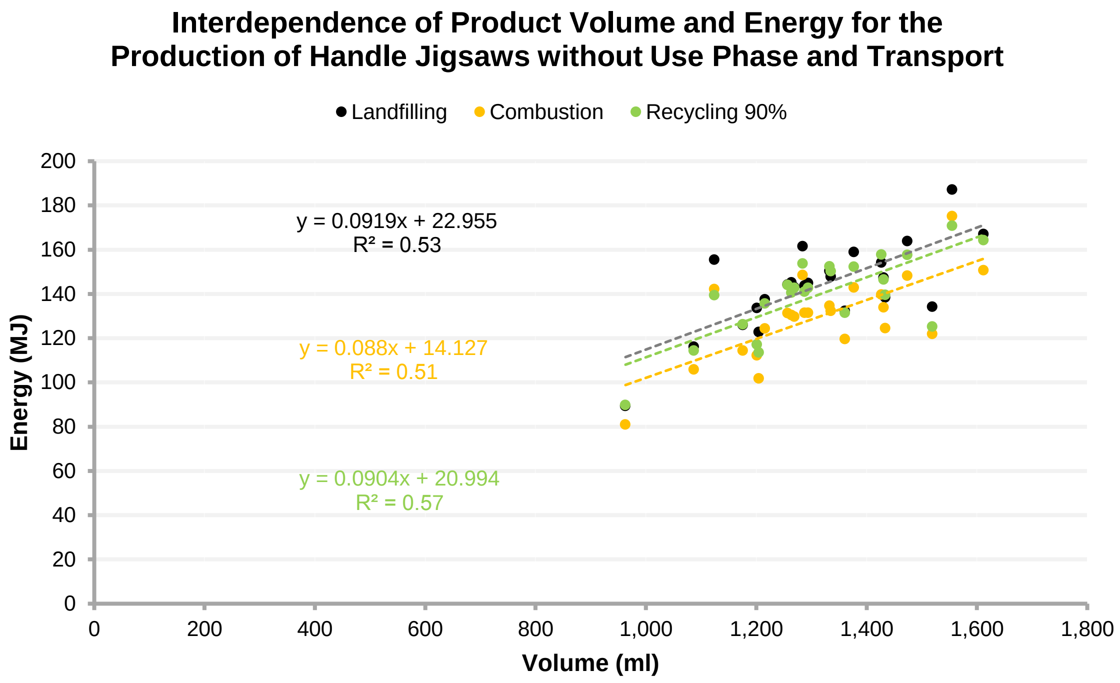


Fig. 6-13 Graph of Volume vs. Energy for Handle Jigsaws.

Statistical analysis for the tools category (24 pcs.):

- Landfilling (*p*-value = 0.00 <= 0.05, correlation = 0.73),
- Combustion (*p*-value = 0.00 <= 0.05, correlation = 0.71),
- Recycling 90% (*p*-value = 0.00 <= 0.05, correlation = 0.75).

The location of the trend curves was reversed from the expected position in Combustion and Recycling 90%. The volume of the product was in the range of 963 ml to 1,612 ml. The combustion point was outside the 0% to 100% recycling curve for 22 samples (91.6%) (Tab. 6-6).

Tab. 6-6 End of Life (EoL) Energy Analysis for Handle Jigsaws.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	HJ	AEG	STS 380	122.731	101.729	113.485
2	HJ	BOSCH	PST 54 PE	150.370	134.660	152.394
3	HJ	KINZO	72179	89.403	80.911	89.839
4	HJ	Black & Decker	KS688E	138.324	124.529	139.572
5	HJ	BOSCH	PST 700 E	116.046	105.842	114.398
6	HJ	Kress	6250E	144.164	131.299	144.010
7	HJ	meister	BPS 750 L	158.918	142.878	152.281
8	HJ	hanseatic	H-ST 500E	137.470	124.300	135.654
9	HJ	Black & Decker	BD 547 E	147.406	133.979	146.563
10	HJ	Ferm	FJS-600N	167.050	150.746	164.329
11	HJ	Black & Decker	KS 656PE	134.179	121.908	125.249
12	HJ	TESCO	FC710J	163.919	148.218	157.638
13	HJ	PARKSIDE	PPHSS 730 SE	187.137	175.133	170.772
14	HJ	MANNESMANN	12884	143.813	131.499	141.038
15	HJ	Black & Decker	KS888E	132.308	119.624	131.477
16	HJ	CMI	C-ST 570P	144.937	131.497	142.689
17	HJ	UNIROPA	6260 E	155.393	142.216	139.375
18	HJ	BOSCH	PST 55-PE	147.838	132.278	150.273
19	HJ	SKIL	4275H1	133.671	112.189	117.088
20	HJ	Ferm	JSV-650P	142.967	129.688	142.761
21	HJ	SPARKY	TH 60 E	145.141	130.480	140.610
22	HJ	AEG	STEP 600 X FIXTEC	154.146	139.740	157.821
23	HJ	_	_	161.510	148.582	153.790
24	HJ	AEG	STSE 400 A	125.938	114.372	126.298

6.2.5 Belt Sanders

The analysed products had a power output 500 W to 900 W (Fig. 6-14). Correlation values above 0.8 indicate a very strong dependence, but the *p*-value in one case (Recycling 90%) exceeds alpha 0.05 (hypothesis rejected). [63] The R^2 indicator was in the wide interval 0.39–0.70. The difference in transport throughout the life cycle (excluding packaging energy requirements) was in the 0.15% to 0.18% interval (average 0.17%).

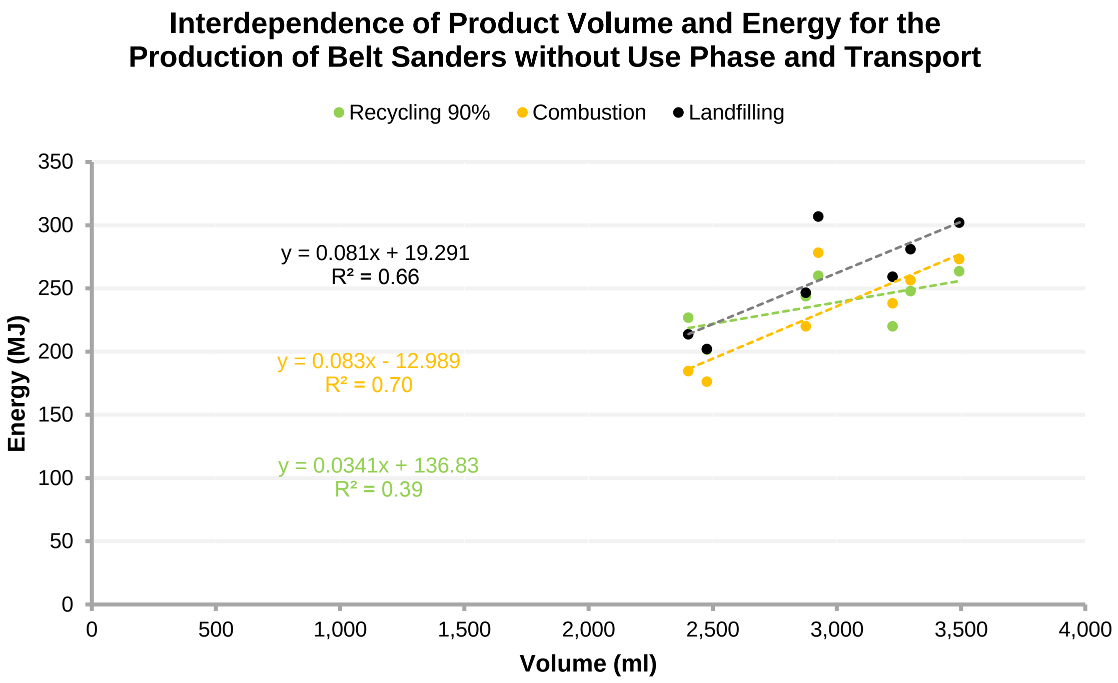


Fig. 6-14 Graph of Volume vs. Energy for Belt Sanders.

Statistical analysis for the tools category (7 pcs.):

- Landfilling (*p*-value = 0.03 <= 0.05, correlation = 0.81),
- Combustion (*p*-value = 0.02 <= 0.05, correlation = 0.84),
- Recycling 90% (*p*-value = **0.13 <≠ 0.05**, correlation = 0.62).

The trends of the Recycling 90% curve cross over the Combustion curve (difference from Random Orbital Sanders). At lower volumes, Combustion is less efficient (less energy is recovered). In 3 cases (42.8%), Combustion is below the recycling 0% to 100% level (Tab. 6-7). The volumetric characteristics of the tools analysed are in the range of 2,403 ml to 3,494 ml.

Tab. 6-7 End of Life (EoL) Energy Analysis for Belt Sanders.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	BS	King Craft	KCB 720	246.499	219.984	243.639
2	BS	Ferm	FBS-800	259.263	238.16	219.824
3	BS	narex	_	306.798	278.16	259.874
4	BS	_	_	280.902	256.32	247.821
5	BS	ETAtool	RBP 900	302.088	273.134	263.523
6	BS	Black and Decker	H1B	202.051	176.073	201.508
7	BS	PARKSIDE	PBSD 600 A1	213.634	184.554	226.779

6.2.6 Percussion Drills

The power output of the products in the Percussion Drills category ranged from 400 W to 1,050 W (Fig. 6-15). Values of the correlation coefficients above 0.9 indicate a very strong dependence of volume on the power requirements for production [63]. The values in Landfilling, Combustion and Recycling 100% are close to zero and are significantly less than alpha = 0.05 (5%). The R^2 indicator was in the range of 0.83–0.91. The difference in transport was in the 0.09% to 0.25% interval (average 0.16%) throughout the life cycle (excluding the energy requirements for packaging).

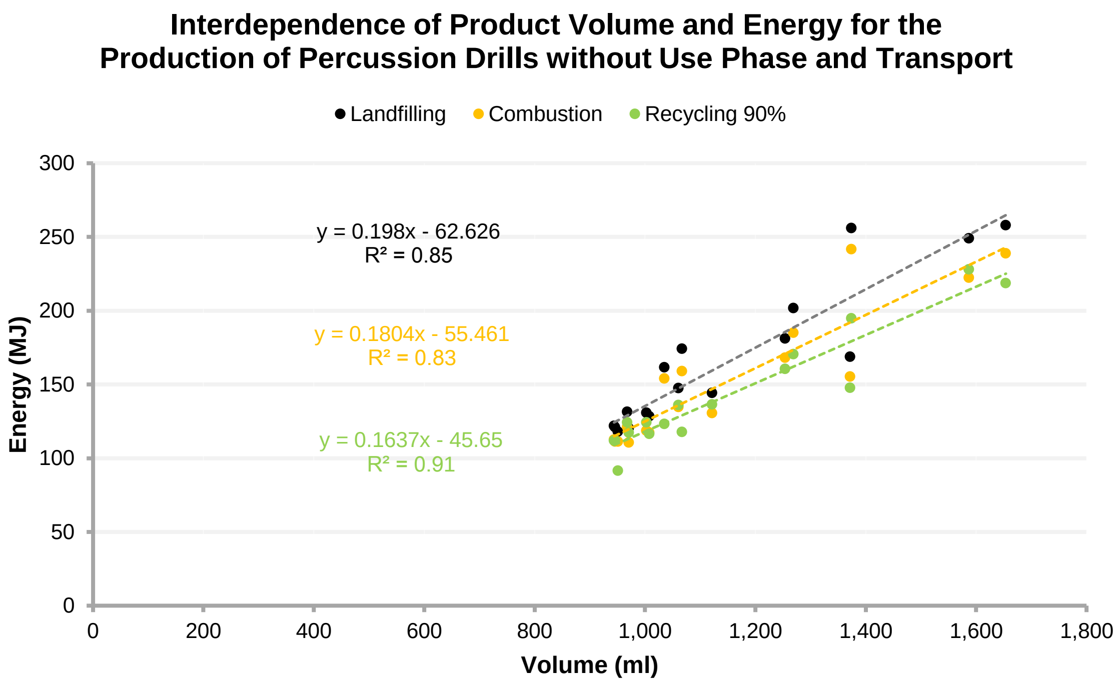


Fig. 6-15 Graph of Volume vs. Energy for Percussion Drills.

Statistical analysis for the tools category (17 pcs.):

- Landfilling (*p*-value = 0.00 <= 0.05, correlation = 0.92),
- Combustion (*p*-value = 0.00 <= 0.05, correlation = 0.91),
- Recycling 90% (*p*-value = 0.00 <= 0.05, correlation = 0.95).

The locations of the Landfilling, Combustion and Recycling 90% trend curves are consistent with the expectations of energy production requirements. In 5 cases (29.4%) the energy for Combustion was lower and was below the effective recycling level of 0% to 100% (Tab. 6-8). The volume of the products ranged from 944 ml to 1,654 ml.

Tab. 6-8 End of Life (EoL) Energy Analysis for Percussion Drills.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	PD	AEG	SB2E 13 RL	255.927	241.521	194.821
2	PD	narex	_	174.127	158.992	117.636
3	PD	BOSCH	CSB 650-2RE	180.953	168.083	160.488
4	PD	LFG	LF-6525K	121.009	111.150	112.102
5	PD	CM	C-39500P	128.368	117.168	116.289
6	PD	Black & Decker	KD664RE	117.847	111.148	91.434
7	PD	HILTI	TE 2-M	248.929	222.250	227.970
8	PD	Kress	SBLR 2365TC	144.192	130.502	136.358
9	PD	PARKSIDE	PSBM 500 C4	130.609	118.519	124.201
10	PD	AEG	SBE 630 R	120.289	110.554	117.215
11	PD	BOSCH	CSB 400-E	147.455	134.670	135.884
12	PD	_	_	161.465	153.935	123.198
13	PD	DeWALT	D250T3	201.658	184.893	170.396
14	PD	WURTH	H24-MLE	257.770	238.686	218.499
15	PD	BOSCH	PSB 500 RE	131.419	121.238	124.309
16	PD	Powerforce	Z1JE-KZ11-13B	168.746	155.131	147.643
17	PD	Tech power	GW 13	121.804	112.534	111.801

6.2.7 Circular Saws

The power output of the product categories analysed (Fig. 6-16) was in the range of 800 W to 1,300 W. In two cases, the *p*-value was greater than alpha = 0.05 (5%) and for this reason we reject the hypothesis. In addition, the correlation coefficient was above 0.4, which corresponds to a moderate dependence [63]. In the case of Recycling 90%, the correlation coefficient corresponded to a very strong dependence, including a *p*-value below alpha 0.05. The R^2 indicator was in the wide interval 0.18–0.82 and corresponded to the *p*-value and correlation coefficient. The difference in transport was in the 0.11% to 0.16% (mean 0.13%) interval throughout the life cycle (excluding the energy requirements for packaging).

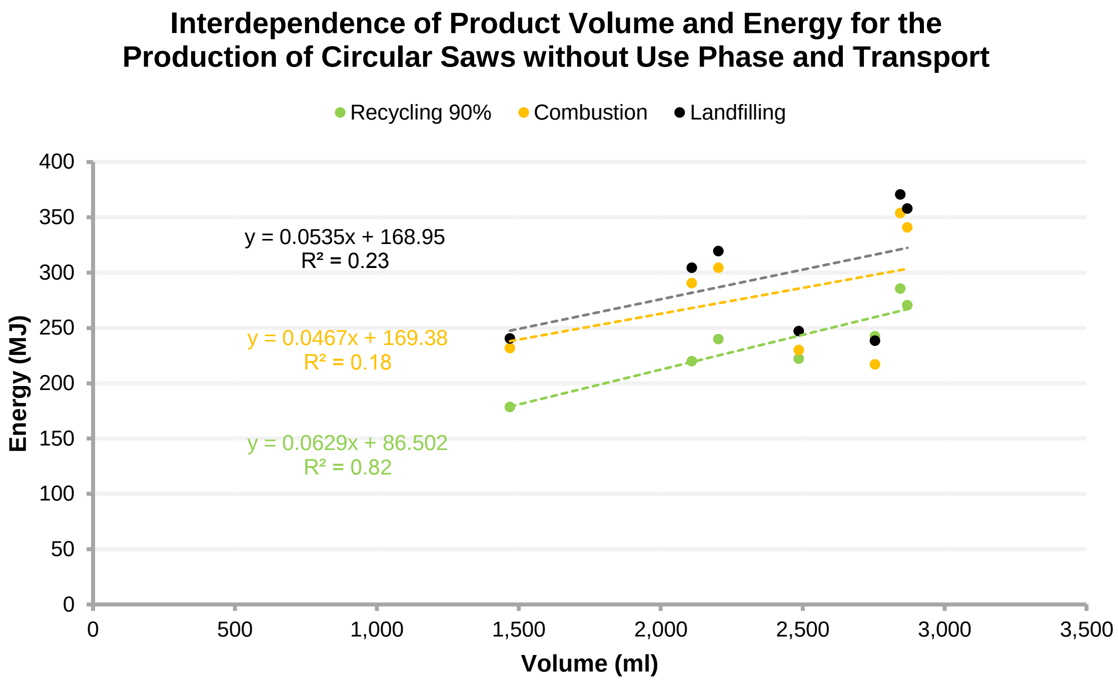


Fig. 6-16 Graph of Volume vs. Energy for Circular Saws.

