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IDENTIFICATION OF ENVIRONMENTAL HOTSPOTS IN SPECTACLE LENS PRODUCTION USING LIFE CYCLE ASSESSMENT

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Abstract

The paper deals with the environmental assessment of spectacle lens production using the Life Cycle Assessment (LCA) method. The functional unit is one average spectacle lens and the system boundary is defined using a Gate-to-Gate approach. The assessment is based on real operational data on electricity and water consumption and was performed in Sphera GaBi using the ReCiPe 2016 Midpoint method. The results identified AR-Coating as the main environmental hotspot; in most evaluated impact categories it contributes approximately 43-44 % of the total impact. From the perspective of water consumption, Duralux was identified as the most important process. The study represents the first phase of a broader assessment that will be extended by material inputs, chemical substances, waste flows and other relevant process flows.

Keywords: life cycle assessment; spectacle lenses; sustainable manufacturing; environmental hotspots; ReCiPe 2016 Midpoint

1. Introduction

Life Cycle Assessment (LCA) is a systematic approach for evaluating the environmental impacts of products, processes and services. It makes it possible to follow the environmental burden associated with individual inputs and processes and to identify the parts of a system that contribute most significantly to the resulting impacts. In an industrial environment, LCA can therefore be used not only for environmental assessment itself, but also as a basis for process optimisation and decision-making support in the field of sustainability.

The importance of environmental assessment of manufacturing processes is increasing especially for technologically demanding products whose production includes a larger number of consecutive operations with different requirements for energy, water, materials and other inputs. Spectacle lenses belong to this group of products. Their production includes several technological steps, from preparation and surface processing of the lens through washing and dyeing to the

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application of surface layers, finishing operations and dispatch. Individual processes may differ considerably in terms of environmental intensity.

The presented study focuses on the environmental assessment of the production of an average spectacle lens in a selected manufacturing company. The functional unit is one average spectacle lens and the assessment is performed within Gate-to-Gate system boundaries. The study is based on real operational data and, in the first phase, focuses on electricity and water consumption in individual manufacturing processes. Based on these data, a model is created in Sphera GaBi and the environmental impacts of individual parts of the manufacturing process are evaluated using the ReCiPe 2016 Midpoint method.

2. Literature Review

Life Cycle Assessment has developed over recent decades from an approach focused mainly on energy balances into a comprehensive method that enables the assessment of a wide range of environmental impacts of products, processes and services. Guinée et al. [1] describe the development of LCA and point to the gradual extension of the method by new approaches, impact types and possibilities for its use in environmental decision-making. An important part of current LCA studies is Life Cycle Impact Assessment (LCIA), for which a number of methods have been developed. One widely used method is ReCiPe 2016, which enables environmental impacts to be evaluated at both midpoint and endpoint indicator levels. Huijbregts et al. [2] state that the midpoint approach enables individual environmental mechanisms, such as climate change, acidification, eutrophication, toxicity or resource use, to be assessed without further aggregation into final damage areas.

In addition to determining environmental impacts, LCA can also be used as a tool for identifying processes suitable for subsequent optimisation. Pieragostini et al. [3] analysed the connection between LCA methodology and optimisation approaches in process engineering and pointed to the possibility of using environmental assessment results directly when designing changes to manufacturing processes. Identification of processes with a high contribution to resulting impact categories can therefore serve as a basis for targeted reduction of resource use, energy consumption or generated emissions.

From the perspective of manufacturing processes, an important topic is the energy intensity of individual technological operations. Cerdas et al. [4] performed an LCA comparing centralised and distributed production of spectacle frames using 3D printing. The results showed that significant optimisation potential was connected with energy consumption at the level of individual manufacturing processes and with the material used. The study also points to the importance of detailed assessment of individual manufacturing steps rather than monitoring only the total environmental footprint of a product.

A study more closely related to the production of optical elements was conducted by Strobl et al. [5], who used LCA to compare two technologies for manufacturing precision glass optics. The authors evaluated, among other aspects, energy consumption and global warming potential of conventional pressing and wafer-scale moulding. According to their results, the proposed technology led to energy savings of approximately 86 % and to a reduction in global warming potential of approximately 79 %. The study also showed that a decisive part of the savings arose in specific technological operations, especially in the preheating phase. The results therefore confirm the importance of a process-oriented approach in which environmental impacts are distributed among individual manufacturing operations and locations with the greatest potential for improvement are subsequently identified.

Environmental aspects of spectacle lenses themselves were addressed by Pillay et al. [6], who analysed the material properties of polymeric spectacle and contact lenses and the options for handling them at the end of life. The authors point mainly to the issue of current management of used lenses and identify material recovery and recycling as a suitable direction for further development. The study shows that in a comprehensive environmental assessment of spectacle lenses, in addition to the energy intensity of manufacturing processes, it is also important to consider product material composition and subsequent life cycle stages.

