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Comparative Life Cycle Assessment of Water-based and Solvent-based Primer Paints for Steel Plate Priming

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Nowadays, hazardous substances such as volatile organic compounds (VOCs) are still being used and released in steel plate priming processes. These releases might have severe negative impacts on the environment. One of the well-established methods for the evaluation of these impacts is the life cycle assessment method. In this study, life cycle assessment (LCA) was used to justify product substitution in a Lithuanian company due to regulatory concerns. In this study, life cycle impacts of this substitution were assessed by using LCA methodology. The results, within the mentioned uncertainties, indicated that the substitution to the water based primer paint was beneficial in all environmental impact categories. The study results also showed the importance of conducting an LCA study, and the shortcomings of local assessments.

Keywords: *Life cycle assessment, water-based primer, solvent-based primer, environmental impact, chemicals substitution.*

Introduction

Environmental concerns caused by the production of products and the supply of services are increasing in our current society, despite exponential growth in technological advances (Magee, 2016). Although it is highly probable that the future of technology will enable the supply of goods and services with negligible environmental impact, today that is not the case. The amount of waste produced in the EU only is about 2.5 billion tonnes per year, and this value has not changed much since 2004 (Eurostat 2016b). The disposal rate is also not showing any decline trend (Eurostat 2015). Similarly, greenhouse gas emissions have not declined dramatically since 2005 (Eurostat 2016a).

There are 4 major criteria that determine the impacts of such human activities on the environment: human needs, state of technologies, policy and policy implementation, and the reaction of the environment towards disturbances. The latter one is generally considered to be risky and hard to control by humans because of the complex feedback loops in the natural ecosystem. This concept is similar to the DPSIR framework used by the European Environment Agency (EEA) (EEA 2007).

From the statistical point of view, there is a very high probability of rendering the environment less suitable for humans whenever a sudden novel intervention is made, because there are much more environmental states that are not suitable for humans than the ones that are suitable, and humans have been optimised by evolution for the current specific situation. Here, 'suitability' indicates the degree of pleasure gained by living in an environment. As the phenomenon of 'pleasure' has evolved for the well-being of humans and determines the human needs, we can use this as an indicator. One can stress to measure stress hormones (Haybron, 2013) over all the population over time as an indicator for pleasure of living in an environment. Of course the results will depend on the culture, thought patterns and other physical properties of the individuals. Hence, we recognise that human needs depend on the culture (i.e., thought patterns) as well as biological needs. As humans try to make the earth more 'suitable' for themselves (here, 'themselves' represent each individual person) by introducing novel human needs, a negative feedback is highly probable by the environment that decreases the suitability for humans. Hence, as in all such non-linear negative feedback systems, an optimum must be found that maximises the suitability of the environment for humans.

After this general picture, one can ask the question of how to optimise the suitability of the environment. We can decrease human needs by changing the culture, implement effective policies to ensure the implementation of the best available techniques, or improve the technological processes and systems that are used to meet human needs. In this article, we will focus on the latter: improvement of technological processes and systems. Particularly, we will use the life cycle assessment (LCA) tool to guide us in the minimisation of the environmental impacts of products (in this case, painted steel sheet) serving a common function. LCA is a well-established method for the evaluation of environmental impacts in critical categories of environmental concern (e.g., climate change) (EC 2010a). LCA is the only method that accounts for emissions and resource use along the whole life cycle of a product and evaluates the impact in multiple impact categories, hence preventing the 'shifting of burdens' from one life cycle stage to another, and from one impact category to another (EC 2010a). The LCA method is a crucial tool that can support the absolute decoupling (EEA 2016) of resource use and economic growth. Despite this fact, according to the authors' knowledge, there are no other LCA studies conducted for similar priming processes studied below.