Statistical analysis for the tools category (7 pcs.):

- Landfilling (*p*-value = **0.27 <≠ 0.05**, correlation = 0.48),
- Combustion (*p*-value = **0.34 <≠ 0.05**, correlation = 0.42),
- Recycling 90% (*p*-value = 0.01 <= 0.05, correlation = 0.90).

The placement of the trend curves Landfilling, Combustion and Recycling 90% corresponded to the expected positions. In one case (14.3%), the Combustion was outside the recycling 0% to 100% level (Tab. 6-9). The volume of the products was in the range of 1,469 ml to 2,869 ml.

Tab. 6-9 End of Life (EoL) Energy Analysis for Circular Saws.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	CS	Black & Decker	KS865N	238.399	216.961	242.382
2	CS	FERM	FKS-165	319.398	304.238	239.838
3	CS	Inspira	IN-1210	357.783	340.739	270.347
4	CS	hanseatic	PSC160D	304.187	290.454	219.756
5	CS	Black & Decker	DN57/D21	240.359	231.596	178.395
6	CS	O.K.	HKS 185	370.635	353.859	285.618
7	CS	Asist	AE5KR120N	247.145	229.99	222.159

6.2.8 Angle Grinders

The power output of the Angle Grinders (Fig. 6-17) was found to be in the range of 500 W to 2,000 W. The *p*-value was close to zero at all the ends of life stages. These values also correspond to correlation coefficients with an almost perfect positive association [63]. The R^2 index was in the narrow interval of 0.92–0.97. The difference in transport was in the 0.08% to 0.14% interval (mean 0.11%) throughout the life cycle (excluding the energy requirements for packaging).

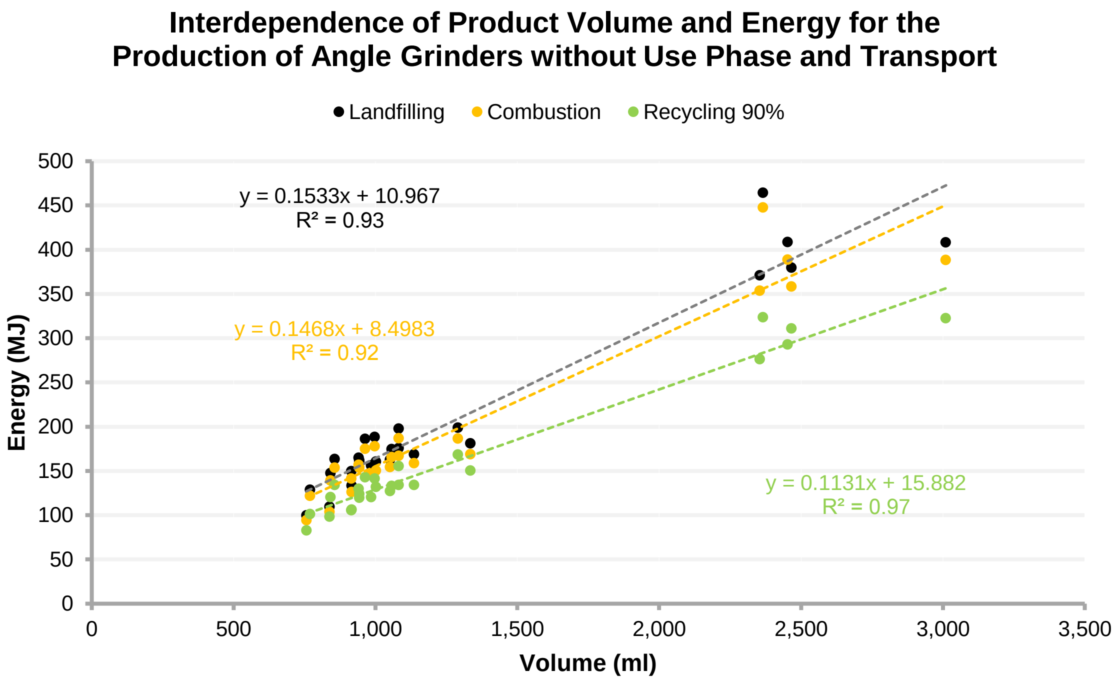


Fig. 6-17 Graph of Volume vs. Energy for Angle Grinders.

Statistical analysis for the tools category (26 pcs.):

- Landfilling (*p*-value = 0.00 <= 0.05, correlation = 0.96),
- Combustion (*p*-value = 0.00 <= 0.05, correlation = 0.96),
- Recycling 90% (*p*-value = 0.00 <= 0.05, correlation = 0.98).

The location of the individual trend EoL cycles was in the expected positions. All samples analysed in Combustion were located on the recycling 0% to 100% curve (Tab. 6-10). The observed volumes ranged from 757 ml to 3,011 ml.

Tab. 6-10 End of Life (EoL) Energy Analysis for Angle Grinders.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	AG	narex	EBU 13	160.293	150.502	131.844
2	AG	FLEX	L 3709/125	164.961	156.687	129.785
3	AG	_	_	464.287	447.696	323.549
4	AG	FERM	FAG-125N	197.737	186.846	155.477
5	AG	FERM	FAG-125/950	174.449	165.584	132.860
6	AG	_	_	160.911	153.566	123.988
7	AG	PRO Work	PWS 125/850-2	175.771	167.038	133.994
8	AG	BOSCH	PWS 720-115	149.741	141.403	105.648
9	AG	MATRIX	AG 1100	168.889	158.781	133.911
10	AG	Budget	BWS 1155	128.505	121.808	101.273
11	AG	Black & Decker	KG 10	147.587	138.949	120.224
12	AG	Kawasaki	K-AG 800-2	156.009	146.886	120.291
13	AG	Basictool	BWS 125/850-2	162.644	154.431	127.171
14	AG	DeWALT	DS81111-QS	186.236	174.949	142.884
15	AG	DeWALT	DS23132-Q	188.469	177.837	141.194
16	AG	KINZO	72193	99.744	94.365	82.558
17	AG	BOSCH	PWS 750-125	133.352	125.981	106.291
18	AG	Ferm	FAG-115N	161.749	154.012	119.759
19	AG	PARKSIDE	PWS 125 B2	198.750	186.412	168.408
20	AG	PARKSIDE	PWS 125 D3	181.112	168.847	150.408
21	AG	HITACHI	G 23ST	408.452	388.830	292.640
22	AG	NOELI	E0020	379.514	358.305	310.913
23	AG	Ferm	FAG-230/2000	370.873	353.467	276.240
24	AG	Ferm	AGM1029 - FDAG	408.028	388.206	322.402
25	AG	narex	EBU 12	163.350	153.747	134.208
26	AG	Einhell	GWS 115-2	109.350	103.500	98.167

6.2.9 Electric Chainsaws

The power range of the analysed tool category was in the 1,050 W to 2,200 W range (Fig. 6-18). The values of the correlation coefficients were above 0.6 in two cases of strong dependence and one above 0.8 in very strong dependence (Recycling 90%) [63]. The *p*-values were close to zero in all cases, confirming the hypothesis. The R^2 was in the wide interval 0.47–0.77. The difference in transport over the entire life cycle (excluding energy requirements for packaging) was in the 0.09% to 0.12% interval (mean 0.10%).

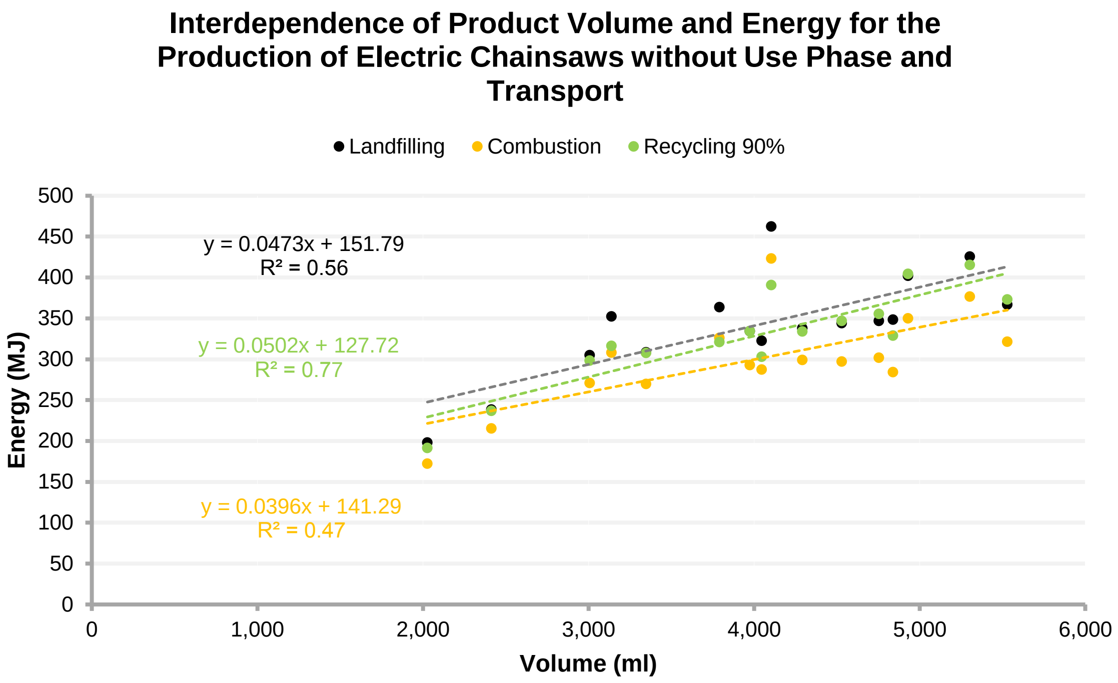


Fig. 6-18 Graph of Volume vs. Energy for Electric Chainsaws.

Statistical analysis for the tools category (16 pcs.):

- Landfilling (*p*-value = 0.00 <= 0.05, correlation = 0.75),
- Combustion (*p*-value = 0.00 <= 0.05, correlation = 0.69),
- Recycling 90% (*p*-value = 0.00 <= 0.05, correlation = 0.88).

The location of the trend curves was reversed for the category analysed in the Combustion and Recycling 90% area. The higher energy position of Recycling 90% over Combustion. 14 samples (87.5%) were outside recycling 0% to 100% (Tab. 6-11). The wide range of volumes was consistent with the nature and method of control with power tools 2,027 ml to 5,530 ml.

Tab. 6-11 End of Life (EoL) Energy Analysis for Electric Chainsaws.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	EC	McCULLOCH	Electramac 16E	238.400	215.221	236.970
2	EC	BOSCH	GKE 40 BC	363.458	325.969	320.797
3	EC	DOLMAR	ES 3	322.686	287.292	303.090
4	EC	Einhell	REK 2040 WK	348.238	284.237	328.887
5	EC	SACHS-DOLMAR	260	198.132	172.360	191.179
6	EC	STIHL	E 14	352.423	308.225	316.121
7	EC	DOLMAR	ES-33A	334.448	292.593	334.350
8	EC	McCULLOCH	Electramac 35ES	304.836	270.756	298.246
9	EC	DOLMAR	ES-38A	308.352	269.706	307.686
10	EC	ASGATEC	KS 1800	462.494	423.175	390.623
11	EC	PARTNER	ES2014	344.239	297.141	346.643
12	EC	florabest	FKS 2200 G4	401.984	349.853	404.163
13	EC	ATIKA	KS 2001/40	425.651	376.396	415.441
14	EC	ATIKA	KS 1800/35	337.920	299.202	333.852
15	EC	PARTNER	P 1640	346.666	301.706	355.439
16	EC	King Craft	KSI 2000	366.806	321.486	372.985

6.2.10 Reciprocating Saws

The power output of the category of products analysed was in the range of 550 W to 850 W (Fig. 6-19). The correlation coefficient at all ends of the life cycle had an almost perfect positive volume dependence on the energy requirements for production [63]. The *p*-value was close to 0 and confirms the hypothesis. The R^2 indicator was in the narrow interval of 0.96–0.97. The difference in transport was in the 0.12% to 0.25% interval (mean 0.21%) throughout the life cycle (excluding the energy requirements for packaging).

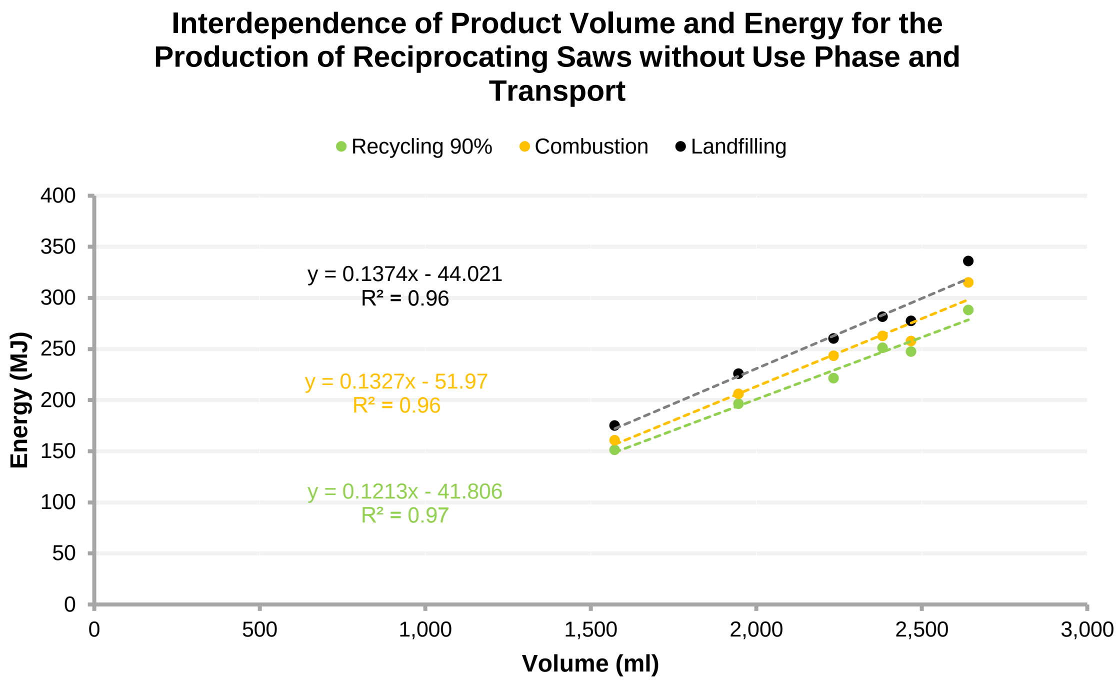


Fig. 6-19 Graph of Volume vs. Energy for Reciprocating Saws.

Statistical analysis for the tools category (6 pcs.):

- Landfilling (*p*-value = 0.00 <= 0.05, correlation = 0.98),
- Combustion (*p*-value = 0.00 <= 0.05, correlation = 0.98),
- Recycling 90% (*p*-value = 0.00 <= 0.05, correlation = 0.99).

The trend locations for Landfilling, Combustion and Recycling 90% match the assumptions. 100% of the analysed products lie in the recycling 0% to 100% interval (Tab. 6-12). The volume of the product category was in the 1,573 ml to 2,641 ml interval.

Tab. 6-12 End of Life (EoL) Energy Analysis for Reciprocating Saws.

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (Combustion) (MJ)	Methodology OPM (90% Recycled) (MJ)
1	RS	King Craft	KMS 710 E	335.915	315.029	288.213
2	RS	ProStar	PMS6000	277.486	257.800	247.328
3	RS	King Craft	KMS 600 E	281.626	262.621	251.237
4	RS	BOSCH	PFZ 550 PE	260.114	243.250	221.272
5	RS	CMI	C-ESS-800	175.007	160.463	151.369
6	RS	Pattfield	_-850SA	225.804	206.156	196.385

6.2.11 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 energy requirements for the production of the product package are compared with the energy for the transport of the goods and the energy expenditure within the range of transport considered. In the case of large and energy-intensive production tools (e.g., Electric Chainsaws, Reciprocating Saws, Circular Saws), the energy to package the product is always within the range of transport requirements. 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.

6.2.12 Use Phase

The user 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%). The power tool extensions correspond to the individual product types for safe, reliable, economical and ergonomic work. From the data obtained, it is clear that the power inputs of the products depending on the volume are very different and have not been given meaning for the calculations. The user phase is not part of the overall calculations, as the power consumption is tens of times the energy for the actual production of the tools.

