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# Carbon Footprint of Different Kinds of Footwear – a Comparative Study

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**Abstract**
*The carbon footprint of a product (CFP) approach is one of the most important tools which gives a possibility to estimate the total amount of greenhouse gas (GHG) emissions in the whole life cycle of consumer goods. A lot of attempts have been undertaken to elaborate methodology for CFP calculation. Because GHG emissions may occur at each stage of the life cycle, the calculation procedures are characterised by a high level of complexity. This is due to the use of a broad range of different materials in the case of the whole footwear manufacturing process. Owing to this fact, a lot of wastes, sewages and toxic gases may be generated at every step of the production process. For each kind of material used, a lot of determinants should be laid down, such as the source of the material as well as distances and means of transportation between manufacturers and consignees. It causes that estimation of total carbon footprint values is not possible, especially in the case of a long and multi-stage supply chain. With the use of the SimaPro LCA software package, the authors calculated the carbon footprint for seven types of outdoor footwear. The CFP was calculated for each step of the life cycle. Based on the calculations, the correlation dependences were revealed and stages with huge emissivity indicated. Then, with the use of a multivariate regression model, the regression function, which determines the total emissivity at each stage, was estimated. This approach gives qualitative indicators which can be taken into account in making decisions about corrective actions.*

**Key words:** *carbon footprint, footwear life cycle, global warming potential, footwear.*

## Introduction

Climate change, which is allegedly the consequence of human activity, is considered as one of the most dangerous environmental problems [1]. At local, national and international levels, a lot of activities aimed at the reduction of greenhouse gas emissions are undertaken. Additionally, monitoring and forecasting actions are implemented in a lot of fields of human activity [2-3]. Also, education plays an important role in designing effective mitigation strategies. It is welcomed that people improve understanding of the connection between own output and global emissions [4]. One of the most effective tools to calculate the total amount of the greenhouse gas emissions of consumer goods is the carbon footprint of a product (CFP) approach. Literature sources give a few similar definitions which describe the carbon footprint. According to [5], CFP is a methodology to estimate the total emissions of greenhouse gases (GHG) in carbon equivalents from a product throughout its life cycle, from the production of raw material used in its manufacture to the disposal of the finished product (excluding in – use emissions). On the other hand, ETAP (an environmental body under European Commission jurisdiction) says: "the Carbon Footprint" is a measure of the impact human activities have on the environment in terms of the amount of greenhouse gases produced, measured in tonnes of carbon dioxide" [6]. The Parliamentary Office of Science and Technology [6] gives a similar definition: "A Carbon Footprint is the total amount of $CO_2$ and other greenhouse gases, emitted over the full life cycle of a process or product. It is expressed as grams of $CO_2$ equivalent per kilowatt hour of generation ($gCO_{2eq}$/kWh), which accounts for the different global warming effects of other greenhouse gases".

The carbon footprint is an aggregate amount of greenhouse gases which are emitted during the life cycle of a product. Greenhouse gas is any gas that has the property of absorbing infrared radiation emitted from the Earth's surface and reradiated back to the Earth's surface. This is the mechanism of the greenhouse effect. Exemplary greenhouse gasses are given as follows: carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), chlorofluorocarbons (HFC, PFC, CFC), ozone ($O_3$), sulfur hexafluoride ($SF_6$) and others. These amounts are described by the carbon dioxide equivalent ($CO_{2e}$), which is expressed in tonnes ($tCO_{2e}$) or kilogrammes ($kgCO_{2e}$). Such an approach allows to compare greenhouse gas emissions using a common rating scale; however, various gases contribute to global warming to different degrees [1], [8]. Quantitative assessment of the influence of a given substance on global warming potential is measured with the use of the global warming potential (GWP) indicator. This parameter is a measure for weighting the climatic impact of emissions of different greenhouse gases [9] over a period of time (usually 20, 100 or 500 years).