Methodology

Life cycle of a product includes all the stages of its production, from extraction of raw materials to disposal of remaining waste (EC 2010a). It includes all of the relevant processes necessary to make the final product. A process can be described as input-output data for each unit of production, for the purposes of environmental impact assessment. In other words, input-output data for each relevant process is sufficient for defining the complete production system of a given product.

Input-output analysis will be used for the description of the foreground processes and data will be collected accordingly from the company itself, and from the literature when there is missing information for these processes.

In this article, LCA will be used as a quantitative tool for the comparison of products that serve the same function. ISO standards (ISO 2006a; ISO 2006b) for LCA exist and many guidelines (e.g., European Commission guidelines (EC 2010a)) are present on how to conduct these studies.

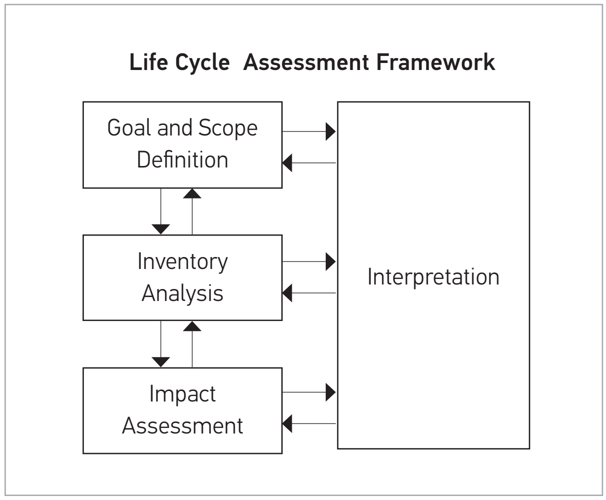
As mentioned, the life cycle of a product can be thought of as interconnected processes that exchange flows. This can be described by the Open Leontief Model (Hendrickson et al., 1998). The model takes into account the external demand by the consumer and determines how much output is needed from each relevant process. This is particularly useful because once the emissions and resource use are known for each process, the environmental impacts can be derived by using various models (Hendrickson et al., 1998). For this purpose, Recipe 2008 method will be used.

ISO 14040 standard defines the basic structure of an LCA study as in Fig. 1.

According to this framework, LCA studies have 4 stages. We will follow these stages in this article. SimaPro 8.1 software will be used for calculations.

Fig. 1

ISO 14040: 2006 LCA framework (Source: ISO 14040)



Results

Goal and scope definition

The analysed company is exceeding the VOC emission limits and is using some hazardous substances according to Industrial Emissions Directive (IED) (2010/75/EU) (EU 2010) and Paints Directive 2004/42/EC (EU 2004). The company has decided to substitute their shop primer paint with another alternative shop primer. The goal of this study is defined as the evaluation of life cycle environmental impacts of 2 'shop primer' paint products produced in Denmark to be used in the Lithuanian company: Shopprimer A and Shopprimer B. The functional unit is selected as coverage of 1 m^2 steel plate during ship building and the use phase (EC 2010a). It will be assumed that both primer paints have the same life expectancy during the use phase.

The waste stage of the primed steel sheet product is unknown and assumptions cannot be made. The primed steel is expected to emit some part of the primer contents into the sea from the ship body due to rusting, but this amount is unknown. Also, there is no information about the recycling of the product. For this reason, the scope of this study excludes the use and waste stages of the product. The construction and maintenance of the capital goods necessary for the foreground processes is assumed to be the same for the initial and the final situation. Packaging information is not available and assumed to be the same as well, although reductions are expected due to the more efficient coverage of the alternative primer. The primer paint preparation process (in Denmark) is also excluded from the foreground processes.

Thus, the only foreground process is the priming process. In the following sections, the transport will be seen as a part of the input of primer paint. The priming process is given in Fig. 2.