Existing knowledge indicates that for the correct interpretation of an LCA of a manufacturing process, it is important not only to determine total environmental impacts, but also to quantify the contributions of individual technological operations, work with transparently defined inputs and take into account limitations arising from the availability and quality of primary data. Studies focused on optical element production also confirm the importance of energy consumption and individual technological operations for the resulting environmental performance of a product [4], [5]. The presented study builds on these findings by focusing, in its first phase, on the identification of environmentally significant processes in spectacle lens production using real operational data on electricity and water consumption.

3. Theoretical Background

Life Cycle Assessment is a methodological approach that enables systematic evaluation of the potential environmental impacts of a product, process or service. The basic LCA framework is defined by ISO 14040 and ISO 14044 and consists of four interconnected phases: goal and scope definition, inventory analysis, impact assessment and interpretation of results [7], [8].

The basic structure of the individual LCA phases and their application in the presented study is shown in Fig. 1.

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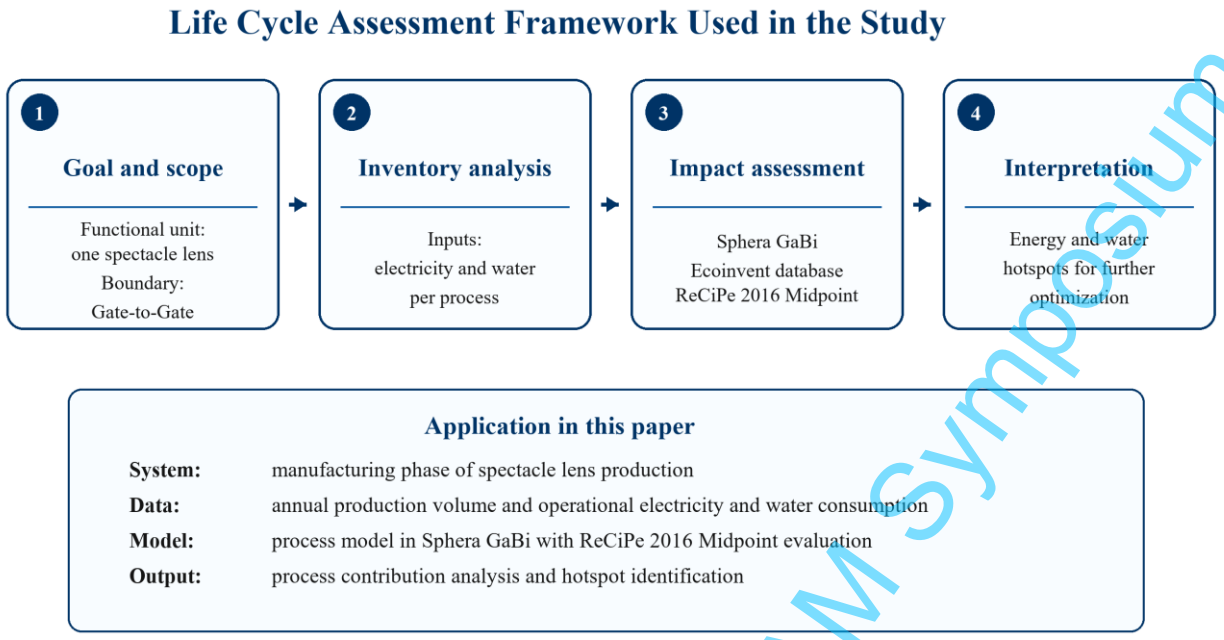

Fig. 1. Life Cycle Assessment framework and its application in the study

Goal and scope definition is the first phase in which the purpose of the assessment, the functional unit, system boundaries, assumptions and limitations of the study are determined [7], [8]. The functional unit represents the reference basis to which individual inputs, outputs and assessment results are related. In this study, the functional unit is the production of one average spectacle lens. The system boundaries were defined using a Gate-to-Gate approach, which includes the defined manufacturing phase of the assessed system.

Life Cycle Inventory (LCI) includes the collection and quantification of relevant input and output flows of the assessed system [7], [8]. Inputs may include, for example, materials, electricity, water and other auxiliary substances, while outputs may include products, waste flows and emissions. In the first phase of the presented study, the inventory analysis includes electricity and water consumption of individual manufacturing processes, subsequently related to the defined functional unit.