At present there exist several standardised methods which give a possibility to calculate the carbon footprint of products [10]. One of the most popular methods is life cycle assessment. This methodology is based on the fact that all environmental burdens connected with a product or service must be assessed. Calculations start

*Table 1. Comparison between carbon footprint calculation standards [9].*

| Standard | Description | Boundaries | Scope of the standard | Product category rule |
|---|---|---|---|---|
| PAS 2050 | The aim of this standard was to initiate a uniform assessment guideline in the field of GHG assessment of a product level. | cradle–to–gate<br>cradle–to–grave | only assessment | not included |
| GHG Protocol | The aim of this tool was to provide additional guidance on the assessment of GHG emissions and offer an international GHG evaluation and reporting standard [11]. | cradle–to–gate<br>cradle–to–grave | assessment and communication | not included |
| ISO 14067 | In this standard the following principles are included:<br>– coherence – gives a possibility to compare between different materials within the same category;<br>– fairness – quantified carbon emissions and reductions in GHG emissions should be treated separately;<br>– possibility of integration of interested parties;<br>– avoidance of double – counting of GHG emissions [11]. | cradle–to–gate<br>cradle–to–grave<br>gate–to–gate<br>partial carbon footprint | assessment and communication | included |

at the raw material acquisition and end with waste removal, and are divided into stages connected with the life cycle of the product. Life cycle assessment is the basis for the carbon footprint calculations described by the following standards: ISO 14067 [11], PAS 2050 [12] and GHG Protocol [13]. ***Table 1*** shows a comparison between these standards in the field of applicability [10]. According to the description of the boundaries, the following categories can be distinguished: cradle to gate [11-13], cradle to grave [11-13], and gate to gate [13]. Cradle–to–grave assessment evaluates the environmental effects associated with each kind of activity from the initial gathering of raw materials until the point when all residuals are returned to the environment (in the form of wastes, gases or sewages). The other point of view: the cradle–to–gate concept is concentrated on a partial product life cycle from extraction (cradle) to the factory gate. Thus, the assessment ends before the product is transported to the consumer). Gate–to–gate assessment is a method of partial LCA calculation. This approach was used in this paper.

Literature sources focusing on complex carbon footprint calculations for footwear are relatively poor. For example, in paper [15] the carbon footprint was determined for leather shoes in order to highlight those steps, which contribute most to the total environmental impact. To obtain results, the authors used simplified semi – quantitative methodology. Studies described in [16] were focused on the correlation between the carbon footprint and thickness of finished bovine leather. In paper [17] the authors calculated the carbon footprint of Puma footwear with the use of the Carbon Trust Methodology Version 1.3 tool. The supply chain model of the life cycle assumed the following steps: primary production of raw materials, manufacturing, distribution, use and disposal. In paper [18] the authors showed that the reuse and recycling of clothing and footwear can reduce the environmental burden in comparison to purchasing new garments.