6.3 Landfilling (LCA Analysis)

The life cycle in landfill mode contained only zero values for all materials and EoL (OPM rules). An example for EoL (Landfilling) is the Reciprocating Saw tool (Fig. 6-20). Landfilling was found to be less energy intensive than Recycling 90% in 13 cases (Tab. 6-13). In other cases, the energy requirements were lower. 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.

Percentage of plastics to total weight for PA6 and PA66 material with GF from 21.90% (sample CS1) to 48.84% (sample BS7) in a given product category.

Tab. 6-13 Comparison of Landfilling and Recycling 90% (Recycling 90% have higher energy requirements).

#		Product	Model	Methodology OPM (Landfilling) (MJ)	Methodology OPM (90% Recycled) (MJ)	Increase (%)
10	SS	PARKSIDE	PSS 250 C3	135.708	136.722	0.7
2	HJ	BOSCH	PST 54 PE	150.370	152.394	1.3
3	HJ	KINZO	72179	89.403	89.839	0.5
4	HJ	Black & Decker	KS688E	138.324	139.572	0.9
18	HJ	BOSCH	PST 55-PE	147.838	150.273	1.6
22	HJ	AEG	STEP 600 X FIXTEC	154.146	157.821	2.4
24	HJ	AEG	STSE 400 A	125.938	126.298	0.3
7	BS	PARKSIDE	PBSD 600 A1	213.634	226.779	6.2
1	CS	Black & Decker	KS865N	238.399	242.382	1.7
11	EC	PARTNER	ES2014	344.239	346.643	0.7
12	EC	florabest	FKS 2200 G4	401.984	404.163	0.5
15	EC	PARTNER	P 1640	346.666	355.439	2.5
16	EC	King Craft	KSI 2000	366.806	372.985	1.7

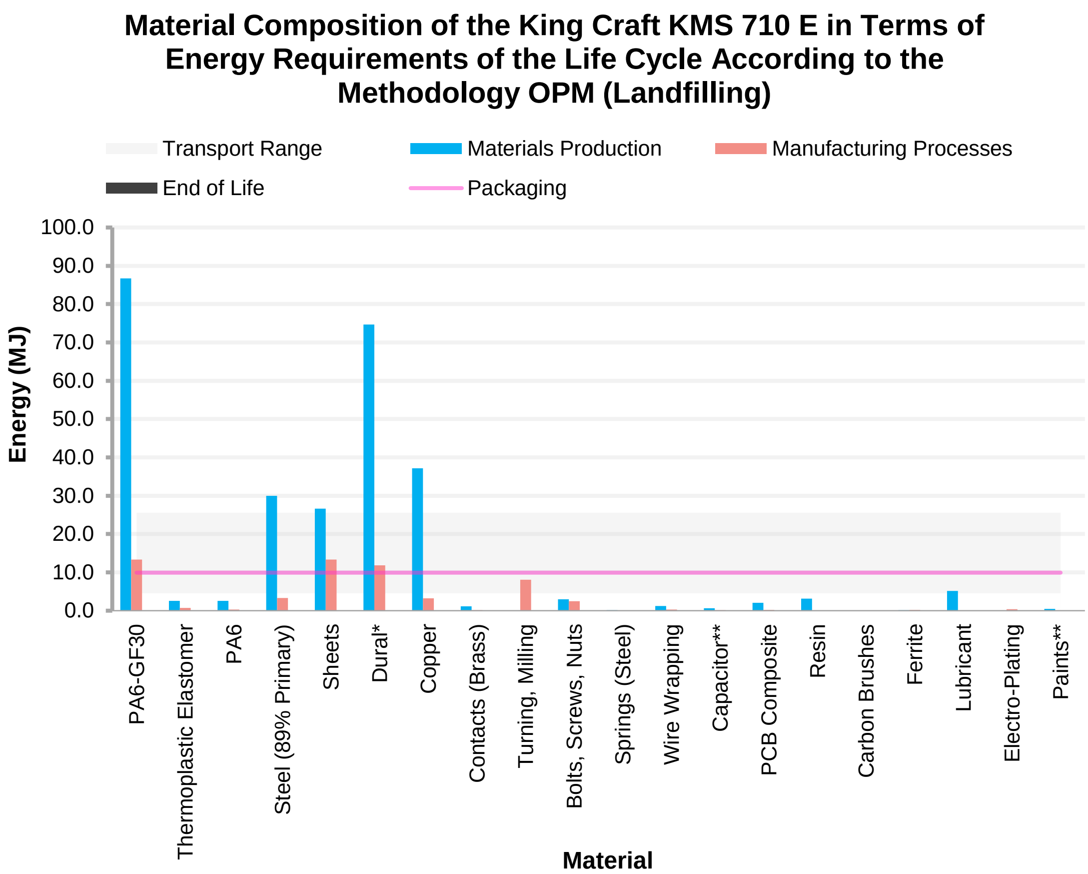


Fig. 6-20 Graph of Reciprocating Saw (Landfilling) – Example of LCA profile (RS1).

6.4 Combustion (LCA Analysis)

The combustion mode (Fig. 6-21) 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. The combusted and non-combusted parts were landfilling. In total, in 61 cases (45.5%), the efficiency of energy recovery by incineration was below Landfilling and Recycling 100%. Combustion was energy efficient in 73 cases (54.5%). The energy recovered was on the recycling curve of 0% to 100% (Recycling 0% = Landfilling, Recycling 100% = Full recycling). The average level of Combustion corresponded to 39.2% ± 7% recycling. The minimum value was 10.6% (sample AG3) and the maximum was 99.6% (sample PD4), corresponding to almost 100% recycling.

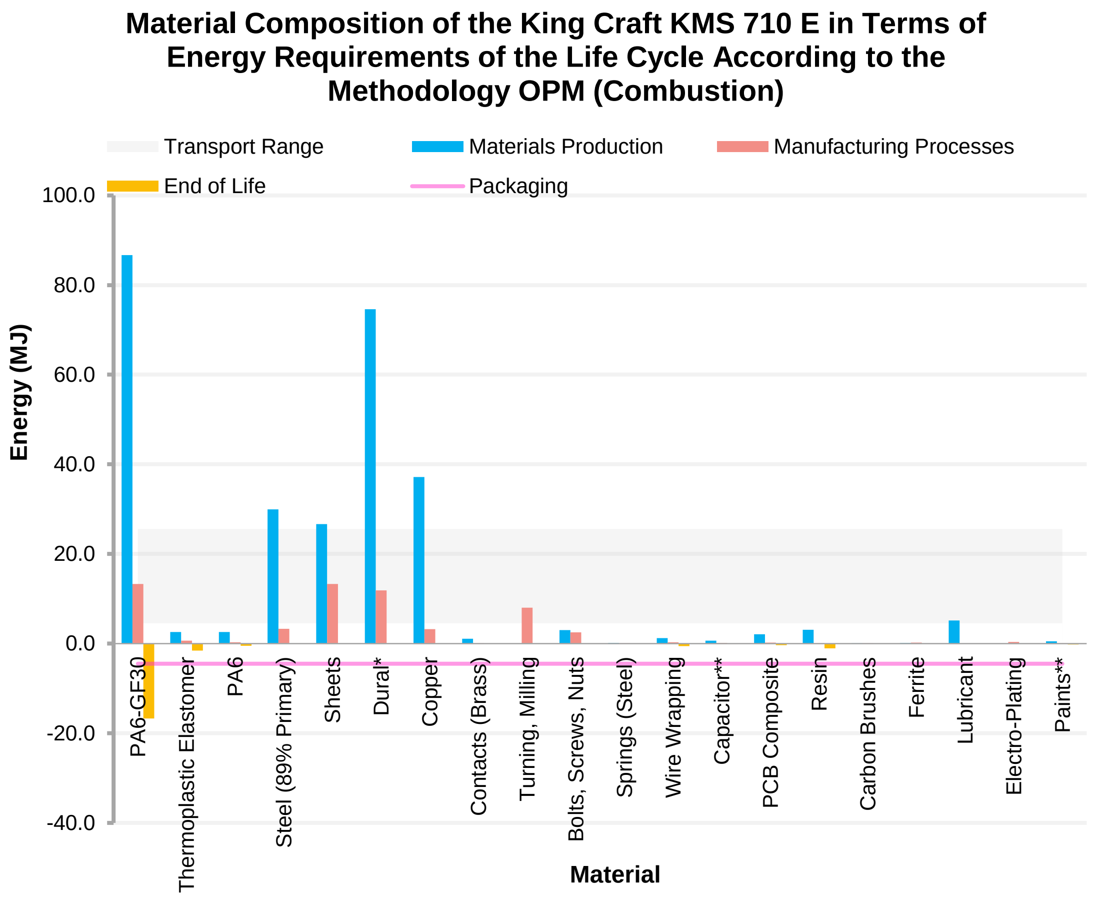


Fig. 6-21 Graph of Reciprocating Saw (Combustion) – Example of LCA profile (RS1).

6.5 Recycling 90% (LCA Analysis)

The return of some plastic material back into circulation is energy intensive because of the higher values for Fuel Share (Recycling) compared to Feedstock Share (Landfilling). Recycling requires high amounts of energy for shredding, separation, and re-milling (Fig. 6-22). The average reduction in energy requirements for 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. 6 pcs. for Handle Jigsaws (samples HJ2, HJ3, HJ4, HJ18, HJ22, HJ24), 4 pcs. for Electric Chainsaws (samples EC11, EC12, EC15, EC16) and 1 pc for Sheet Sanders (sample SS10), Belt Sanders (sample BS7) and Circular Saws (sample CS1). The balance between recycling is even for Electric Chainsaws, where the difference in decline is minimal. 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 0% = Landfilling point could not be found and could not be determined.

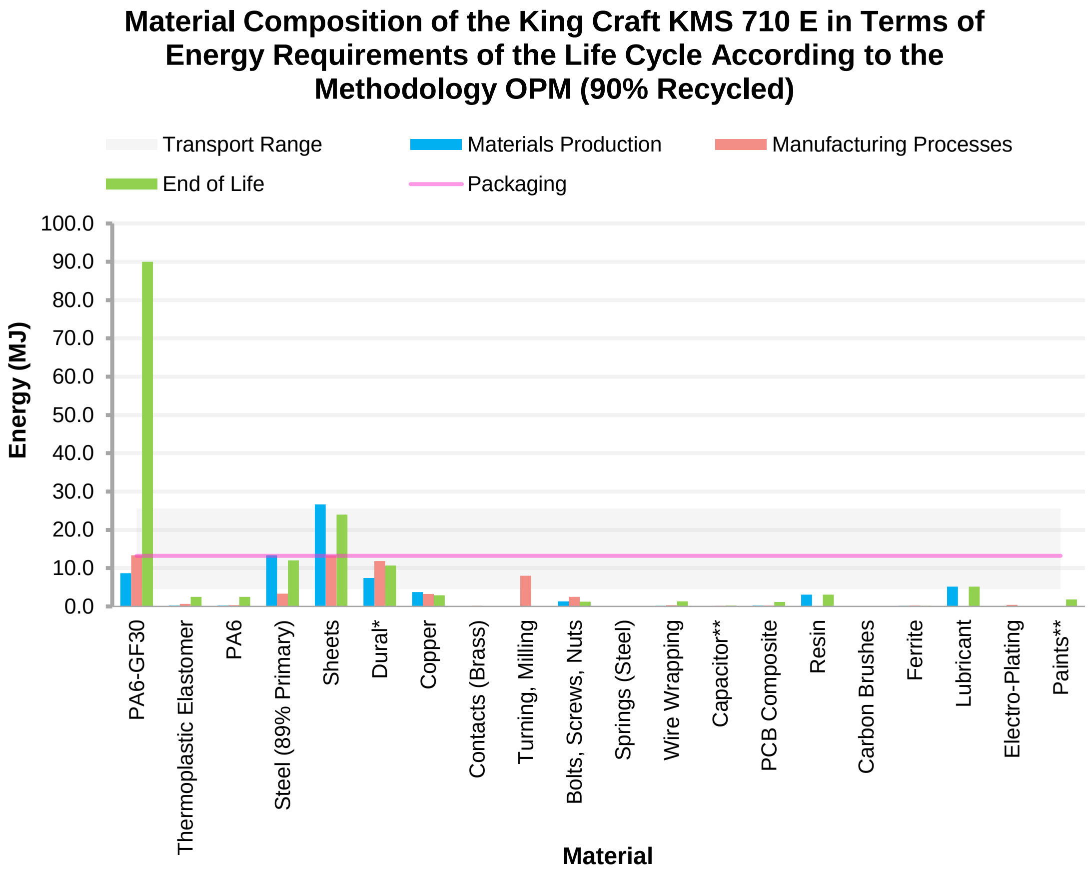


Fig. 6-22 Graph of Reciprocating Saw (Recycling 90%) – Example of LCA profile (RS1).

6.6 Turning Point (LCA Analysis)

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 cycle of Combustion (the point where the amount of energy in combustion is equal to the energy recovered by recycling). For products with a high proportion of used plastics on the inner part and on the outer cover, it was not possible to find a Turning Point on the whole recycling scale 0% to 100% for a total amount of 45.5%.

In the case of finding the Turning Point on the recycling line, it was possible to determine if more energy was recovered by incineration than by recycling 45% (Fig. 6-23). In 47 cases, more energy is recovered in Combustion than in Recycling 45% (Total 35% of samples). This energy gained by the combustion product is up to 12% more efficient relative to recycling by 45%. Recycling 45% is up to 28% more efficient relative to Combustion. On average, there is a 4.1% efficiency due to recycling relative to combustion at alpha = 0.05. Detailed descriptions and values for each sample are given in Appendix C.

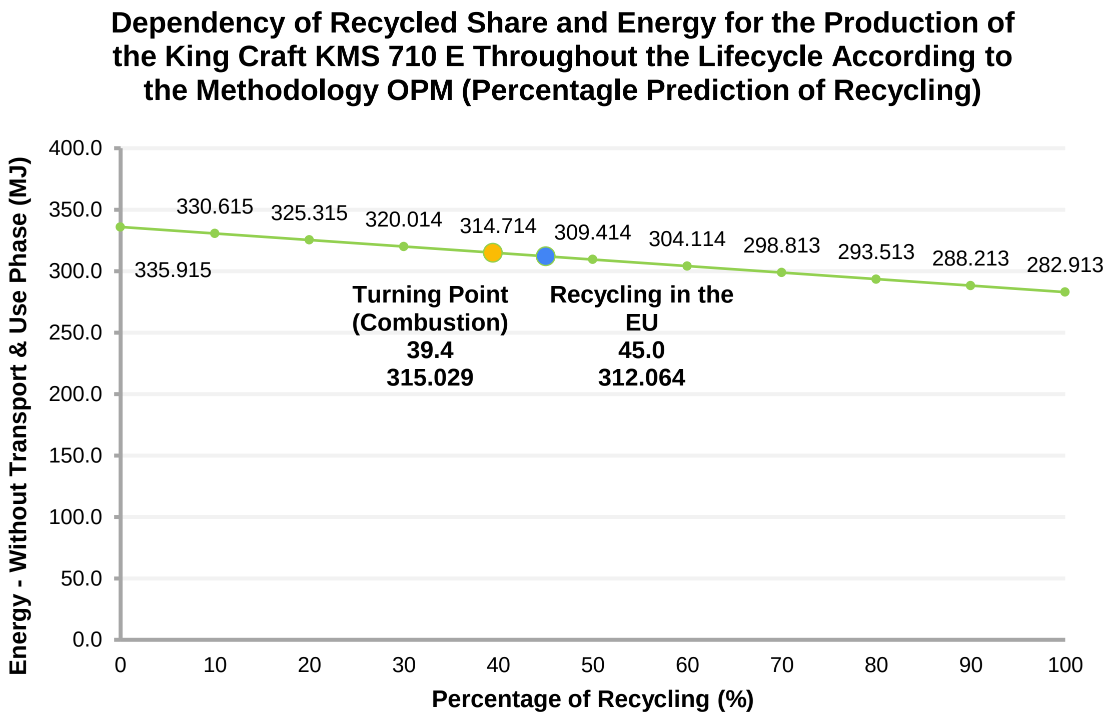


Fig. 6-23 Graph of Reciprocating Saw – Example of Turning Point and Recycling 45% (RS1).

6.7 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. It was found that the most accurate correlation coefficient, which describes the dependence of volume and energy requirements for production, was for the Angle Grinder tool categories that report 97.1 to 98.0%. The lowest value of the correlation indicator was found for the Sheet Sanders tools 62.5% to 76.0%. Values above 0.60 show a strong dependence on a perfect positive association of almost 1.00. The volume vs. energy requirement graphs were further divided into 3 EoL phases. To determine the energy requirements and optimal energy equations, each tool category was calculated in each EoL phase. A total of 30 simulations were run to determine the energy requirements for production in MJ and another 30 simulations of n = 1,000 to determine the same requirements in kWh. In total, 60,000 points were calculated to determine MJ and kWh. Up to 60,000,000 calculations were performed overall. Details of the calculations are provided in the MonteCarlo-Energy-MJ.xlsm and MonteCarlo-Energy-kWh.xlsm.