At first, metal sheets are heated to vaporise any moisture present on the steel surface. This is a necessary preliminary step before the metal cleaning and metal

Fig. 2

Priming process in the company

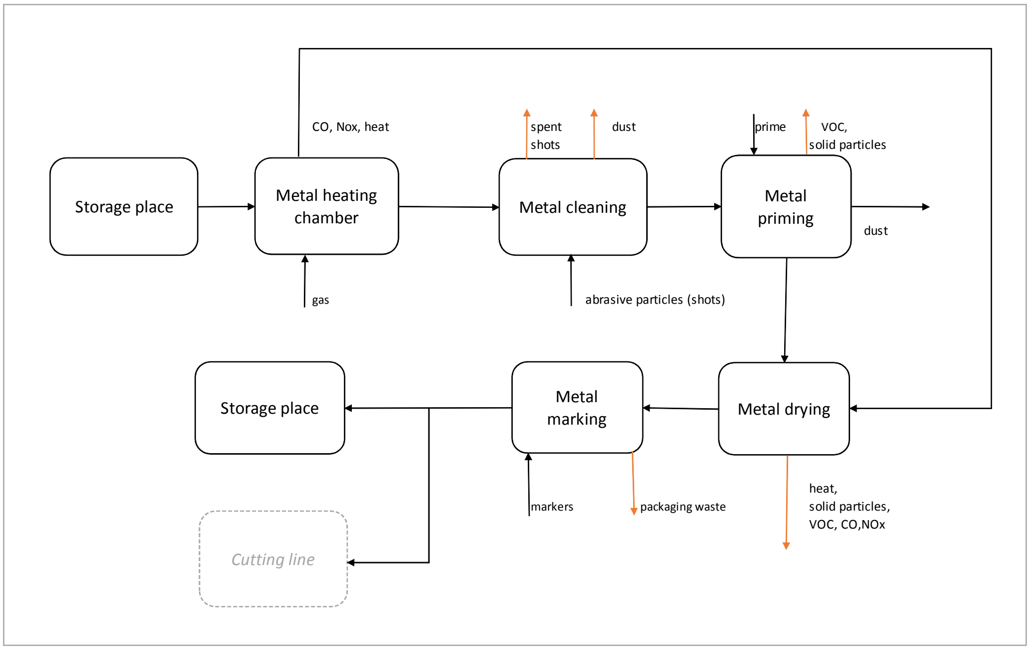
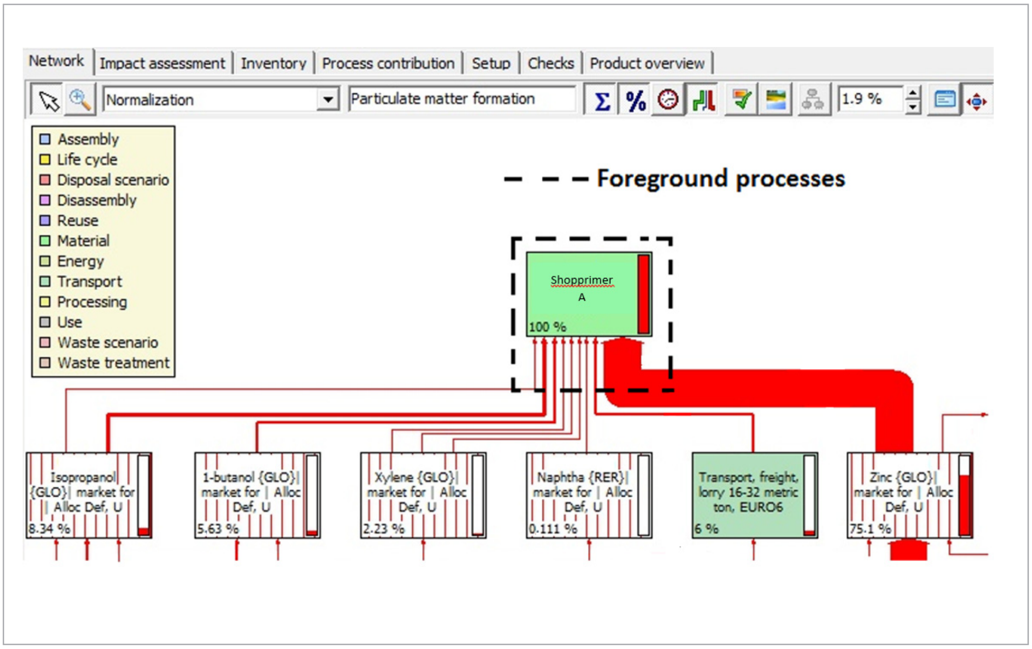