Life Cycle Impact Assessment (LCIA) converts inventory data into potential environmental impacts through classification and characterisation of individual input and output flows [7], [8]. In the presented study, the ReCiPe 2016 Midpoint method was used for impact assessment. ReCiPe 2016 enables evaluation of individual environmental issues, for example in the categories of climate change, acidification, eutrophication, toxicity, resource use and freshwater consumption [2].

Interpretation of results is the final LCA phase and consists of evaluating the results of inventory analysis and LCIA with regard to the defined goal and scope of the study [7], [8]. Interpretation includes identification of the most significant processes, assessment of limitations and uncertainties, and formulation of conclusions and recommendations. The results can subsequently be used to determine areas with the greatest potential for reducing the environmental impacts of the assessed system.

Depending on the goal of a study, the boundaries of the assessed system may be limited to a specific part of the life cycle. In the presented study, the Gate-to-Gate approach was selected because the aim is to assess the manufacturing phase in detail and to identify differences between individual technological operations. The first phase of the assessment focuses on environmental impacts related to electricity and water consumption. Additional inputs will be included in the subsequent extension of the model.

4. Materials and Methods

The methodology of the study is based on the principles of Life Cycle Assessment defined by ISO 14040 and ISO 14044. The manufacturing phase of spectacle lenses in a selected manufacturing company was chosen for the assessment of environmental impacts. The functional unit was defined as the production of one average spectacle lens and the system boundaries were defined using the Gate-to-Gate approach.

The assessed system includes individual manufacturing operations from the glass warehouse through surface production preparation, surface production, washing and inspection, dyeing, AR-Coating and Duralux surface treatments, grinding including assembly, up to the distribution department. In the first phase of the study, electricity and water inputs related to individual manufacturing processes were evaluated.

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Sphera GaBi software and the ecoinvent database were used to create the model. Electricity was modelled using the database process CZ: Electricity grid mix and water consumption using the process EU-28: Tap water from groundwater. Environmental impacts were subsequently evaluated using the ReCiPe 2016 Midpoint method.

4.1 Data Collection and Preparation of the LCA Model

Collection of high-quality inventory data represents one of the key parts of Life Cycle Assessment because their accuracy and scope directly affect the results of subsequent environmental evaluation. The input data used in this study were obtained from internal operational records of the selected manufacturing company.

The provided documents contained data on annual production of spectacle lenses, quarterly electricity consumption and quarterly water consumption for the monitored period. Annual production amounted to 2,171,483 spectacle lenses. Individual operational consumption values were then recalculated to the defined functional unit, i.e. the production of one average spectacle lens.

The use of aggregated operational data for a longer monitored period makes it possible to capture normal production operation and partially reduce the influence of short-term fluctuations related, for example, to changes in production volume or exceptional operational events. In this phase of the study, no direct measurement in the manufacturing plant or independent verification of primary data was performed. Input data checking consisted mainly of verifying their logical continuity, units used, correctness of recalculations and assignment of individual consumption values to the corresponding manufacturing processes.

4.2 Inventory Inputs of Individual Manufacturing Processes

Based on the provided operational data, electricity and water inputs were determined for individual manufacturing processes. All values were related to the functional unit of one average spectacle lens. An overview of the inventory inputs used is given in Table 1.

Manufacturing process	**Electricity consumption [kWh/piece]**	**Water consumption [L/piece]**
Glass warehouse	0.06	0
Surface production preparation	0.03	0
Surface production	0.35	0.86
Washing, de-icing and surface inspection	0.06	0.30
Dyeing	0.16	1.41
AR-Coating	0.95	1.59
Duralux	0.41	3.09
Grinding, including assembly	0.10	0.10
Distribution department	0.05	0

Table 1. Inventory inputs for the production of one average spectacle lens

Individual manufacturing processes show different requirements for electricity and water consumption. The highest electricity consumption was determined for AR-Coating, where it reaches 0.95 kWh per spectacle lens. Other energy-significant operations include Duralux with a value of 0.41 kWh/piece and surface production with a value of 0.35 kWh/piece.

From the perspective of water consumption, the highest value is reached by Duralux, namely 3.09 L/piece. It is followed by AR-Coating with a consumption of 1.59 L/piece and dyeing with a value of 1.41 L/piece. These inventory values were subsequently used as inputs for creating the LCA model.

4.3 Model Development and Environmental Impact Assessment

Based on the processed inventory data, a process model for the production of one average spectacle lens was created in Sphera GaBi. Individual blocks of the model represent the monitored manufacturing processes and the corresponding electricity and water inputs were assigned to each of them.

Electricity consumption in the model was represented by the Czech energy mix CZ: Electricity grid mix. The database process EU-28: Tap water from groundwater was used for water consumption. All inputs were related to the same functional unit, which enabled subsequent comparison of the contributions of individual manufacturing processes.