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

- Random Orbital Sanders (OS_{MJ} = 83.8% ± 0.6%)
- Sheet Sanders (SS_{MJ} = 64.9% ± 4.9%)
- Electric Planers (EP_{MJ} = 78.1% ± 4.3%)
- Handle Jigsaws (HJ_{MJ} = 77.2% ± 1.7%)
- Belt Sanders (BS_{MJ} = 80.7% ± 1.3%)
- Percussion Drills (PD_{MJ} = 84.8% ± 2.2%)
- Circular Saws (CS_{MJ} = 74.3% ± 5.9%)
- Angle Grinders (AG_{MJ} = 97.0% ± 0.3%)
- Electric Chainsaws (EC_{MJ} = 82.5% ± 2.4%)
- Reciprocating Saws (RS_{MJ} = 96.1% ± 0.4%)

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. The computational equations are shown for the graphs of each tool category and types of EoL.

6.7.1 Random Orbital Sanders

Prediction interval with correlation coefficient (greater than 0.8) showing a high dependence of MJ energy and ml volume (Fig. 6-24). The samples report almost the same correlation coefficients of 0.83. The prediction interval is within the range of 25 MJ to 275 MJ. The data obtained from the LCA analysis were for 6 pcs. of power tools.

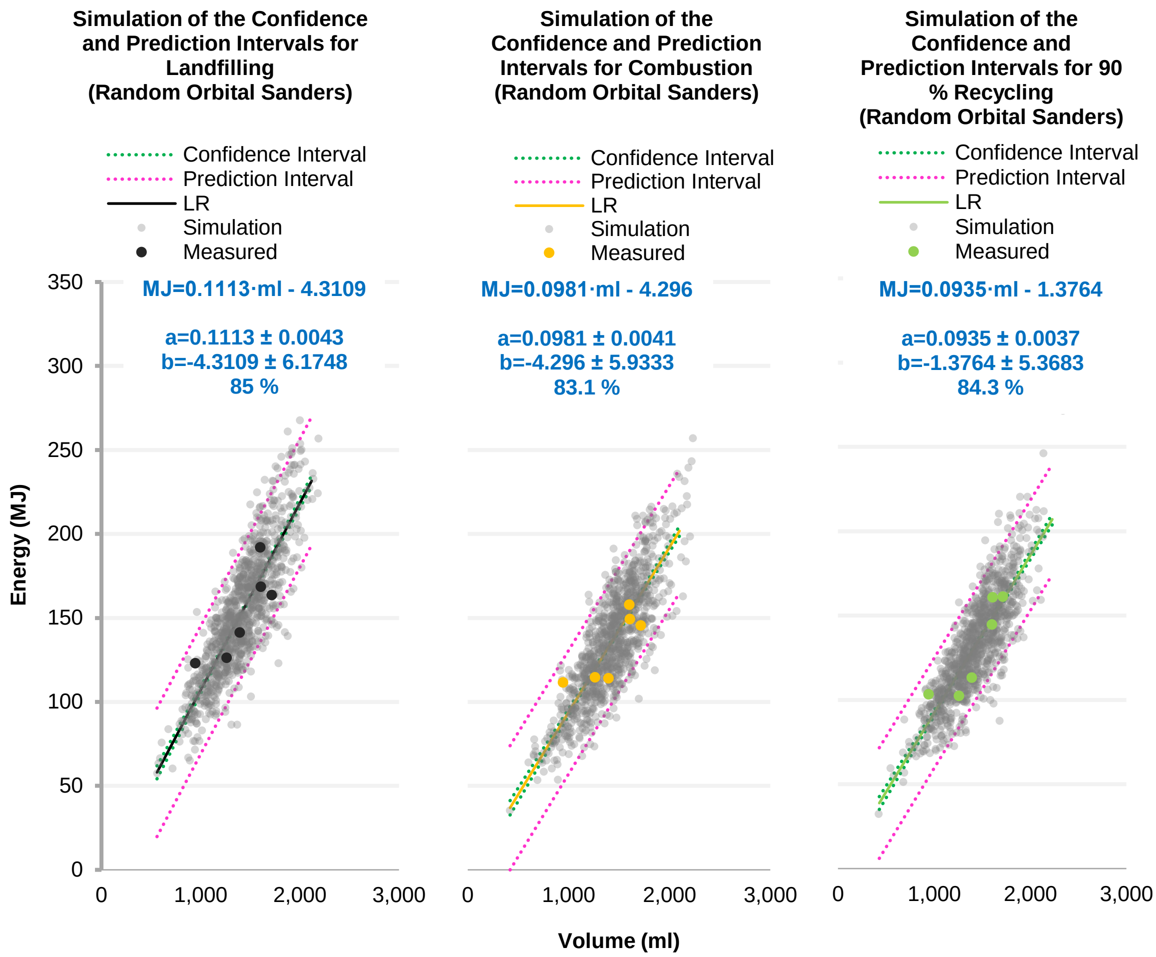


Fig. 6-24 Monte Carlo simulation for Random Orbital Sanders (Landfilling, Combustion and Recycling 90%).

6.7.2 Sheet Sanders

The Sheet Sanders tool (16 pcs.) has the narrow prediction interval of 25 MJ to 225 MJ. Monte Carlo simulation (Fig. 6-25) increased the correlation coefficient by up to 15.8%. The values of the correlation coefficient above 0.6 represent a strong dependence.

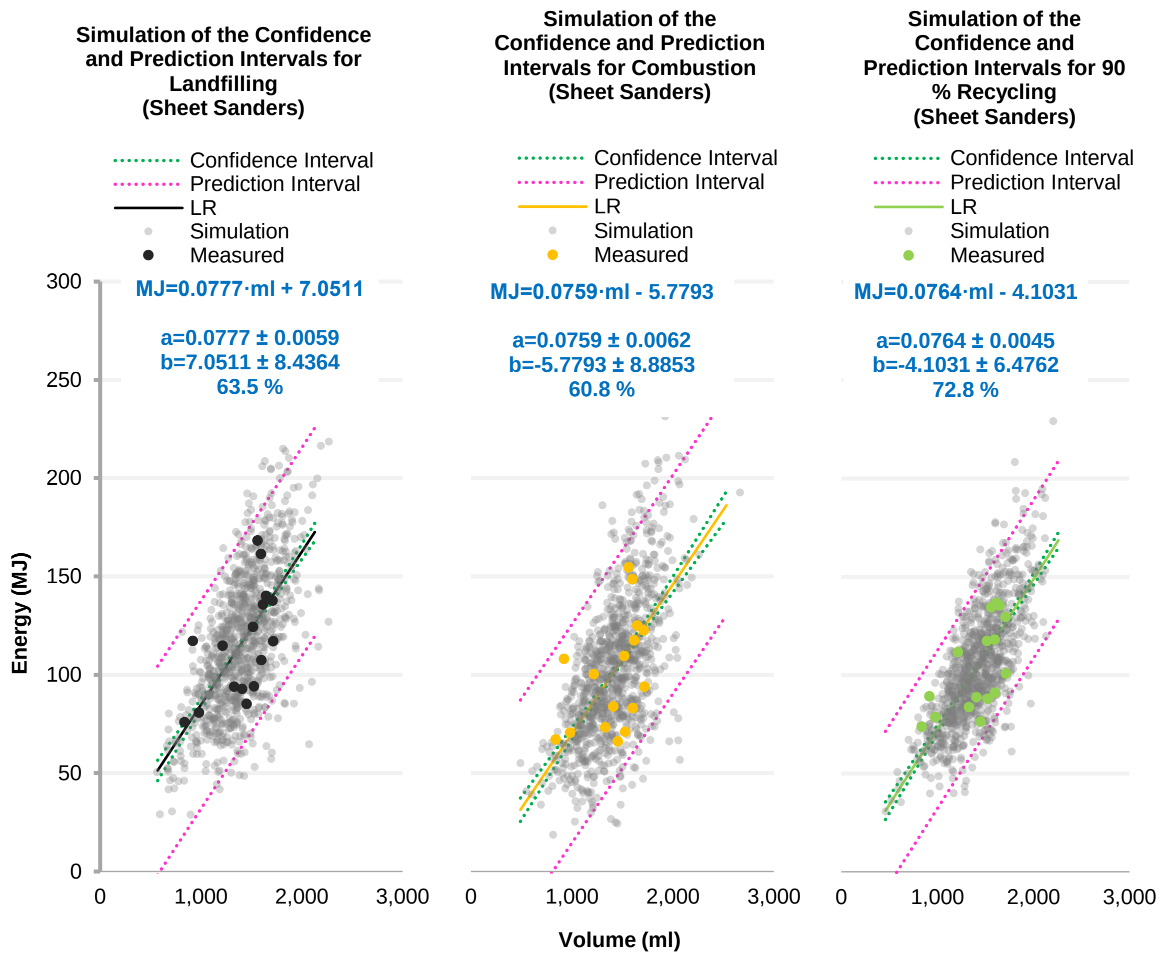


Fig. 6-25 Monte Carlo simulation for Sheet Sanders (Landfilling, Combustion and Recycling 90%).

6.7.3 Electric Planers

The Monte Carlo simulation (Fig. 6-26) increased the correlation coefficient by 19.6%, where values above 0.6 in two cases indicate a strong dependence, and above 0.8 a very strong dependence. The prediction interval is within the range of 50 MJ to 450 MJ for the Sheet Sanders category (9 pcs.), but on a larger range of energy production requirements.

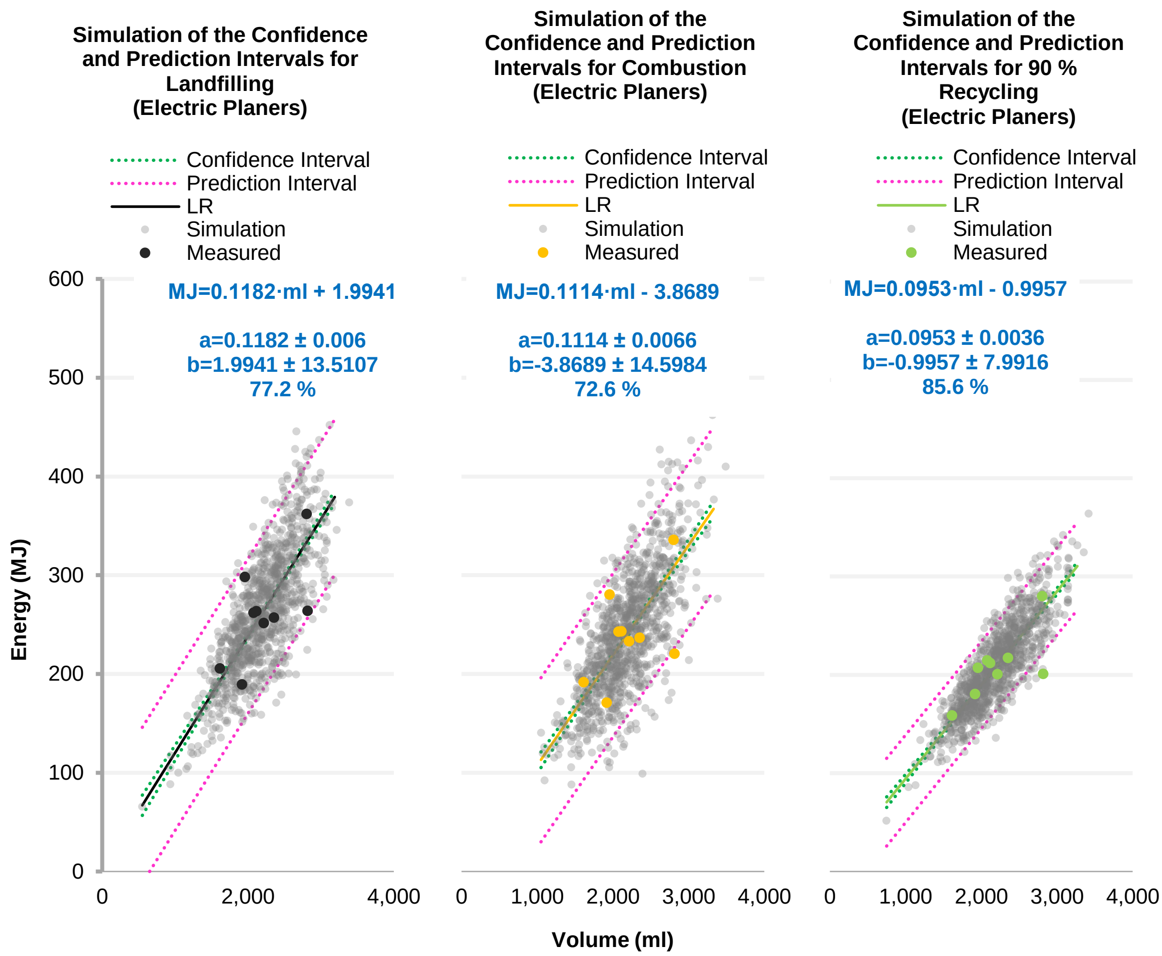


Fig. 6-26 Monte Carlo simulation for Electric Planers (Landfilling, Combustion and Recycling 90%).

6.7.4 Handle Jigsaws

A high number of samples analysed, 24 pcs., has a low correlation coefficient, which was increased by a maximum of 5% through Monte Carlo simulation (Fig. 6-27). The prediction interval is the narrowest range of energy requirements, only 75 MJ to 225 MJ. The values of the correlation coefficient are of the same nature as those of Electric Planers.