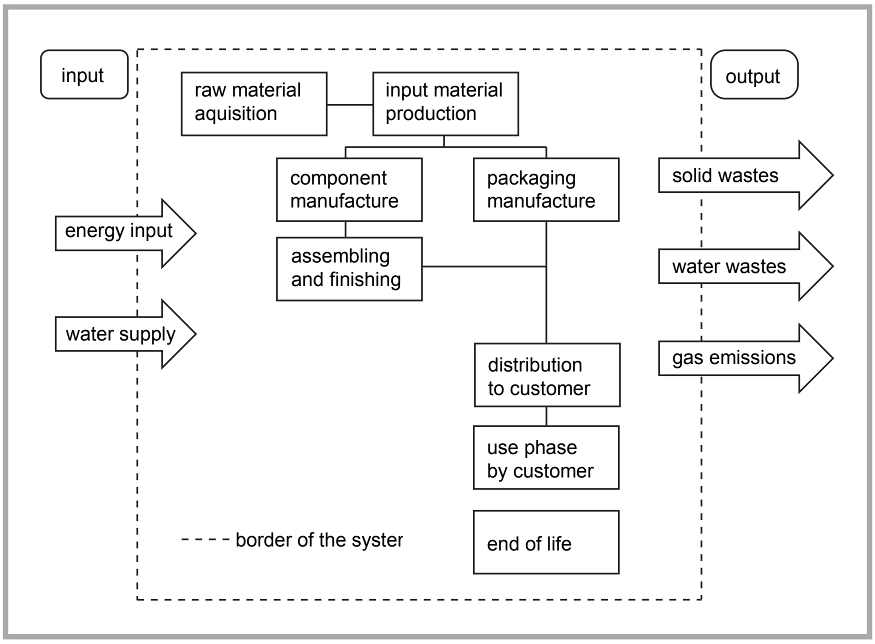


***Figure 1.*** *Life cycle system of footwear with boundaries [3].*

In this work the life cycle of footwear was divided into 8 stages, while calculations were made at stages 3, 4, 5, 6 and 8:

stage 1 – raw material acquisition,
stage 2 – production of input materials (such as leather, plastic, rubber, textile, metal, wood, wool, cork, cardboard, paper, chemicals, and others),
stage 3 – footwear component manufacture,
stage 4 – footwear assembling and packaging,
stage 5 – packaging manufacture,
stage 6 – distribution to customers,
stage 7 – use phase,
stage 8 – end of life.

In order to implement the life cycle assessment, the system boundaries were defined, shown in ***Figure 1***.

The aggregated amount of the carbon footprint, expressed as a carbon dioxide equivalent, was calculated with the use of ***Equation (1)*** [3].

$$CFP = \sum_{k=1}^{l}\left(\sum_{i=1}^{m} p_i + \sum_{j=1}^{n} w_j\right) = \sum_{k=1}^{l}\left(\sum_{i=1}^{m} f_i t_i + \sum_{j=1}^{n} x_j y_j\right), \quad (1)$$

where:
$k = 1, ..., 8$ – is an aggregation index corresponding to the number of stages,
$p_i$ – is the total volume of greenhouse gases during the $i^{th}$ process,
$w_j$ – is the total volume of greenhouse gases connected with the manufacturing of the $j^{th}$ part of a shoe,
$f_i$ – factor representing the emissivity of a unit process over its duration $t_i$,
$x_j$ – factor of emissivity of a unit material and its mass $y_j$.

*Table 2. Models and types of footwear used for footprint calculations.*

| Model | Description | Main upper materials (as a fraction of the percentage of the total shoe mass) | Outsole material (as a fraction of the percentage of the total shoe mass) | Total weight of pair of shoes, g | Total weight of product (with a package), g |
|---|---|---|---|---|---|
| M1 | Children is footwear size 35 | Bovine hides (chrome tanned leather) – 33.9%, acrylonite butadiene – styrene 7.3% | Thermoplastic polyurethane (TPU) – 38% | 333.95 | 435.30 |
| M2 | Children is footwear size 32 | Bovine hides (chrome tanned leather) – 25.6%, acrylonite butadiene – styrene – 6.6% | High density polyethylene (HDPE) – 39.7% | 365.71 | 467.77 |
| M3 | Children is footwear size 32 | Bovine hides (chrome tanned leather) – 30.4%, acrylonite butadiene – styrene – 8.4% | Thermoplastic polyurethane – 39% | 273.97 | 400.78 |
| M4 | Women's footwear of ballerina type size 37 | Chrome – tanned bovine leather – 24.4%, acrylonite butadiene – styrene – 3.4% | Natural rubber – 71.4% | 304.38 | 414.38 |
| M5 | Outdoor fotwear size 42 | Chrome – tanned bovine leather – 18.4%, metals (steel and cooper) – 14%, polyvinyl chloride – 3.8% | Thermoplastic polyurethane and polyurethane foam – 56.3% | 1549.10 | 1706.36 |
| M6 | Children is footwear size 32 | Cotton thread – 18.8%, acrylonite butadiene – styrene – 0.6% | Polyvinyl chloride – 67.6% | 343.08 | 466.01 |
| M7 | Men's outdoor fotwear size 42 | Chrome – tanned bovine leather – 26.6%, polyester – 2.5% | Desmodur + synthetic rubber – 48.6% | 699.55 | 840.18 |