For the LCIA phase, the ReCiPe 2016 Midpoint method was used. The environmental impact categories available in the created model were evaluated, including Climate Change, Terrestrial Acidification, Terrestrial Ecotoxicity, Freshwater Consumption, Freshwater Ecotoxicity, Freshwater Eutrophication, Fossil Depletion, Metal Depletion, Human Toxicity, Ionising Radiation, Marine Ecotoxicity, Marine Eutrophication, Fine Particulate Matter Formation, Photochemical Ozone Formation and Land Use.

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At this stage, the model includes only environmental impacts related to electricity and water consumption. Material inputs, specific chemical substances, surface layers, waste flows, reject rates and direct emissions from manufacturing processes are not yet part of the model. The results therefore cannot be interpreted as a complete environmental profile of a spectacle lens, but rather as the first assessment phase focused on the energy and water intensity of the evaluated manufacturing processes.

5. Model and Results

Based on the processed inventory data, a model of the manufacturing phase of one average spectacle lens was created in Sphera GaBi. The model includes individual manufacturing processes defined within the Gate-to-Gate system boundaries and enables their contribution to individual environmental impact categories to be evaluated.

5.1 Spectacle Lens Production Model

The created model captures the manufacturing process from the glass warehouse through surface production preparation, surface production, washing and inspection, dyeing, AR-Coating and Duralux surface treatments, grinding including assembly, up to the distribution department. The corresponding electricity and water inputs recalculated to the functional unit of one average spectacle lens were assigned to each process.

Fig. 2 shows the model in a simplified publication form. Individual blocks represent the monitored manufacturing operations and their connection to database inputs for electricity and water.

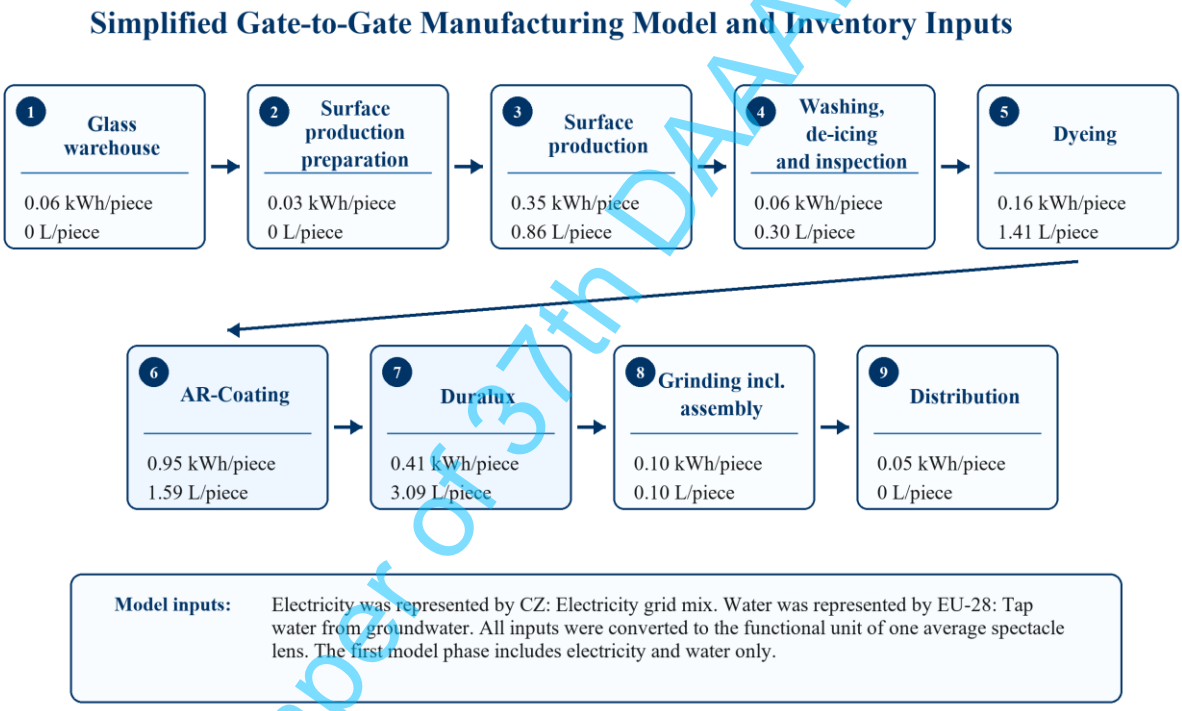

Fig. 2. Model of manufacturing processes and inventory inputs

The results of the created model were subsequently evaluated using the ReCiPe 2016 Midpoint method. For each impact category, the total value of environmental burden and the contribution of individual manufacturing processes were determined.