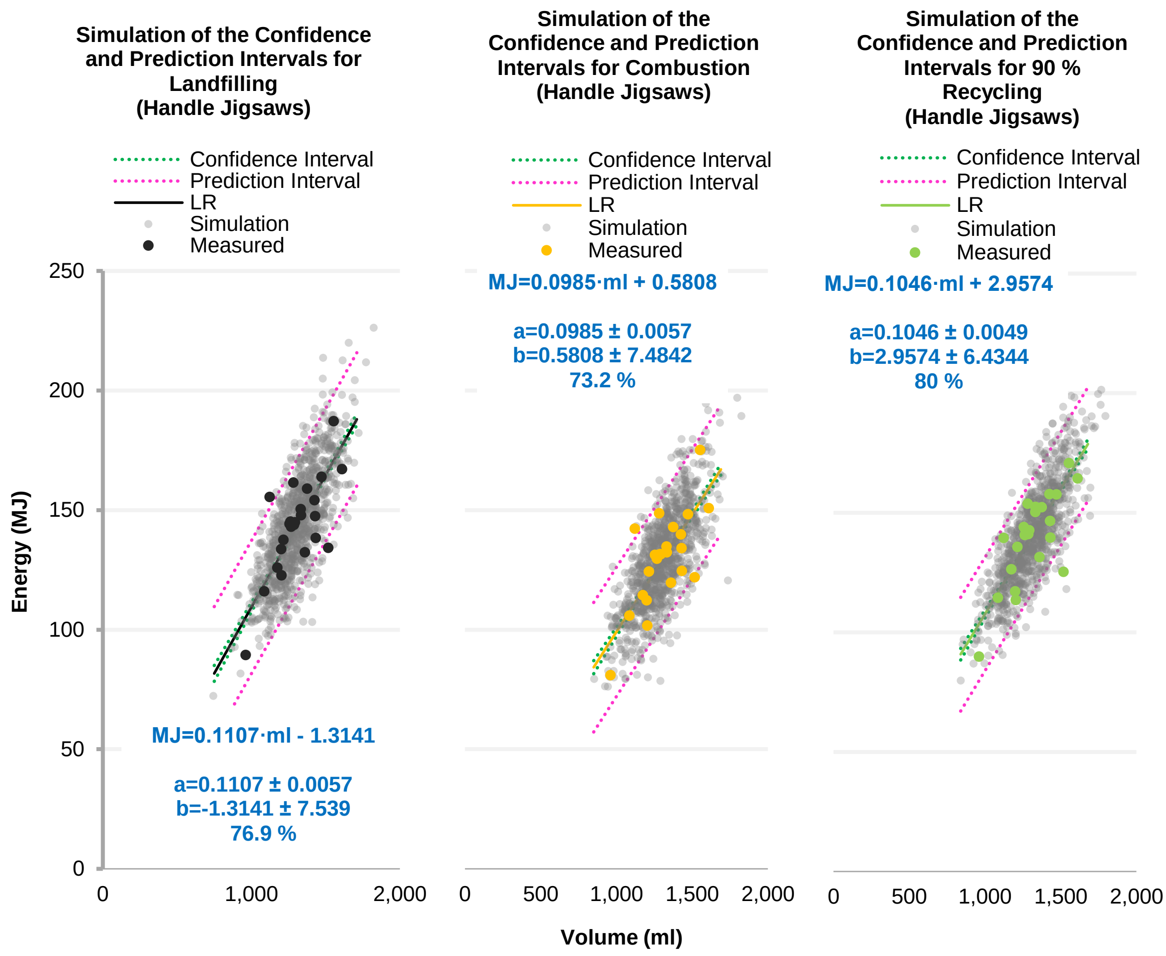
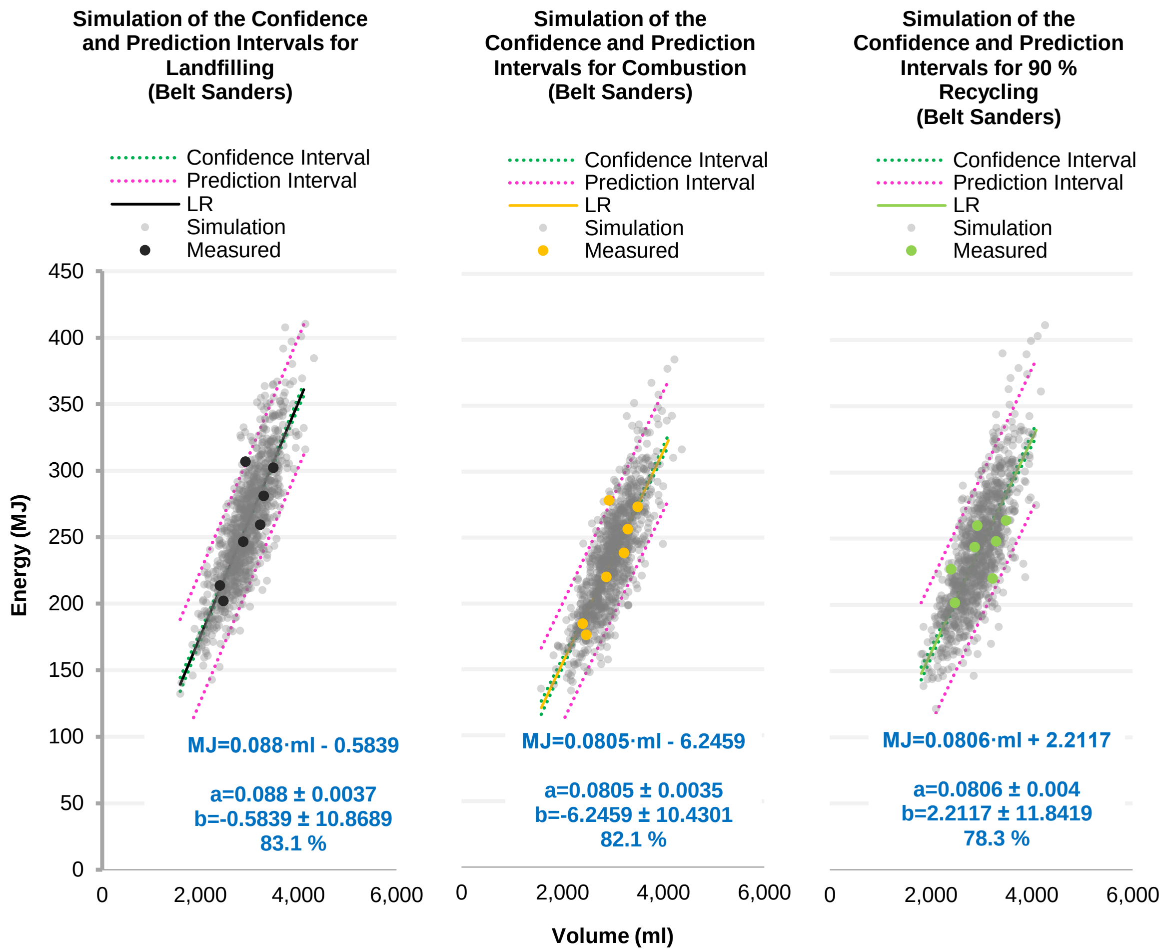


Fig. 6-27 Monte Carlo simulation for Handle Jigsaws (Landfilling, Combustion and Recycling 90%).

6.7.5 Belt Sanders

7 samples of Belt Sanders were analysed with two very strong and one strong correlation coefficient. It was reached by Monte Carlo simulation (Fig. 6-28), to improve the correlation coefficient by 16.3%. Prediction Interval is on a large energy range to produce 100 MJ to 400 MJ.



Figr. 6-28 Monte Carlo simulation for Belt Sanders (Landfilling, Combustion and Recycling 90%).

6.7.6 Percussion Drills

Analysed category of products with a number of 17 pcs. that have a very strong dependence of the MJ volume on the ml volume of the product. The correlation coefficient was not improved due to simulation (Fig. 6-29). The prediction interval was within the range of 50 MJ to 275 MJ.

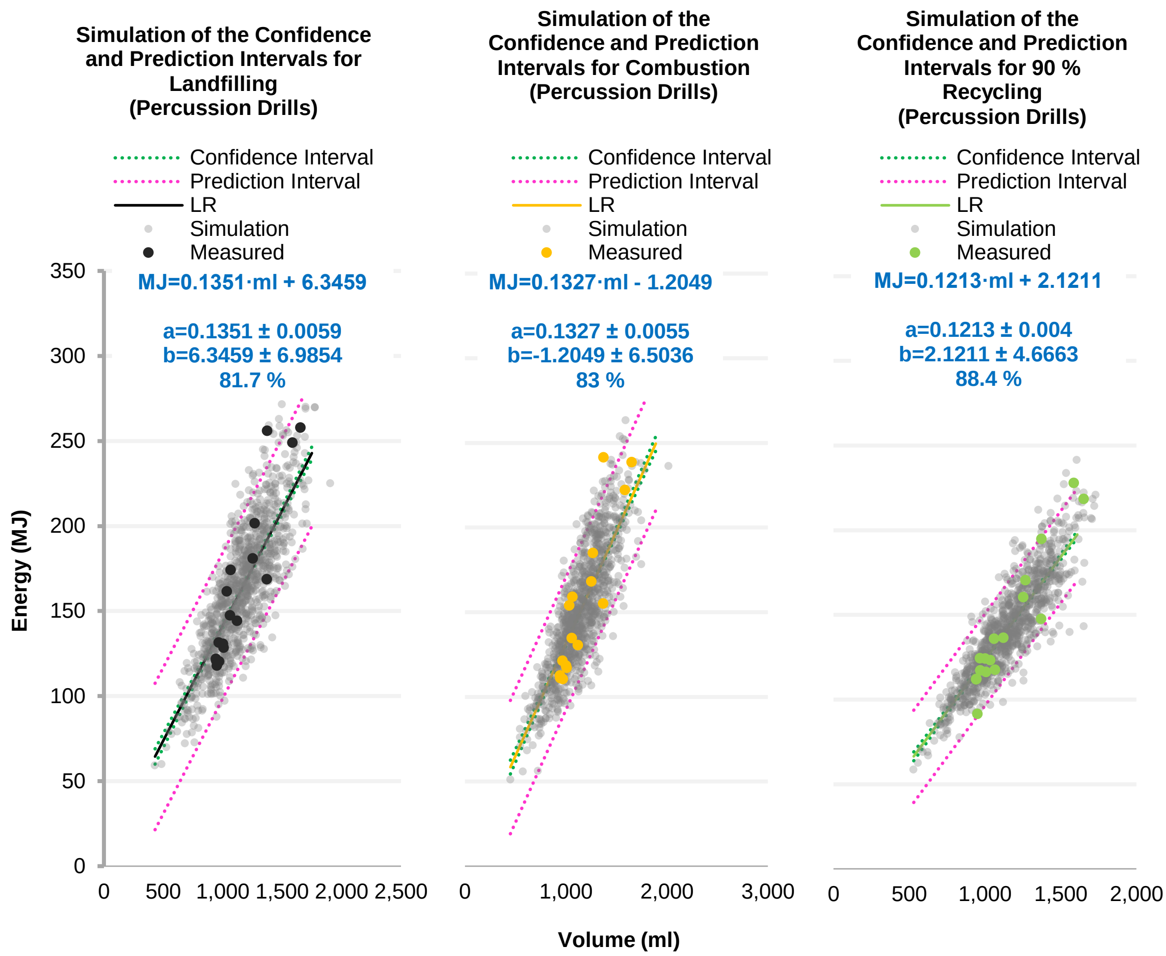


Fig. 6-29 Monte Carlo simulation for Percussion Drills (Landfilling, Combustion and Recycling 90%).

6.7.7 Circular Saws

The highest improvement of 23.6% in the correlation coefficient was achieved for a total of 7 samples. The values of the correlation coefficient are in the range of strong and very strong dependence (Fig. 6-30). The prediction interval is in the wide energy range of 75 MJ to 700 MJ.

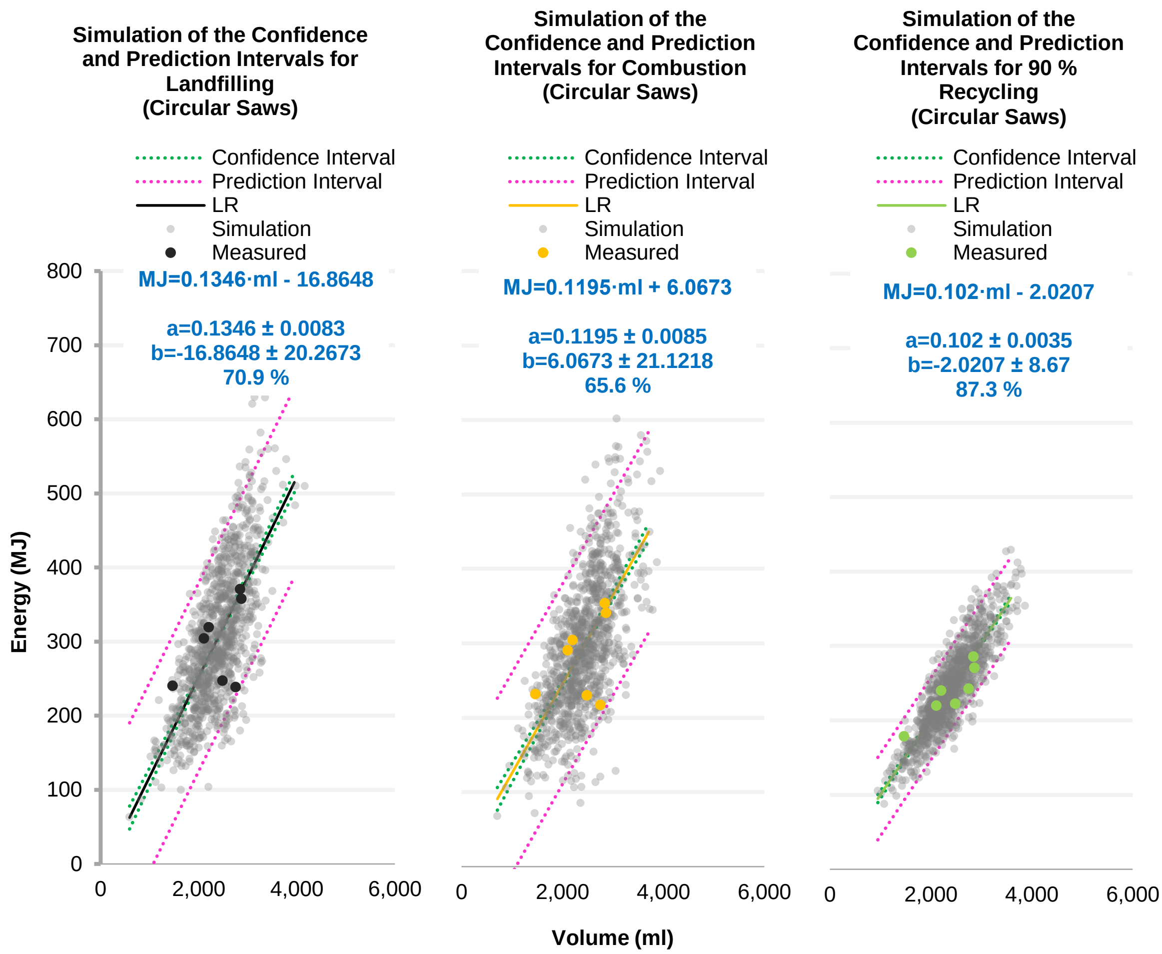


Fig. 6-30 Monte Carlo simulation for Circular Saws (Landfilling, Combustion and Recycling 90%).

6.7.8 Angle Grinders

Analysed category of products with the highest number of samples 26 pcs. The Monte Carlo simulation (Fig. 6-31) achieved an improvement in the correlation coefficient of up to 1%, and these are the best results from the simulation. The product category shows an almost perfect positive dependence. The prediction interval is narrow within a range of 50 MJ to 550 MJ.

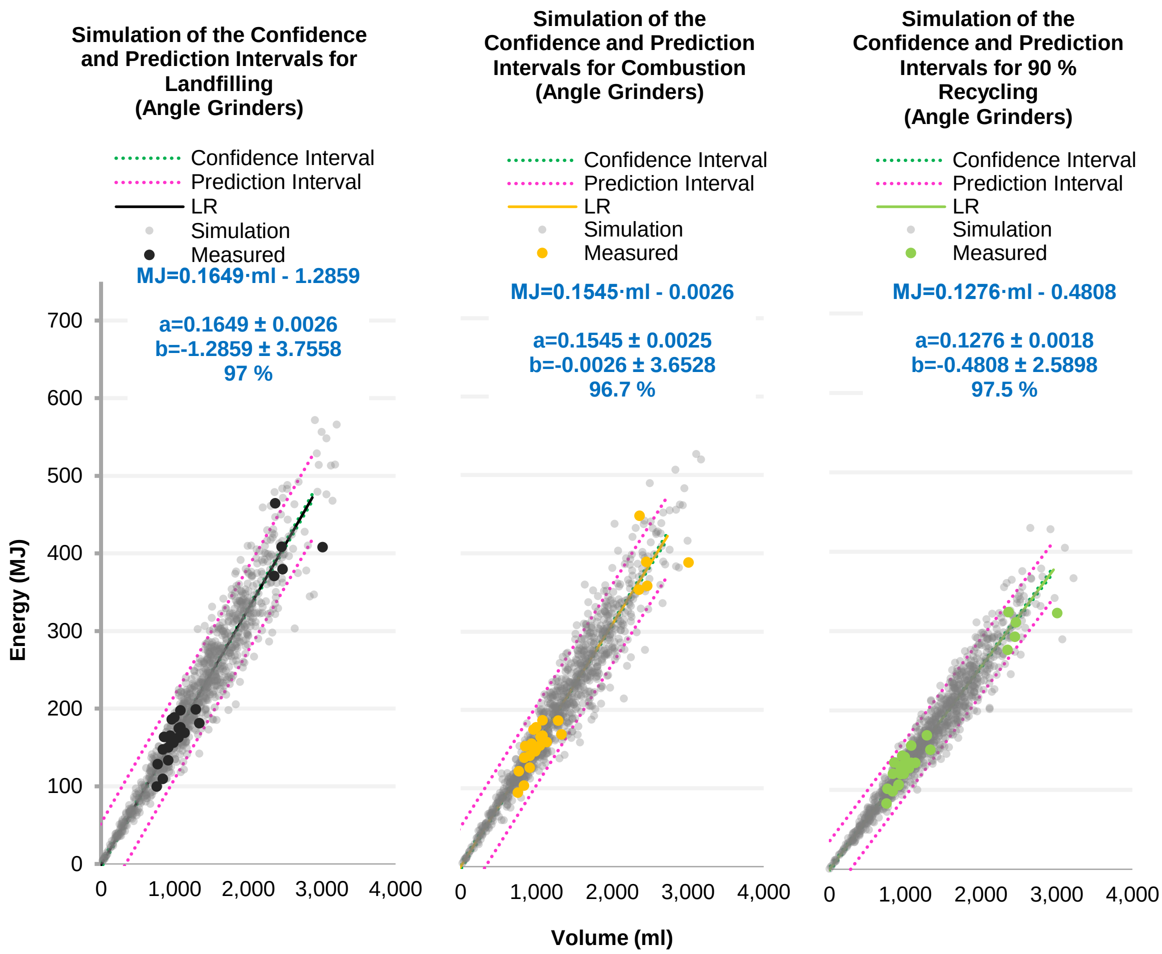


Fig. 6-31 Monte Carlo simulation for Angle Grinders (Landfilling, Combustion and Recycling 90%).

6.7.9 Electric Chainsaws

Power tools Electric Chainsaws samples achieve up to 10.8% improvement in correlation coefficient by Monte Carlo simulations (Fig. 6-32). The prediction interval was 100 MJ to 700 MJ with a very strong dependence. The number of samples analysed was 16 pcs.