The implementation of ***Equation (1)*** in the life cycle system required the following simplifications:

- Omission of emission amounts in stages 1 and 2. Their influence is included in stage 3.
- In stage 4, the power consumption was calculated only for processes which took place in the footwear factory.
- In stage 5, only the basic package was considered.
- In stage 6, the distance between the manufacturer and consignee was estimated as the that between the factory and the capital city of the country.
- The use phase (stage 7) was excluded from the calculations because its percentage in a total amount of CFP is less than 1%.
- In case of doubt, the conservatism rule was used. In accordance with this rule, the option with higher emissivity was chosen.

The main goal of the following investigations was calculation of the carbon footprint for seven models of footwear at all stages of the life cycle. The results obtained gave a possibility to identify those stages, where the emissivity is the highest. This paper is a continuation of the research cycle initiated by the authors of [19].

## Materials and methods

### Used materials

The test material was represented by 7 types of outdoor footwear (M1 – M7) derived from domestic production (Poland). ***Table 2*** shows characteristics of the materials used.

In order to ensure simplicity and clarity of final results, calculations were made for two components: the upper and sole. Depending on the footwear type, the following elements were placed in an upper set of materials: lining, tongue, reinforcement of the tongue, toe puff, counter, latch, reinforcement of the vamp, velcro, velcro belt, velcro frame, ornament leather, ribbon, ribbon reinforcement, thread, laces, eyelett, zip fasterner, lining (vamp and quarter), lining reinforcement, collar, foam of the collar, protective edge of the shoe puff, tex, heel counter, and cushioning elements. Such elements as filling on the outsole, latex foam, heel, nails, insole board and midsole were included in the sole part of the shoe.

### Methodology of carbon footprint calculation for footwear

Data acquisition, which was necessary to implement ***Equation (1)***, was made via a questionnaire. It consisted of the five following sheets:

- Introduction – this worksheet presents the general assumptions and goals of the $CO_2$Shoe tool and contains advice how to fill in the questionnaire.
- General data – in this sheet, general information about the footwear model evaluated and about footwear manufacture are provided (like the enterprise name, location, model name, category as well as the size, shoe weight and packaging weight).
- Components and packaging – in this sheet the specifications of materials and their amounts are included in relation to each component as well as the end of life of the materials (type of solid waste and end – of – life waste). This sheet also refers to the transportation, which is described by the distance between the manufacturer and customer.
- Assembling – in this sheet data (like total energy consumption for manufacturing, chemical consumption, total waste consumption, wastewater and end of life of solid wastes in manufacturing) related to assembling and finishing are collected.

***Table 3.*** *Correlation matrix of the total $CO_{2e}$ and $CO_{2e}$ at stages 3, 4, 5, 6, 8 (*significance level α = 0.05, ** significance level α = 0.01).*

| Source of correlation | Total $CO_{2e}$ | $CO_{2e}$ in stage 3 | $CO_{2e}$ in stage 4 | $CO_{2e}$ in stage 5 | $CO_{2e}$ in stage 6 | $CO_{2e}$ in stage 8 |
|---|---|---|---|---|---|---|
| total $CO_{2e}$ | 1 | 0.855* (p < 0.05) | 0.423 (p = 0.344) | 0.825* (p = 0.022) | 0.370 p = 0.414) | 0.457 (p = 0.303) |
| $CO_{2e}$ in stage 3 | 0.855* (p < 0.05) | 1 | -0.393 (p = 0.384) | 0.642 (p = 0.120) | 0.544 (p = 0.207) | 0.848* (p = 0.016) |
| $CO_{2e}$ in stage 4 | 0.423 (p = 0.344) | -0.393 (p = 0.384) | 1 | -0.038 (p = 0.935) | 0.337 (p = 0.459) | -0.239 (p = 0.606) |
| $CO_{2e}$ in stage 5 | 0.825* (p = 0.022) | 0.642 (p = 0.120) | -0.038 (p = 0.935) | 1 | 0.380 (p = 0.401) | 0.321 (p = 0.482) |
| $CO_{2e}$ in stage 6 | 0.370 (p = 0.414) | 0.544 (p = 0.207) | 0.337 (p = 0.459) | 0.380 (p = 0.401) | 1 | 0.534 (p = 0.217) |
| $CO_{2e}$ in stage 8 | 0.457 (p = 0.303) | 0.848* (p = 0.016) | -0.239 (p = 0.606) | 0.321 (p = 0.482) | 0.534 (p = 0.217) | 1 |