5.2 Environmental Impact Assessment Results

For clearer interpretation, the LCIA results were evaluated both as total impact values and as contributions from individual manufacturing operations. Table 2 does not compare impact categories with one another; each row shows the share of the total impact in that category attributable to selected processes. The reported process shares sum to approximately 100 % in each row.

In most evaluated categories, AR-Coating has the highest share. With the exception of Freshwater Consumption, its contribution is approximately between 42 % and 44 % of the total value of the relevant category. In the Climate Change category, the total impact of producing one average spectacle lens reached 1.5046 kg CO2 eq./piece; the share of AR-Coating was 43.7 %.

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Besides AR-Coating, the results repeatedly show the importance of Duralux, surface production and dyeing. Their importance is most visible in Freshwater Consumption, where Duralux contributes significantly alongside AR-Coating, which corresponds to its highest water consumption among all monitored manufacturing processes. The process distribution results are shown in Table 2.

Impact category	AR-Coating [%]	Duralux [%]	Surface production [%]	Dyeing [%]	Other processes [%]
Climate Change	43.7	18.9	16.2	7.4	13.8
Terrestrial Acidification	43.9	18.9	16.1	7.4	13.8
Terrestrial Ecotoxicity	43.7	18.9	16.1	7.4	13.8
Freshwater Consumption	31.8	30.5	13.6	13.3	10.8
Freshwater Ecotoxicity	43.4	19.3	16.0	7.6	13.7
Freshwater Eutrophication	43.3	19.4	16.0	7.6	13.6
Fossil Depletion	43.7	18.9	16.1	7.4	13.9
Metal Depletion	42.0	20.8	15.8	8.3	13.1
Human Toxicity	43.3	19.4	16.0	7.7	13.6
Marine Ecotoxicity	43.6	19.1	16.1	7.5	13.8
Fine Particulate Matter Formation	43.8	18.9	16.1	7.4	13.8
Land Use	43.8	18.9	16.1	7.4	13.8

Table 2. Process contributions of selected manufacturing processes to individual impact categories [%]

Note: The values express the share of a process in the total value of the given impact category. Percentages are summed only within one row, not across impact categories. Less significant processes are included in Other processes.

The process distribution shows that AR-Coating represents the main environmental hotspot in most evaluated impact categories. Its dominant position is mainly connected with the highest electricity consumption among all monitored manufacturing operations.

A different distribution can be observed in Freshwater Consumption. In this category, the shares of AR-Coating and Duralux are much more balanced than in the other categories, while the greater importance of Duralux is connected with its highest water consumption per functional unit. The results therefore show that hotspot interpretation depends on the nature of the evaluated impact category and on the type of input that influences it most strongly.

5.3 Contribution of Electricity and Water to Environmental Impacts

For a more detailed interpretation of the results, the contribution of electricity and water to the resulting values of individual impact categories was also determined. The results showed that electricity consumption represents the dominant source of environmental impacts in most categories. A summary comparison of the contribution of electricity and water in individual impact categories is graphically shown in Fig. 3.

In the Climate Change category, approximately 99.96 % of the resulting impact is connected with electricity, while the contribution of water is only 0.04 %. Similar results were also recorded for Fossil Depletion, Fine Particulate Matter Formation, Ionising Radiation and Land Use, where the contribution of electricity exceeds 99 %.

The important exception is Freshwater Consumption. In this case, the contribution of electricity is 47.21 %, while direct water consumption contributes 52.88 % to the result. Water is therefore a slightly more important input than electricity in this category.