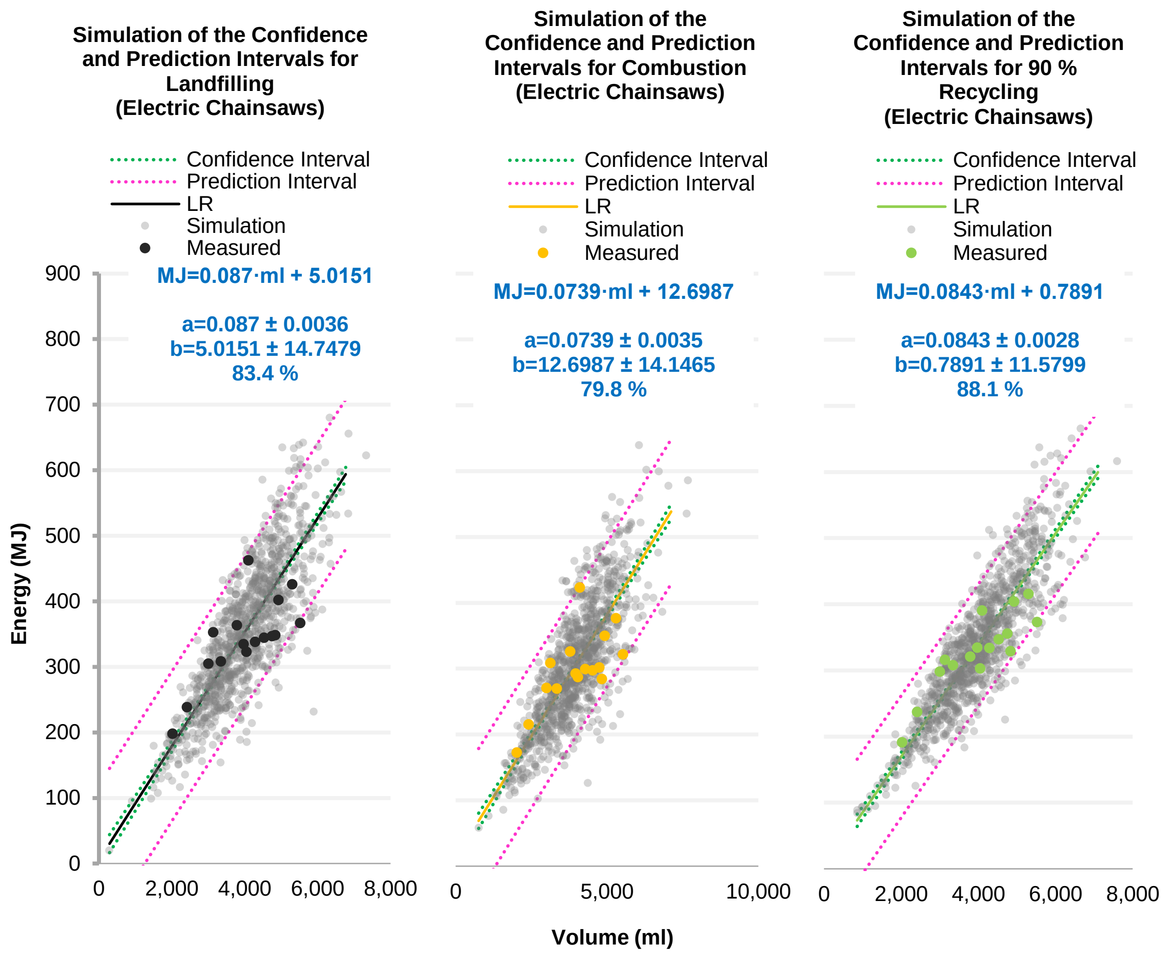


Fig. 6-32 Monte Carlo simulation for Electric Chainsaws (Landfilling, Combustion and Recycling 90%).

6.7.10 Reciprocating Saws

Power tool samples with a sample size of 6 pcs. achieved high correlation coefficient values (Fig. 6-33). The simulation values were almost 3.1% lower than the data obtained from the LCA calculation. The correlation coefficient values have almost perfect positive dependence. The prediction interval is within the range of 100 MJ to 400 MJ and is very narrow.

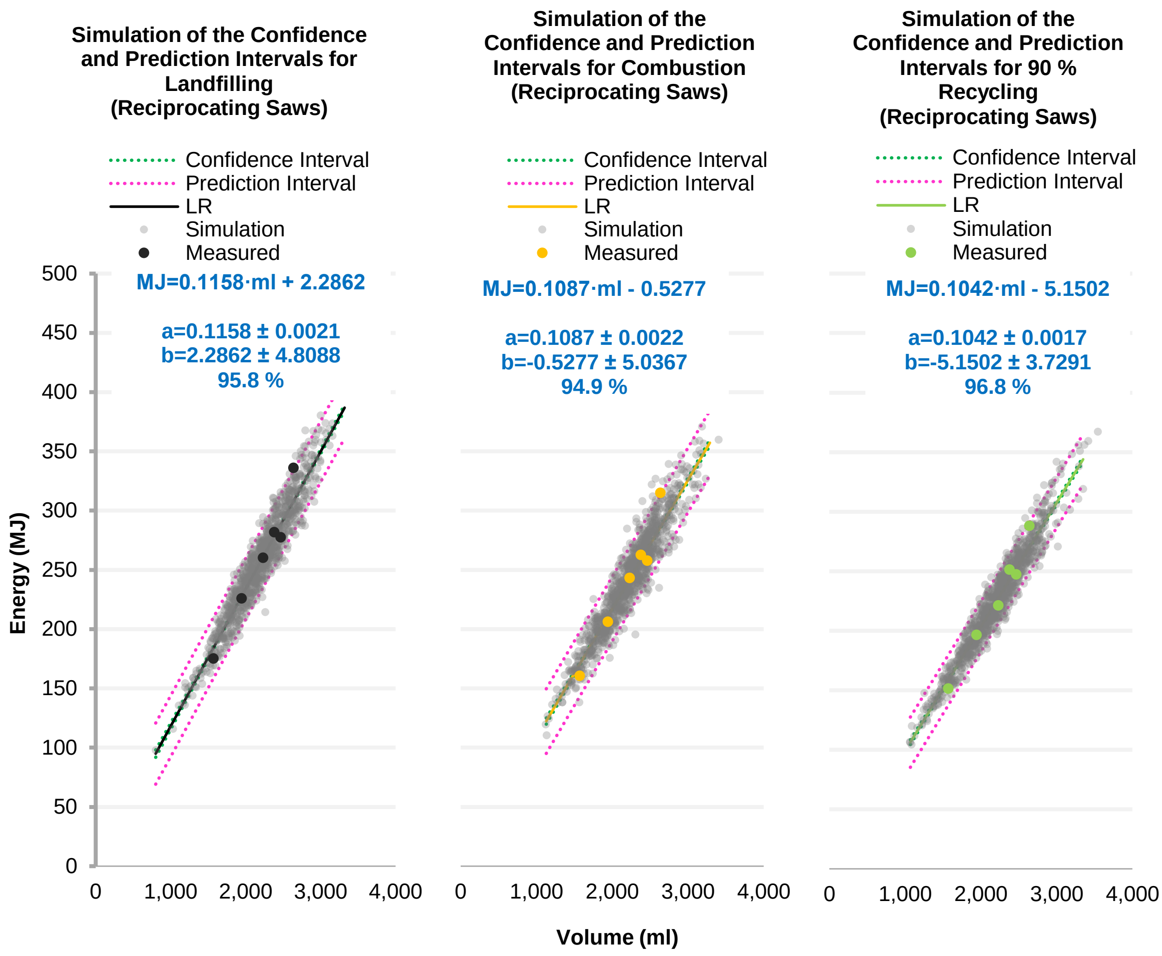


Fig. 6-33 Monte Carlo simulation for Reciprocating Saws (Landfilling, Combustion and Recycling 90%).

6.8 Energy for the Categories of Power Tools

The calculation of energy requirements for production was calculated by Monte Carlo simulation in units:

- Energy Requirements in Units MJ,
- Energy Requirements in Units kWh.

The results from the Monte Carlo simulation for the energy requirements for production in kWh were calculated directly from the LCA analysis of the individual samples. The values obtained for the *p*-value = 0.05 with normal distribution had better results for the correlation coefficient r_{xy} (kWh) in 100% compared to the correlation coefficient r_{xy} (MJ). The improvement in the correlation coefficient r_{xy} was in the range of 0.0% to 7.4% (Tab. 6-14).

Tab. 6-14 Energy correlation coefficients MJ and kWh and their comparison of power tools.

Alias	Category of Power Tools	End Of Life	MJ r_{xy} (%)	kWh r_{xy} (%)	Difference r_{xy} (%)
OS	Random Orbital Sanders	Landfilling	85.0	87.0	2.0
OS	Random Orbital Sanders	Combustion	83.1	84.0	0.9
OS	Random Orbital Sanders	Recycling	84.3	88.1	3.8
SS	Sheet Sanders	Landfilling	63.5	70.7	7.2
SS	Sheet Sanders	Combustion	60.8	63.3	2.5
SS	Sheet Sanders	Recycling	72.8	76.6	3.8
EP	Electric Planers	Landfilling	77.2	80.0	2.8
EP	Electric Planers	Combustion	72.6	74.1	1.5
EP	Electric Planers	Recycling	85.6	88.0	2.4
HJ	Handle Jigsaws	Landfilling	76.9	80.1	3.2
HJ	Handle Jigsaws	Combustion	73.2	78.1	4.9
HJ	Handle Jigsaws	Recycling	80.0	82.4	2.4
BS	Belt Sanders	Landfilling	83.1	85.8	2.7
BS	Belt Sanders	Combustion	82.1	84.2	2.1
BS	Belt Sanders	Recycling	78.3	81.4	3.1
PD	Percussion Drills	Landfilling	81.7	86.2	4.5
PD	Percussion Drills	Combustion	83.0	85.2	2.2
PD	Percussion Drills	Recycling	88.4	91.1	2.7
CS	Circular Saws	Landfilling	70.9	74.3	3.4
CS	Circular Saws	Combustion	65.6	73.0	7.4
CS	Circular Saws	Recycling	87.3	89.0	1.7
AG	Angle Grinders	Landfilling	97.0	97.0	0.0
AG	Angle Grinders	Combustion	96.7	97.2	0.5
AG	Angle Grinders	Recycling	97.5	98.0	0.5
EC	Electric Chainsaws	Landfilling	83.4	86.4	3.0
EC	Electric Chainsaws	Combustion	79.8	84.1	4.3
EC	Electric Chainsaws	Recycling	88.1	90.0	1.9
RS	Reciprocating Saws	Landfilling	95.8	97.1	1.3
RS	Reciprocating Saws	Combustion	94.9	96.2	1.3
RS	Reciprocating Saws	Recycling	96.8	97.0	0.2

The graph of the relationship between Energy MJ and volume ml contains the different product categories in the three EoL phases (Fig. 6-34). The range of products analysed is from 0 MJ to 600 MJ and with volumes from 0 ml to 7,000 ml. The near-zero initial values and linearization correspond to the energy-volume dependence (correlation coefficients with strong dependence). The fan-shaped distribution of the tool categories reflects their type, design, ergonomics and use. This distribution of categorised tools, including the three EoL phases, shows the nature characteristics that are embedded in the tools themselves. Tools with low volume, high energy and high concentration of individual parts correspond to the higher steepness of the curve. This phenomenon is characteristic for Percussion Drills, Angle Grinders, and Reciprocating Saws. A less steep curve rise corresponds to tools such as Sheet Sanders, Belt Sanders and Electric Chainsaws, which are larger in volume for ergonomic reasons as they require sufficient grip and guidance of the tool. Higher volumetric proportions with lower energy requirements are reflected in the high internal air volume in the tools as a result of different product designs (high variability in tool design). The Electric Chainsaws tool category was the only one with a higher energy requirement within the Recycling 90%. The usual arrangement (from most energy per production to least) is Landfilling, Combustion and Recycling 90%. Electric Chainsaws have a higher energy expenditure 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 equation for determining the energy to produce products in MJ and kWh grouped product types into 4 classes:

- Energy Class E1 (Angle Grinders, Percussion Drills),
- Energy Class E2 (Random Orbital Sanders, Electric Planers,),
- Energy Class E3 (Handle Jigsaws, Circular Saws, Reciprocating Saws),
- Energy Class E4 (Sheet Sanders, Belt Sanders, Electric Chainsaws).

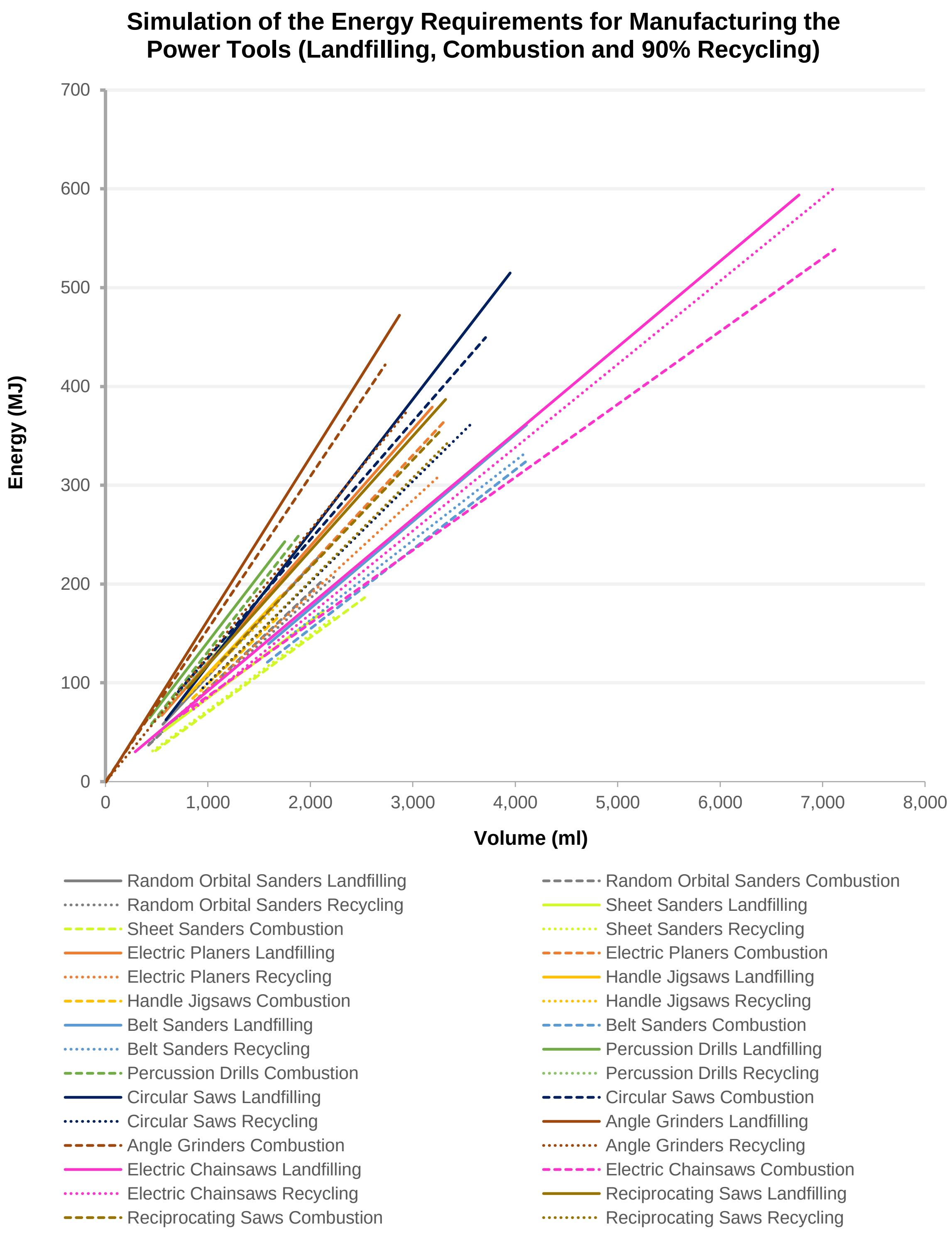


Fig. 6-34 Energy simulation of power tools category (Landfilling, Combustion & Recycling 90%).

The calculation equations of the energy requirements for production are included in the graphs in Chapters 6.7.1 to 6.7.10. The equations determined from the Monte Carlo simulation describe the MJ dependence of the energy MJ on the ml volume of the product (Tab. 6-15). They describe the observed dependence with *p*-value = 0.05 (95% confidence level). The calculations can be performed on categorised products including the three ends of EoL. The maximum values represent energy-intensive power tools.