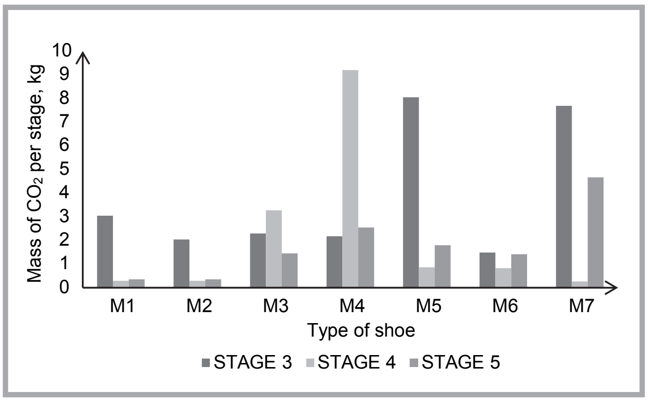


***Figure 2.*** *Total $CO_2$ emissions (kg) for stages 3, 4, 5.*

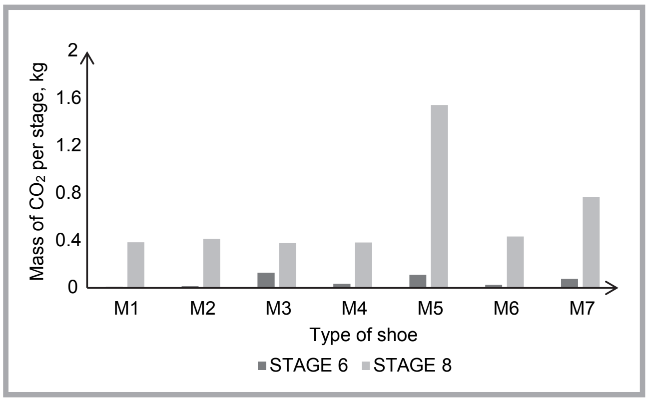


***Figure 3.*** *Total $CO_2$ emissions (kg) for stages 6, 7, 8.*

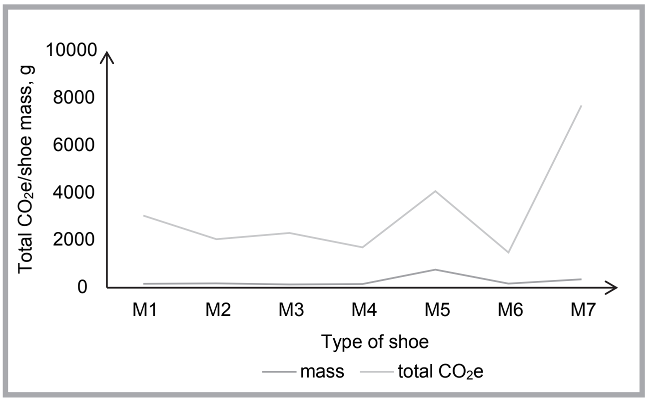


***Figure 4.*** *Relation between the mass of a pair of shoes and the total $CO_2$ emissions (as a sum of the upper and outsole emissions).*