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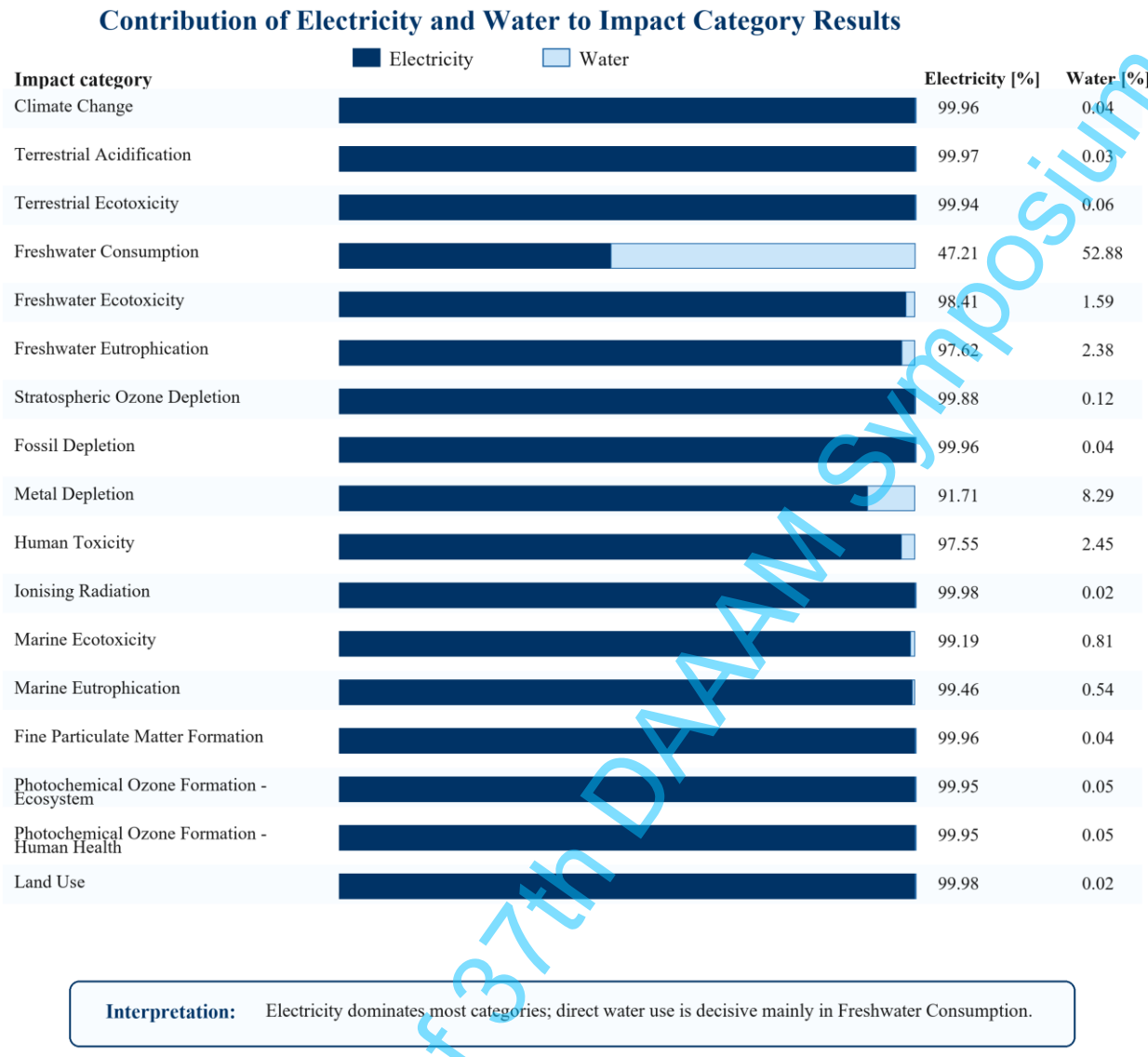

Fig. 3. Summary contribution of electricity and water by impact category

Fig. 3 shows the pronounced dominance of electricity in most evaluated categories. The exception is mainly Freshwater Consumption, where the contribution of water increases to 52.88 %, while the contribution of electricity is 47.21 %.

Based on the results, it can be stated that the main factor influencing most evaluated environmental categories in the current model is electricity. From this point of view, the most significant area is AR-Coating, whose consumption is 0.95 kWh per spectacle lens.

From the perspective of water management, the most important process is Duralux, whose consumption reaches 3.09 L of water per piece. Its significance is therefore most clearly reflected in Freshwater Consumption.

Based on the results of the first assessment phase, AR-Coating can be identified as the main monitored area from the perspective of energy intensity, and Duralux as the main monitored area from the perspective of water consumption. A clear summary of the most important LCA results is shown in Fig. 4.