Percentage comparison of max. energy consumption for EoL Recycling 90% versus Landfilling:

- Random Orbital Sanders ($OS_{LF\text{-}RC}$ = 81.3%),
- Sheet Sanders ($SS_{LF\text{-}RC}$ = 94.3%),
- Electric Planers ($EP_{LF\text{-}RC}$ = 80.3%),
- Handle Jigsaws ($HJ_{LF\text{-}RC}$ = 88.5%),
- Belt Sanders ($BS_{LF\text{-}RC}$ = 89.0%),
- Percussion Drills ($PD_{LF\text{-}RC}$ = 83.1%),
- Circular Saws ($CS_{LF\text{-}RC}$ = 78.6%),
- Angle Grinders ($AG_{LF\text{-}RC}$ = 78.7%),
- Electric Chainsaws ($EC_{LF\text{-}RC}$ = 97.9%),
- Reciprocating Saws ($RS_{LF\text{-}RC}$ = 97.4%).

The highest energy savings are achieved at Recycling 90% for Angle Grinders and Circular Saws with a value of approx. 78.6%. The least efficient Recycling 90% is found in the Sheet Sanders, Reciprocating Saws, and Electric Chainsaws product category (more than 94%). The reason for this is the large amount of plastic (outer cover and internal components) to achieve a suitable design and ergonomics (grip of the device).

Tab. 6-15 Equations for calculating energy requirements for manufacturing power tools.

Category of Power Tools	End Of Life	Equation	r_{xy} (%)	max. (MJ)
Random Orbital Sanders	Landfilling	MJ = 0.113 ml - 6.3417	87.4	244.455
Random Orbital Sanders	Combustion	MJ = 0.0987 ml - 5.0446	85.4	222.022
Random Orbital Sanders	Recycling	MJ = 0.0923 ml + 0.3706	87.1	198.878
Sheet Sanders	Landfilling	MJ = 0.0858 ml - 1.8374	71.4	180.105
Sheet Sanders	Combustion	MJ = 0.0767 ml - 6.1391	62.5	160.992
Sheet Sanders	Recycling	MJ = 0.0802 ml - 7.3565	76.0	169.927
Electric Planers	Landfilling	MJ = 0.1244 ml - 12.4813	80.3	430.425
Electric Planers	Combustion	MJ = 0.1197 ml - 20.542	75.8	391.108
Electric Planers	Recycling	MJ = 0.0962 ml - 2.5479	87.8	345.671
Handle Jigsaws	Landfilling	MJ = 0.1148 ml - 6.8751	81.5	200.858
Handle Jigsaws	Combustion	MJ = 0.1006 ml - 2.5794	77.1	170.414
Handle Jigsaws	Recycling	MJ = 0.1057 ml + 1.1723	82.4	177.727
Belt Sanders	Landfilling	MJ = 0.0916 ml - 10.1117	85.0	372.784
Belt Sanders	Combustion	MJ = 0.0789 ml - 1.5414	84.0	336.278
Belt Sanders	Recycling	MJ = 0.0863 ml - 14.8796	80.5	331.958
Percussion Drills	Landfilling	MJ = 0.1464 ml - 4.6675	86.0	254.479
Percussion Drills	Combustion	MJ = 0.1369 ml - 7.926	85.4	223.498
Percussion Drills	Recycling	MJ = 0.1253 ml - 2.8582	91.2	211.347
Circular Saws	Landfilling	MJ = 0.1398 ml - 26.7613	74.8	507.416
Circular Saws	Combustion	MJ = 0.1268 ml - 10.7441	72.2	502.604
Circular Saws	Recycling	MJ = 0.1016 ml - 0.3742	89.1	398.873
Angle Grinders	Landfilling	MJ = 0.1643 ml - 0.6158	97.1	470.901
Angle Grinders	Combustion	MJ = 0.1543 ml - 0.3622	97.1	451.764
Angle Grinders	Recycling	MJ = 0.1274 ml - 0.0324	98.0	370.747
Electric Chainsaws	Landfilling	MJ = 0.0914 ml - 12.6966	85.5	591.437
Electric Chainsaws	Combustion	MJ = 0.0817 ml - 13.4431	84.4	563.673
Electric Chainsaws	Recycling	MJ = 0.0854 ml - 2.9266	90.0	578.982
Reciprocating Saws	Landfilling	MJ = 0.117 ml - 0.1189	96.5	350.837
Reciprocating Saws	Combustion	MJ = 0.1096 ml - 2.7789	96.0	356.717
Reciprocating Saws	Recycling	MJ = 0.1029 ml - 1.9729	97.3	341.858

6.9 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 analysis. Energy production requirements in kWh (values were converted to kWh directly in the LCA analysis 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 phases.

The distribution of the product categories in the graph (Fig. 6-35) of the kg CO_2 eq. emissions corresponds to the fan charts of the energy for production in MJ and kWh (converting 1 MJ = 0.2778 kWh).

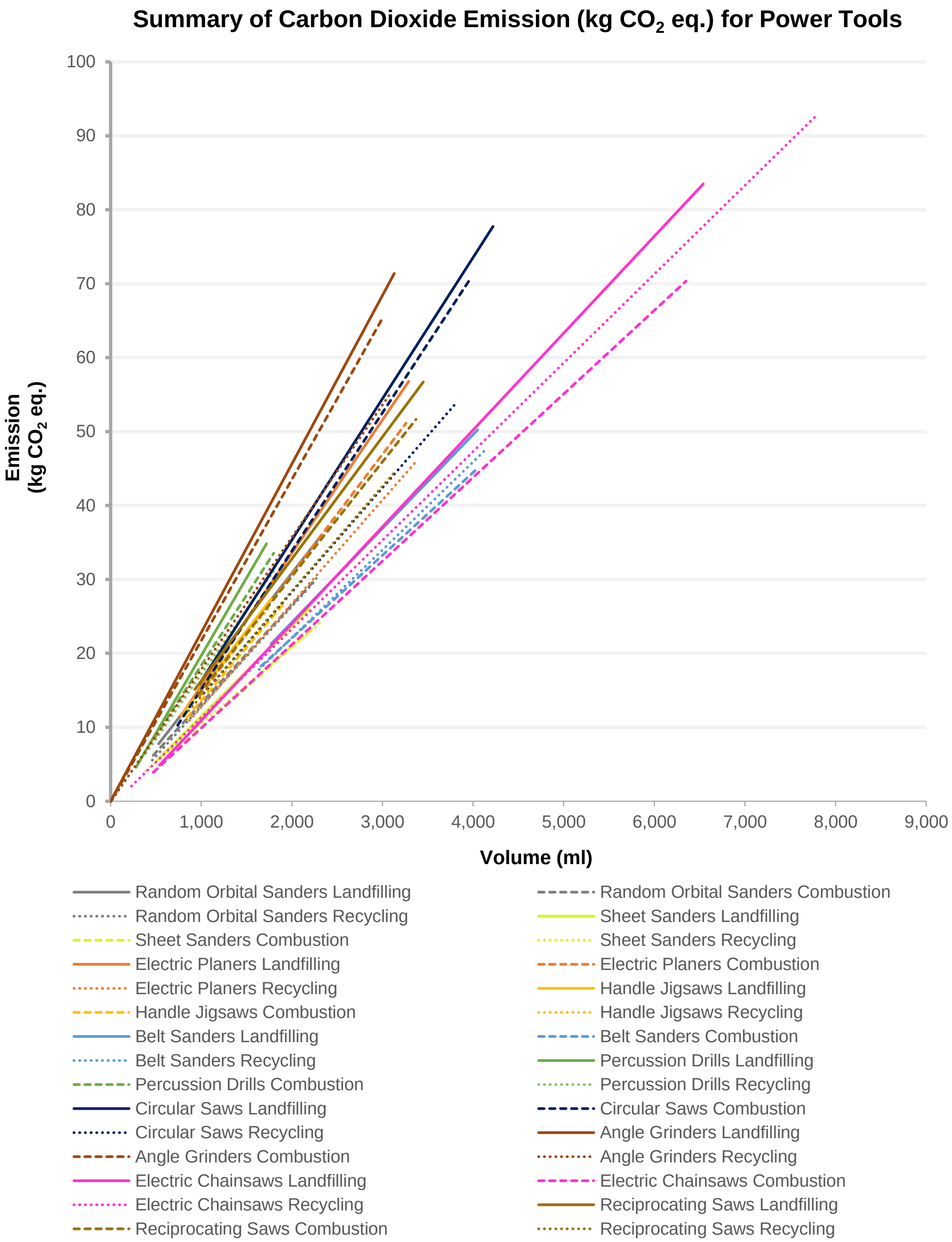


Fig. 6-35 Emission kg CO_2 eq. simulation of power tools category (Landfilling, Combustion & Recycling 90%).

Calculation of emissions for categorised products in the three stages of EoL (Tab. 6-16). The equations for determining the kg CO_2 eq. emissions fit the input data. The positions of max. kg CO_2 eq. are different in the three cases Sheet Sanders, Belt Sanders and Electric Chainsaws (EoL Recycling 90% is higher than Combustion). Another difference is that EoL Recycling 90% for Electric Chainsaws is higher than Landfilling. The reason for these differences is the maximum values from the Monte Carlo simulations for the energy in kWh.

Tab. 6-16 Equations for calculating emission kg CO_2 eq. requirements for manufacturing power tools.

Alias	Category of Power Tools	End Of Life	Equations (kg CO_2 eq.)	max. (kg CO_2 eq.)
OS	Random Orbital Sanders	Landfilling	$kgCO_2$(LF)-OS = 0.0157 ml - 0.5501	36.031
OS	Random Orbital Sanders	Combustion	$kgCO_2$(CM)-OS = 0.0133 ml - 0.0458	30.145
OS	Random Orbital Sanders	Recycling	$kgCO_2$(RC)-OS = 0.0135 ml - 0.6592	29.851
SS	Sheet Sanders	Landfilling	$kgCO_2$(LF)-SS = 0.0122 ml - 0.7163	26.002
SS	Sheet Sanders	Combustion	$kgCO_2$(CM)-SS = 0.0109 ml - 0.954	23.353
SS	Sheet Sanders	Recycling	$kgCO_2$(RC)-SS = 0.0104 ml + 0.0894	24.113
EP	Electric Planers	Landfilling	$kgCO_2$(LF)-EP = 0.018 ml - 2.4227	56.797
EP	Electric Planers	Combustion	$kgCO_2$(CM)-EP = 0.0162 ml - 1.6797	51.132
EP	Electric Planers	Recycling	$kgCO_2$(RC)-EP = 0.014 ml - 1.2567	46.203
HJ	Handle Jigsaws	Landfilling	$kgCO_2$(LF)-HJ = 0.0159 ml - 0.7933	27.350
HJ	Handle Jigsaws	Combustion	$kgCO_2$(CM)-HJ = 0.0144 ml - 0.789	26.859
HJ	Handle Jigsaws	Recycling	$kgCO_2$(RC)-HJ = 0.015 ml - 0.0319	26.068
BS	Belt Sanders	Landfilling	$kgCO_2$(LF)-BS = 0.0127 ml - 1.2017	50.233
BS	Belt Sanders	Combustion	$kgCO_2$(CM)-BS = 0.0112 ml - 0.3311	45.141
BS	Belt Sanders	Recycling	$kgCO_2$(RC)-BS = 0.0119 ml - 1.703	47.801
PD	Percussion Drills	Landfilling	$kgCO_2$(LF)-PD = 0.021 ml - 1.2947	34.825
PD	Percussion Drills	Combustion	$kgCO_2$(CM)-PD = 0.019 ml - 0.6383	33.562
PD	Percussion Drills	Recycling	$kgCO_2$(RC)-PD = 0.0175 ml - 0.3419	31.683
CS	Circular Saws	Landfilling	$kgCO_2$(LF)-CS = 0.0191 ml - 2.8581	77.744
CS	Circular Saws	Combustion	$kgCO_2$(CM)-CS = 0.0187 ml - 3.557	70.869
CS	Circular Saws	Recycling	$kgCO_2$(RC)-CS = 0.0141 ml + 0.0978	53.537
AG	Angle Grinders	Landfilling	$kgCO_2$(LF)-AG = 0.0228 ml + 0.0182	71.382
AG	Angle Grinders	Combustion	$kgCO_2$(CM)-AG = 0.0218 ml - 0.0742	65.544
AG	Angle Grinders	Recycling	$kgCO_2$(RC)-AG = 0.0179 ml - 0.0955	54.858
EC	Electric Chainsaws	Landfilling	$kgCO_2$(LF)-EC = 0.0131 ml - 2.1882	83.486
EC	Electric Chainsaws	Combustion	$kgCO_2$(CM)-EC = 0.0113 ml - 1.4077	70.347
EC	Electric Chainsaws	Recycling	$kgCO_2$(RC)-EC = 0.012 ml - 0.7109	92.769
RS	Reciprocating Saws	Landfilling	$kgCO_2$(LF)-RS = 0.0165 ml - 0.2223	56.703
RS	Reciprocating Saws	Combustion	$kgCO_2$(CM)-RS = 0.0155 ml - 0.5875	51.648
RS	Reciprocating Saws	Recycling	$kgCO_2$(RC)-RS = 0.0142 ml + 0.0105	44.599

6.10 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. 6-36). 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).

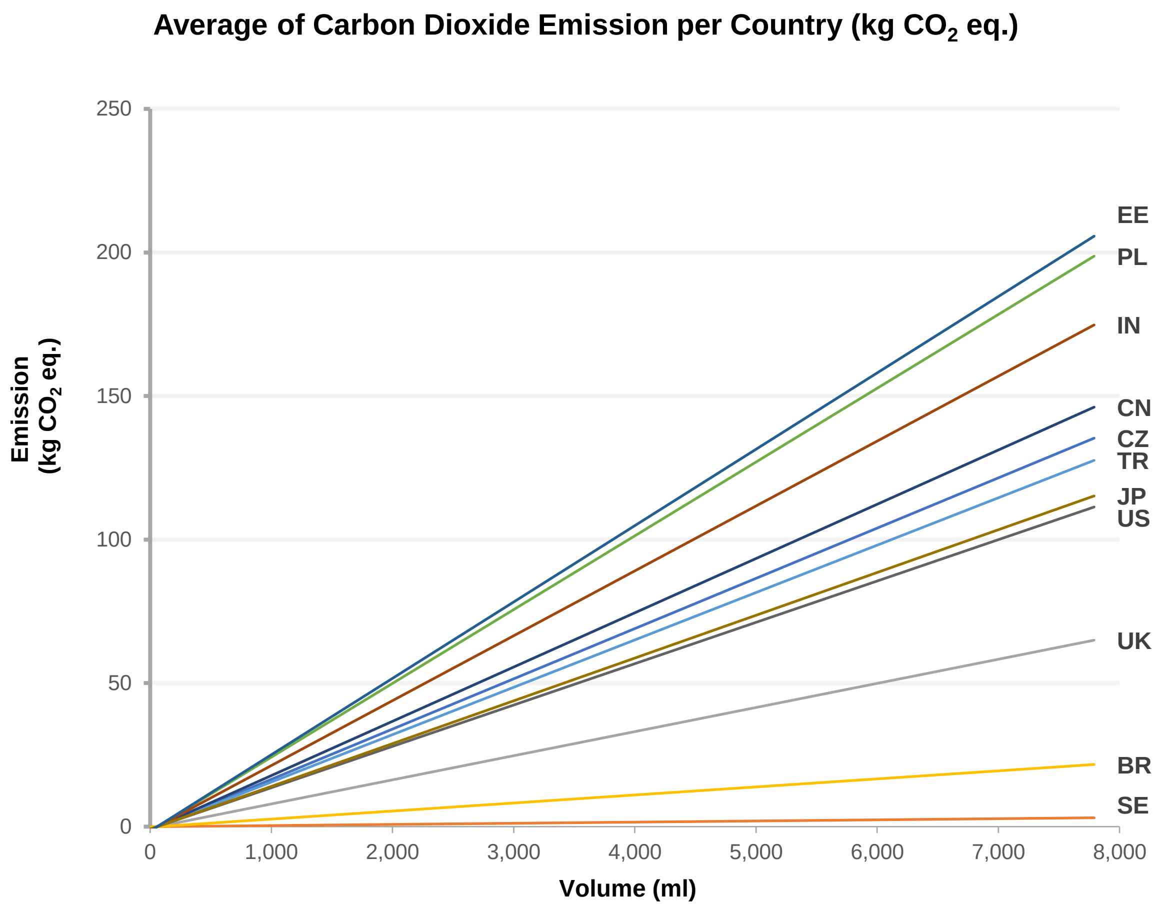


Fig. 6-36 Graph of simulation volume and emissions kg CO_2 eq. per country.

The emission equations for each country are mathematical formulations of the kg CO_2 eq. emissions for each country of the graph (Fig. 6-37). The maximum emission values for power tools range from 3,091 kg CO_2 eq. in Sweden to 205,662 kg CO_2 eq. in Estonia. The values correspond to the energy mixes of each country. Equations are presented in the table below (Tab. 6-17).