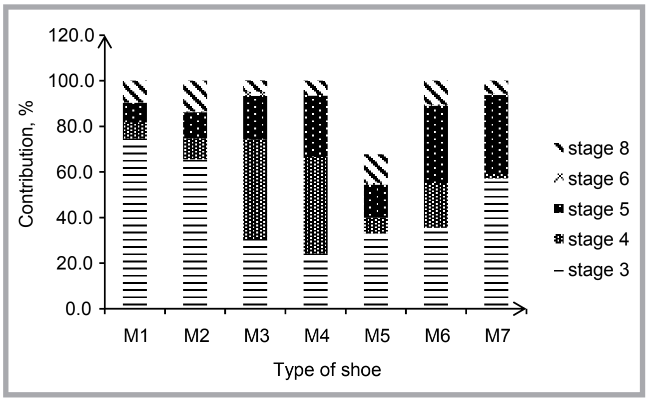


***Figure 5.*** *Percentage contribution of $CO_2$ emissions to the total value of $CO_2$ emissions.*

- Distribution – this sheet collects data about transportation from the manufacturer to an average distribution point.

Completion and processing of this questionnaire in the evaluation was a necessary step in order to create a final report with calculated values of $CO_2$ emissions for each step.

## Results and discussion

The result of the questionnaire input was a dataset about the carbon footprint for each model of footwear, M1 – M7, used in this experiment. ***Figures 1*** and ***2*** show the total $CO_2$ emissions for each stage analysed: 3, 4, 5, 6 and 8. The maximum value was reached for stage 3 in the M5 model, which was expressed in terms of equivalent $CO_{2e}$ as 8.049 kg (***Figure 2***). By contrast (***Figure 3***), stage 6 (distribution to a customer) was the least toxic of stages (the minimal value of equivalent $CO_2$ was reported in M1 and reached the level 0.009 kg). The large variation between particular types of shoes was manifested by high values of the coefficient of variation for each steps: 76% – step 3, 104% – step 4, 85% – step 5, 92% – step 6 and 69% – step 8. Hence, this information can be important to initiate reduction operations.

It is possible to assume that footwear mass is one of the most important elements which have a close relation with $CO_2$ emissions (it is evident especially between M1 – M6, where the correlation reached the level of 0.82).

Reduction of the footwear mass can be an important operation which allows to reduce $CO_2$ emissions, especially when the basic materials are substituted by others with a low specific weight.

In order to form a qualitative description of the contributions of each stages to the total carbon footprint value, correlation coefficients between particular emissions and total emissions were calculated (***Table 4***).

The correlation matrix components show that the total volume of emissions has a strong linear relationship with emissions from stage 3 (correlation at a level of 0.855 and for a statistical significance less than the confidence interval value $\alpha = 0.05$) and with those from stage 5 (correlation at a level of 0.815 and for a statistical significance less than the confidence interval value $\alpha = 0.05$). In all

***Table 4.*** *Model summary for predictors $X_3$, $X_4$, $X_5$, $X_6$, $X_8$.*

| R | R-square | Adjusted R-square | Standard error of estimate | Durbin – Watson statistics |
|---|---|---|---|---|
| 1.000 | 0.999 | 0.996 | 133.211 | 2.542 |

***Table 5.*** *ANOVA results for model proposal.*

| Model | Sum of squares | df | Mean square | F | Significance |
|---|---|---|---|---|---|
| Regression | 2.828E7 | 5 | 5656179.344 | 318.746 | 0.042 < 0.05 |
| Residual | 17745.093 | 1 | 17745.093 | | |
| Total | 2.830E7 | 6 | | | |

other cases, the values of correlation stay between 0.370 for stage 6 and 0.467 for stage 8. The correlation coefficients correspond to the percentage contribution of each life cycle stage to the total value of $CO_2$ emissions.