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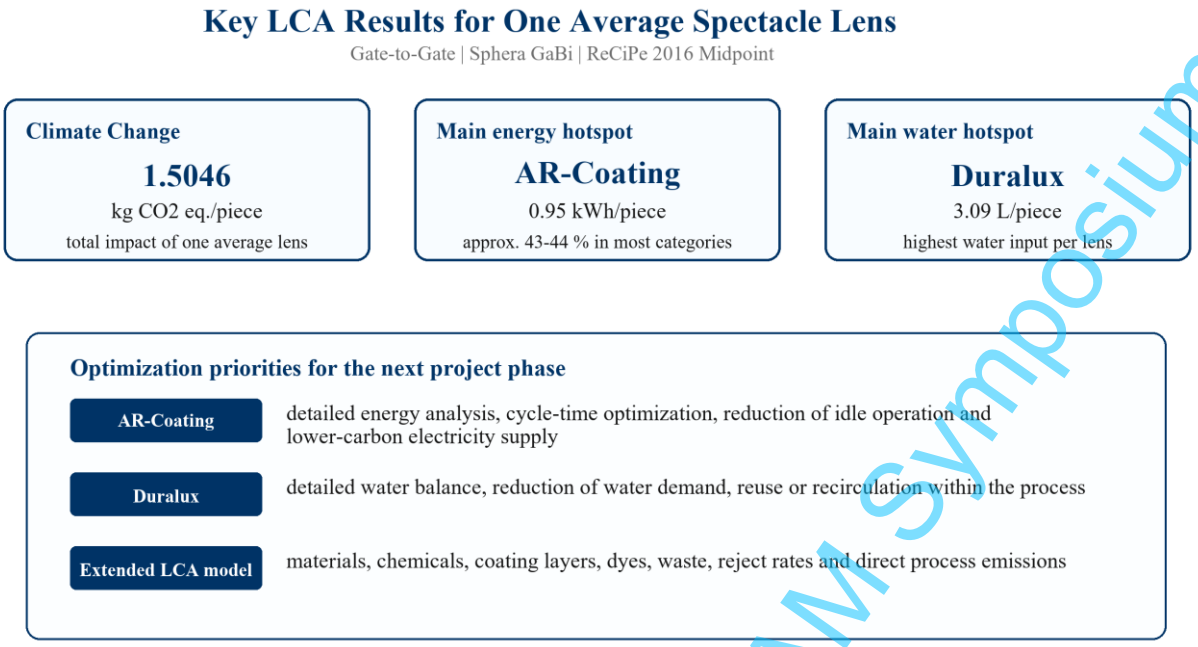

Fig. 4. Summary of key LCA results for the production of one average spectacle lens

The summary results confirm the different character of the main identified hotspots. AR-Coating is dominant mainly from the perspective of energy intensity, while the importance of Duralux is connected especially with water consumption. A more detailed interpretation of the results, their limitations and optimisation possibilities is discussed in the following section.

6. Discussion

The assessment showed that the environmental impacts of the monitored manufacturing phase are strongly influenced by electricity consumption in the current model. AR-Coating was identified as the main environmental hotspot, with the highest contribution in all evaluated impact categories. In most categories, its share was approximately 43-44 %. This is mainly related to its high electricity consumption of 0.95 kWh per average spectacle lens.

The importance of energy intensity of manufacturing processes is also consistent with findings reported in the scientific literature. Cerdas et al. [4], when assessing the production of optical products, point to the importance of energy consumption and manufacturing technologies for the resulting environmental burden. Similarly, Strobl et al. [5], in the assessment of precision glass optics production, demonstrated that a change in a specific manufacturing technology can lead to a significant reduction in both energy consumption and global warming potential. The results of the presented study therefore confirm that process-oriented assessment makes it possible to identify specific technological operations on which subsequent optimisation measures should focus.

In addition to AR-Coating, Duralux was also identified as a significant process. Its importance, however, results mainly from high water consumption, which amounts to 3.09 L per spectacle lens. This difference is visible especially in Freshwater Consumption, where the contribution of water to the resulting environmental impact reaches 52.88 %. The results therefore show that when optimising production, it is not sufficient to monitor only energy intensity; it is also necessary to distinguish between the character of individual environmental categories and the inputs that influence them.

From a practical point of view, the results suggest that the greatest potential for reducing impacts associated with electricity consumption lies in AR-Coating. In the next phase, it would therefore be appropriate to perform a more detailed analysis of the energy intensity of this operation and to identify individual sources of consumption. Improvement options may include optimisation of production cycle length, reduction of equipment operation during idle periods, modernisation of energy-intensive parts of the technology, or the use of electricity with lower emission intensity. For Duralux, on the other hand, attention should be focused primarily on possibilities for reducing water consumption, reusing water or recirculating it within the manufacturing process.

However, several limitations must be considered when interpreting the results. The presented study represents the first phase of a more comprehensive environmental assessment of spectacle lens production and its system boundaries are currently defined using a Gate-to-Gate approach. The model includes only environmental impacts associated with electricity and water consumption. Material inputs, specific chemical substances, surface layers, dyes, waste flows, reject rates and direct emissions from manufacturing processes were not included in this phase.

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This limitation is particularly relevant to Human Toxicity, Freshwater Ecotoxicity, Marine Ecotoxicity and Terrestrial Ecotoxicity. Their current results principally reflect indirect emissions associated with the electricity and tap-water supply datasets, rather than measured releases from lens production. Adding chemical coatings and resin materials would introduce burdens from their production, including upstream feedstocks, solvents and additives where applicable. Their contribution would depend on the actual formulation, mass used per lens and available characterisation factors [2]. A small material mass could therefore contribute disproportionately to toxicity-related categories; electricity consumption alone cannot establish the final ranking.