Tab. 6-17 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

6.11 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 5 Angle Grinders designs were the source for determining the energy requirements for the production and emissions of kg CO_2 eq. Using the established VEME method, the values for each design in MJ at the three ends of EoL (Landfilling, Combustion and Recycling 90%) were calculated.

Total emissions kg CO_2 eq. by production location were calculated for the Angle Grinders category at all considered production locations. Verification was performed by volumetric comparison of student designs and input data from Angle Grinders. The angle grinder design of T. Kreidlová, to which the VEME method was applied, did not meet the parameters for angle grinders with a diameter of 125 mm disc. The characteristic of the volume is below the measured value (volume of 666 ml). The average values for angle grinders with a grinding wheel diameter of 125 mm are 1,087.5 ml ± 34.5 ml from the analysed grinders. The most suitable volume characteristic is the original angle grinder design by R. Sovják, which is close to commonly produced grinders with a volume of 1.099 ml. The information and results obtained are presented in the table – without use phase, transport and packaging (Tab. 6-18).

Tab. 6-18 Design of Angle Grinders (order from top): D. Lob, K. Sychrová, A. Matušková ,T. Kreidlová, R. Sovják.

	Disc diameter	115	mm
	Volume	974	ml
	Energy (Landfilling)	159.412	MJ
	Energy (Combustion)	149.926	MJ
	Energy (Recycling 90%)	124.055	MJ
	Emission (Landfilling)	22.225	kg CO_2 eq.
	Emission (Combustion)	21.159	kg CO_2 eq.
	Emission (Recycling 90%)	17.339	kg CO_2 eq.
	Disc diameter	115	mm
	Volume	820	ml
	Energy (Landfilling)	134.110	MJ
	Energy (Combustion)	126.164	MJ
	Energy (Recycling 90%)	104.436	MJ
	Emission (Landfilling)	18.714	kg CO_2 eq.
	Emission (Combustion)	17.802	kg CO_2 eq.
	Emission (Recycling 90%)	14.583	kg CO_2 eq.
	Disc diameter	115	mm
	Volume	969	ml
	Energy (Landfilling)	158.591	MJ
	Energy (Combustion)	149.155	MJ
	Energy (Recycling 90%)	123.418	MJ
	Emission (Landfilling)	22.111	kg CO_2 eq.
	Emission (Combustion)	21.050	kg CO_2 eq.
	Emission (Recycling 90%)	17.250	kg CO_2 eq.
	Disc diameter	115	mm
	Volume	666	ml
	Energy (Landfilling)	108.808	MJ
	Energy (Combustion)	102.402	MJ
	Energy (Recycling 90%)	84.816	MJ
	Emission (Landfilling)	15.203	kg CO_2 eq.
	Emission (Combustion)	14.445	kg CO_2 eq.
	Emission (Recycling 90%)	11.826	kg CO_2 eq.
	Disc diameter	125	mm
	Volume	1,099	ml

Energy (Landfilling)	179.950	MJ
Energy (Combustion)	169.214	MJ
Energy (Recycling 90%)	139.980	MJ
Emission (Landfilling)	25.075	kg CO_2 eq.
Emission (Combustion)	23.884	kg CO_2 eq.
Emission (Recycling 90%)	19.577	kg CO_2 eq.

The results of the analysis show a percentage of energy usage and savings in 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 emissions released corresponds to the amount of kg CO_2 eq. of the energy mix of the countries for the analysed designs (Fig. 6-37).

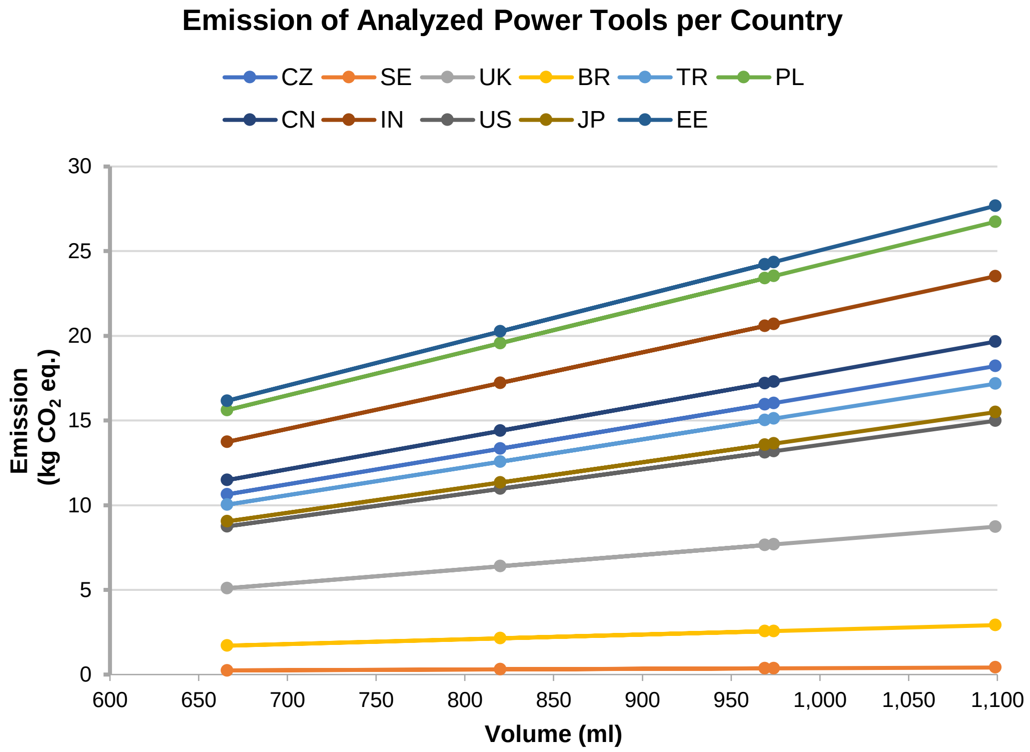


Fig. 6-37   Graph of designed angle grinders with dependency volume and emissions kg CO_2 eq. per selected countries.

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.

6.11.1 Economical & Environmental Benefits

The amount of energy consumption for production has a direct impact on the amount of emissions kg CO_2 eq. with respect to its place of origin. Due to the increase in the price of emission allowances, we can determine the financial expenditure on the release of emissions kg CO_2 eq. into the air. The price of emission allowances is at EUR 50 per ton CO_2 eq. [64]. The value of emission allowances can cost up to 100 EUR per ton CO_2 eq. in 2030. [65]. 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. With a production quantity of 100,000 pcs. of Angle Grinders product with a disc diameter of 115 mm and an emission allowance price of 50 EUR per ton CO_2 eq. is presented in the table (Tab. 6-19). An example of optimising the shape of an Angle Grinders product with a disc diameter of 115 mm and a volume of 974 ml to 820 ml without using other emission reduction methods (high material recycling rate). Financial savings are 13,474 EUR in the Czech Republic between the two design variants on product volume optimization alone.

Tab. 6-19 Economical and environmental benefits of designed angle grinders per selected countries.

Country	**Emission** (ton CO_2 eq.)		**Price** (EUR per ton CO_2 eq.)	
volume ml	974	820	974	820
CZ	1,603	1,333	80,139	66,664
SE	36	30	1,825	1,517
UK	768	639	38,416	31,948
BR	257	214	12,832	10,676
TR	1,511	1,257	75,560	62,855
PL	2,353	1,957	117,632	97,843
CN	1,730	1,439	86,506	71,953
IN	2,070	1,722	103,487	86,085
US	1,318	1,097	65,922	54,834
JP	1,363	1,134	68,165	56,692
EE	2,436	2,026	121,781	101,299

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 phases. 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.

7.1 Categorisation of Power Tools

Due to the different nature of power tools (design, type of use), it was necessary to categorize them. The appropriateness of the categorisation was verified with a fan chart (Fig. 6-34) showing the separate product groups. A detailed analysis showed that it would be possible to merge certain product categories into the same categories with different ranges in terms of energy production requirements. This solution was not used, the tools remained in separate categories.

7.2 Material Analysis

For the LCA analysis, 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 in 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. Plastics with typical odours of PB, PVC, or EPDM were classified directly as such material. Almost all of the parts were disassembled with respect to their construction. The parts that were strictly costed by design in section were the rotors. This procedure was chosen because of the ease of disassembly into parts of the material. 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.

7.3 3D Scanning and Digitalization

Digitizing 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. Conditions did not change during scanning, and this inaccuracy was accepted. 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 part was not considered in the full LCA analysis. Model adjustments from the scanner software were performed in the Rhinoceros 7.0 software. All surfaces that were not part of the k power tools were removed and a solid model with an accuracy of up to 0.001 mm^3 was created.

7.4 OPM Calculations

The LCA analysis was processed at the three ends 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 anew or recalculated.

The materials calculated directly from the existing OPM indicators were: Composite Materials with Glass Fibres, TPE, EPDM, Dural, V-Belts, Foil Capacitors, Wet Colour, Lubricants. These materials were obtained by direct calculation from sources of the OPM method and are determined with sufficient accuracy relative to existing data. It was not possible to determine the material properties of the Lubricants, so they were assigned a default unit of 1 OP = 45 MJ crude oil. 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 printed circuit board (composite board) methodology were calculated using the individual materials in OPM. The resulting calorific value was compared to the energy generated during combustion. The energy of the feedstock share 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 [56]. The printed circuit board (technical ceramics) is calculated in the same way but with a reduction in Feedstock share. Recalculating these values may result in differences. Taking into account the very small weights for PCB (composite board) 18.6 g ± 2.6 g (board of technical ceramics) 6.3 g ± 2.4 g, this procedure was acceptable.

The missing Manufacturing Processes (Turning, Milling, Hot Rolling, Low Pressure Die Casting, Compressed Air) had to be found and integrated into the energy ranges according to the OPM method. Values obtained from articles focusing on machining and manufacturing processes were converted to OP/kg units from input units. Compressed Air was left at 7 bar and calculated to direct kWh consumption for a given air flow rate [51]. The resulting value was compared to the typical energy cost of compressed air in industry [66]. 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 expenditure for Cold Rolling is greater than that for Hot Rolling [67]. The parameters for Hot Rolling are adequately specified for the OPM calculations.

7.5 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. The problematic parts were mainly ferrites, but were of negligible weight. To simplify the calculations at the EoL (recycling), a value of 90% was established due to the use of the amount of recycled steel. This value was set as the baseline recycling level. This was chosen to simplify the calculations. In real practice, the level of recycling varies from material to material. The recycling level is also very different within EU countries and the compliance with WEEE requirements are very different. For these reasons, a consistent recycling level was chosen. A recycling level of 0% to 100% is calculated under the following conditions.

7.6 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.

7.7 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 I/O 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. LCA analyses 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.

Savings may be ignored when producing one piece of product, but when producing tens of thousands to millions of pieces, the savings are significant. The enormous increase in the price of emission allowances today and in the future allows the optimization of products, transport, and material composition. Optimised products will result in a reduction in kg CO_2 eq. and financial savings for the purchase of emission allowances.

7.8 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. The amount of products analysed would be appropriate for 30 samples in each category. There is also potential in the range of categories of tools analysed (now 10 categories). It would be very interesting to find relationships in other tool categories such as demolition hammers, etc. 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).

The life phases of the products (transport) could be calculated at different EoL (Landfilling, Combustion, and Recycling 90%) and separately by type of transport. 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.

Material analysis provides an extensive database of the composition of individual products including weight parameters of parts and groups of parts. In terms of the amount of valuable materials that are part of the product, calculations can be made in terms of the percentage of these materials in the given product categories. By transforming the volumetric characteristics into mass characteristics, it is possible to determine the recycling potential of products in recycling centres.

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 life cycle of EoL power tools, in particular, is 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%.

An LCA analysis was performed that contained 402 individual End of Life (EoL) analyses 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 landfills (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.

In 6 samples from 30 groups of categories the *p*-value is higher than the significance level alpha. All samples under *p*-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 EoL Landfilling is 13.2% ± 1.6%. EU WEEE recycling requirements are set at 45%. In 47 cases, more energy is recovered in combustion than in recycling 45% (total 35% of samples). This energy recovered by the Combustion product is up to 12% more efficient 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 a 5% 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 user 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 the 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 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 optimization 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 user phase (operation of the product). However, these emissions are closely related to the location of the user 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 user 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 labeling 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 optimization, 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 user 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.

9 LIST OF PUBLICATIONS

2018

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11 LIST OF SYMBOLS AND ABBREVIATIONS

11.1 List of Used Abbreviations

VEME	Volumetric Evaluating Method for Ecodesign
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Costs
EoL	End of Life
3D	3 Dimension
OPM	Oil Point Method
LiDS	Lifecycle Design Strategies
MECO	Materials Energy Chemistry Others
MET	Material Energy Toxicity
ERPA	Environmentally Responsible Product Assessment
WEEE	Waste Electrical and Electronic Equipment
DfA	Design for Assembly
DfD	Design for Disassembly
DfM	Design for Maintenance
IO	Input Output
IOT	Input Output Tables
IOA	Input Output Analysis
KEPI	Key Indicators of Environmental Performance
TPI	Toxic Potential Indicator
WGK	Water Pollution Classes
MAK	Maximal Admissive Concentration

MSDS	Material Safety Data Sheet
EMS	Environmental Management System
ACLONDS	Activities Criteria Lifecycle phases Outcome Design Strategies Structure
AB	Aktiebolag
EU	European Union
ISO	International Organization for Standardization
RoHS	Restriction of the use of Hazardous Substances
EuP	Energy Using Products
PC	Personal Computer
PDA	Personal Digital Assistant
SLF	Standard Logistic Function
TQM	Total Quality Management
CAD	Computer Aided Design
VBA	Visual Basic for Applications
LED	Light-Emitting Diode
HD	High Definition
BUT	Brno University of Technology
IMID	Institute of Machine and Industrial Design
KHT	Kungliga Tekniska högskolan
RMIT	Royal Melbourne Institute of Technology
EIA	Environmental Impact Assessment
XLS	Microsoft Excel Spreadsheet
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
NURBS	Non-Uniform Rational Basis Spline

MS	Microsoft
EUR	National Currency of the EU
OBJ	Object File
STL	Stereolithography
PLY	Polygon File Format
STEP	Standard for the Exchange of Product Data
DXF	Drawing Exchange Format
PVC	Polyvinyl Chloride
PB	Polybutadiene
EPDM	Ethylene-Propylene-Diene Monomer Rubber
ABS	Acrylonitrile Butadiene Styrene
TPE	Thermoplastics Elastomer
PP	Polypropylene
GF	Glass Fibres
PA6	Polyamid 6
PA66	Polyamid 66
POM	Polyoxymethylene/Polyacetals
PE	Polyethylene
PET	Polyethylene Terephthalate
PU	Polyurethane
HDPE	High-Density Polyethylene
PMMA	Polymethyl Methacrylate
PBT	Polybutylene Terephthalate
PCB	Printed Circuit Board
MMC	Metal Powders Composites
CFRP	Carbon-Fibre-Reinforced Polymer

BR	Brazil
CN	China
CZ	Czechia
EE	Estonia
IN	India
JP	Japan
PL	Poland
SE	Sweden
TR	Turkey
UK	United Kingdom of Great Britain and Northern Ireland
US	United States of America
etc.	et citera
min.	minimum
max.	maximum
CO_2	Carbon Dioxide
p-value	Probability Value
t-value	Result of a Statistical Test
R^2	Correlation Between the Two Variables
r_{xy}	Correlation Coefficient
LF	Landfilling
CM	Combustion
RC	Recycling
OS	Random Orbital Sander
SS	Sheet Sander
EP	Electric Planer
HJ	Handle Jigsaw

BS	Belt Sander
PD	Percussion Drill
CS	Circular Saw
AG	Angle Grinder
EC	Electric Chainsaw
RC	Reciprocating Saw
pcs.	pieces
pc.	piece

11.2 List of Used Units

kWh	kilowatt hour
OP	Oil Point
J	Joule
MJ	megajoule
W	Watt
bar	metric unit of measurement for pressure
g	gram
kg	kilogram
mg	milligram
mm	millimetre
km	kilometre
mm^3	cubic millimetre
ml	millilitre
s	second
h	hour
l/min	litre per minute

OP/kg	Oil Point per kg
MJ/kg	megajoule per kg
g/m^2	grams per square metre
OP/m	Oil Point per metre
OP/mm	Oil Point per millimetre
OP/m^2	Oil Point per square metre
OP/mm^2	Oil Point per square millimetre
$kg\ CO_2\ eq.$	carbon dioxide emission equivalent in kilogram
$g\ CO_2\ eq.$	carbon dioxide emission equivalent in gram
$kg\ CO_2\ eq./kWh$	carbon dioxide emission equivalent in gram per kilowatt
$g\ CO_2\ eq./kWh$	carbon dioxide emission equivalent in gram per kilowatt
$ton\ CO_2\ eq.$	carbon dioxide emission equivalent in ton (1,000 kilogram)

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

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