According to the data shown in ***Figure 5***, the highest volumes of greenhouse gasses were produced during stage 3 for the following models: M1 (74.5%), M2 (65.4%) and M7 (57.1%). In the case of models M3 and M4, dominant was stage 4 (43.5% and 42.4%, respectively). The smallest values of emissions were observed for M7 (1.9%). In stage 5, the total volume of greenhouse gases emitted stayed between 8.7% for M1 and 34.7 for M7. Stage 6 had a small share (less than 2%). In the case of stage 8, the percentages ranged between 5% in M3 to 13.3% in M2, which means that the intensity of activities undertaken for the reduction of emissions should be geared towards the most emissive stages, i.e. stage 3 in M1, M2 & M7, stage 4 in M3 & M4, and stage 5 in M7. In order to develop a unidirectional relationship which connects the total emissions with particular emissions at each stage, the following regression model was created according to ***Equation (2)*** below:

$$Y: f(X, \xi), \qquad (2)$$

Where, $Y$ is a dependent variable (total volume of $CO_2$ emissions from all stages), and is a fifth – piece combination $X = [X_3, X_4, X_5, X_6, X_8]$, where indexes 3, 4, 5, 6 & 8 correspond to the numbers of stages. Moreover, it is assumed that the random component $\xi$ has a standard normal distribution. When the data obtained from all stages were put into ***Equation (2)***, function $Y$ took the following form:

$$Y(X) = 1044.760X_3 - 89.057X_4 + \\ + 297.174X_5 - 921.885X_6 - \\ + 3925.486X_8 + 1370.817. \qquad (3)$$

Details on this model are described in ***Table 4***.

Model (2) is a multivariable function which can be implemented in an optimisation procedure. It is possible to minimise function Y with the use of certain sets of constraints, which can be changed depending on the technical possibilities.

## Conclusions

In this paper, the authors performed the calculation of the carbon footprint for seven models of footwear available on the market. Knowledge in the field of real amounts of emissions from each stage is very important to minimise the negative impact of the final product on the environment. On the other hand, it is possible to take actions which can optimise the manufacturing processes by, for example, switching to new suppliers with a low carbon balance [20], liquidation of gaps in transport, improving energy effectiveness [21], less consumption of raw materials [22], switching to natural materials [2-25], switching from traditional coal energy to biomass renewable energy [26], and waste and material management [27-30]. Moreover, analysis of LCA gives an opportunity to determine a market position for a certain company. The preliminary analysis, done in this paper, gives a possibility to suggest several ready – made solutions, which can be implemented by manufacturers or consumers in industrial practice. The solutions are suggested for the most emissive stages: 3, 4 and 5.

**Stage 3**

- Reduction of the weight of materials used in component manufacture. This could give a great positive impact on the carbon footprint of the final product, because a small reduction in weight could significantly reduce the total carbon footprint value.
- Use of materials with lesser impact. For example, replacement of chrome tanned bovine leather by other material with lesser environmental impact, for instance, by glutaraldehyde bovine tanned leather. Reduction of the weight of the outsole is possible by replacement of PU material with, for example, natural rubber, SBR, synthetic rubber, PVC or other material with similar properties.

**Stage 4**

- Replacement of solvent-based adhesives (SBAs) by others with lesser impact, such as water – based adhesives (WBAs). WBA can be used on current production lines with existing equipment.
- Reduction of chemical consumption, especially during finishing and assembling processes.
- Increase in the consumption of renewable energy sources.
- Reduction of electricity consumption by use of energy – efficient machinery and improved factory insulation to minimise heat loss.

**Stage 5**

- Reduction of the weight of cardboard boxes by replacing the material by another with lesser impact, such as 100% recycled paper.

All of undertaken decisions should take into account the consequences. For example, when the mass of a shoe goes down, then it is possible that the durability of the final product will deteriorate too. However, this fact is negative from an ecological point of view because it makes the purchase of a new pair necessary. In order to verify the real effectiveness of the operation, it is necessary to control the quality of modified products. In this case, the criteria established for the EU Ecolabel for Footwear may be helpful [31-32]. In this paper the use of the product stage was omitted because there is no reliable method for estimation of the carbon footprint at this stage. It does not alter the fact, that quality aspects should be taken into considerations by manufacturers and companies. In this case the responsibility for product quality goes hand-in-hand with environmental protection.

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