Direct process emissions may also change these categories. If present, solvent releases to air, residues of uncured resin or coating constituents in wastewater, and releases associated with handling coating waste would need to be recorded by substance, quantity and receiving compartment. Treatment and capture efficiencies determine which flows reach the environment; chemical consumption must not be treated as an equivalent mass emitted. Coating application, curing, cleaning or waste treatment could consequently become more prominent hotspots, although the direction and magnitude of any change cannot be quantified from the current utility-only inventory. The next phase should combine supplier composition data, safety data sheets, material balances and measured or justified emission estimates, and assess sensitivity to missing substances and uncertain characterisation factors [2]. These are potential environmental impacts, not measurements of worker exposure or site-specific toxicity risk.

Another source of uncertainty is the way primary data were obtained and processed. The study uses aggregated operational data for the monitored period, which were subsequently recalculated to one average spectacle lens. This procedure makes it possible to create a representative view of normal manufacturing operation, but it may not precisely capture differences between individual lens types, surface treatment variants or specific production routes.

The issue of input data quality and its influence on LCA results is also emphasised by Miranda Xicotencatl et al. [9] and Lesage et al. [10]. Their studies show that differences in the database used, data implementation and uncertainty of inventory inputs can significantly influence the resulting values of environmental categories. For this reason, the next project phase will also include a more detailed check and refinement of the original input data on electricity and water consumption and of the way they are assigned to individual manufacturing processes.

A related DAAAM study by Tomaskova and Bicova [11] identifies chemicals, waste, water pollution and air emissions alongside resource and energy consumption as relevant environmental aspects of machining. Although it concerns metalworking rather than spectacle lenses and uses an environmental-aspect register rather than LCIA, it supports systematically mapping material inputs and process outputs when extending this manufacturing inventory.

In the next phase, the inventory analysis will also be extended by material inputs, chemical substances used, waste flows and other relevant process flows. The values presented in this study may therefore be partially adjusted based on refined primary data and the extended inventory. Extension of the model will also make it possible to assess whether AR-Coating and Duralux remain the main environmental hotspots after material and chemical inputs are included, or whether the importance of individual manufacturing processes changes in some impact categories.

Despite the stated limitations, the first phase of the study provides an important overview of the energy and water intensity of individual manufacturing processes and enables areas with the greatest potential for further analysis and optimisation to be identified. The results thus create an initial basis for the gradual construction of a more comprehensive environmental profile of spectacle lens production.

7. Conclusion

The presented study dealt with the first phase of an environmental assessment of the production of an average spectacle lens using the Life Cycle Assessment method. The functional unit was defined as the production of one average spectacle lens and the system boundaries were defined using the Gate-to-Gate approach. The assessment was performed in Sphera GaBi using the ReCiPe 2016 Midpoint method.

In the first phase, environmental impacts associated with electricity and water consumption in individual manufacturing processes were assessed. The results showed that the main environmental hotspot is AR-Coating, which contributes approximately 43-44 % to the total result in most evaluated categories. In the Climate Change category, the total impact of producing one average spectacle lens was 1.5046 kg CO2 eq./piece, while the share of AR-Coating reached 43.7 %.

From the perspective of water consumption, Duralux was identified as the most important process, with a consumption of 3.09 L of water per spectacle lens. Its importance was most clearly reflected in Freshwater Consumption. At the same time, the results showed that in most evaluated categories electricity consumption represents the dominant source of environmental impacts, while water has a more substantial importance mainly in categories directly related to freshwater resource consumption.

From a practical point of view, the results suggest that the main potential for reducing environmental impacts lies in reducing the energy intensity of AR-Coating and optimising water consumption in Duralux. The study therefore provides a basis for more targeted analysis of selected manufacturing operations and for the formulation of specific optimisation measures.

At the same time, it is necessary to emphasise that the presented results represent only the first phase of a more comprehensive environmental assessment of spectacle lens production. In the next phase, the inventory analysis will be extended by material inputs, chemical substances used, waste flows and other relevant process flows. Further processing

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will also include a more detailed check and refinement of the original input data on electricity and water consumption and the way they are assigned to individual manufacturing processes. For this reason, the values presented in this study may be partially adjusted in the subsequent phase.

The extended model will subsequently make it possible to create a more comprehensive environmental profile of spectacle lens production and to verify whether the importance and ranking of environmental hotspots identified in the first assessment phase change after additional material and process inputs are included.

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