Fig. 3

Scope for the initial situation after inventory analysis. Zeroth and some of the first tier processes are shown for the initial situation. Not all the relevant background processes are shown, the node cut-off value is taken to be 1.9% for 'particulate matter formation' and tiers above first tier are excluded from this figure (but not from the study). Foreground processes are indicated with dashed lines



priming processes. During the process, natural gas is consumed as input. The metal cleaning process uses abrasive shots to clean the steel surface and no chemicals are being used. In the metal priming process, the primer paint is sprayed over the steel sheet surface. The mist of the excess primer paint is vacuumed and treated to assure the emission air quality standards. Nevertheless, VOCs are emitted during the priming. In the metal drying process, excess heat from the metal heating chamber is used to dry the primer paint. VOCs are also released to the atmosphere from the drying of primer. After drying, primed metal sheets are marked and taken to the storage place. The company does not produce any by-products.

The foreground processes are indicated in Fig. 3 and Fig. 4, for the initial and the final situation, respectively.

Inventory analysis

For the initial situation where Shopprimer B is being used, the input-output information for the priming process is given in Fig. 5.

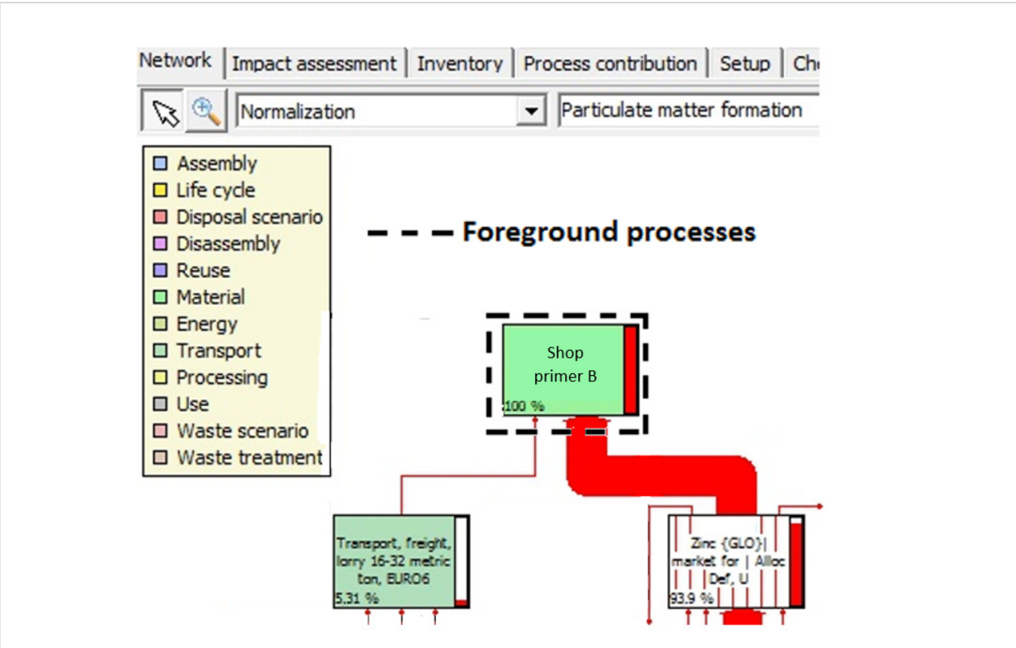
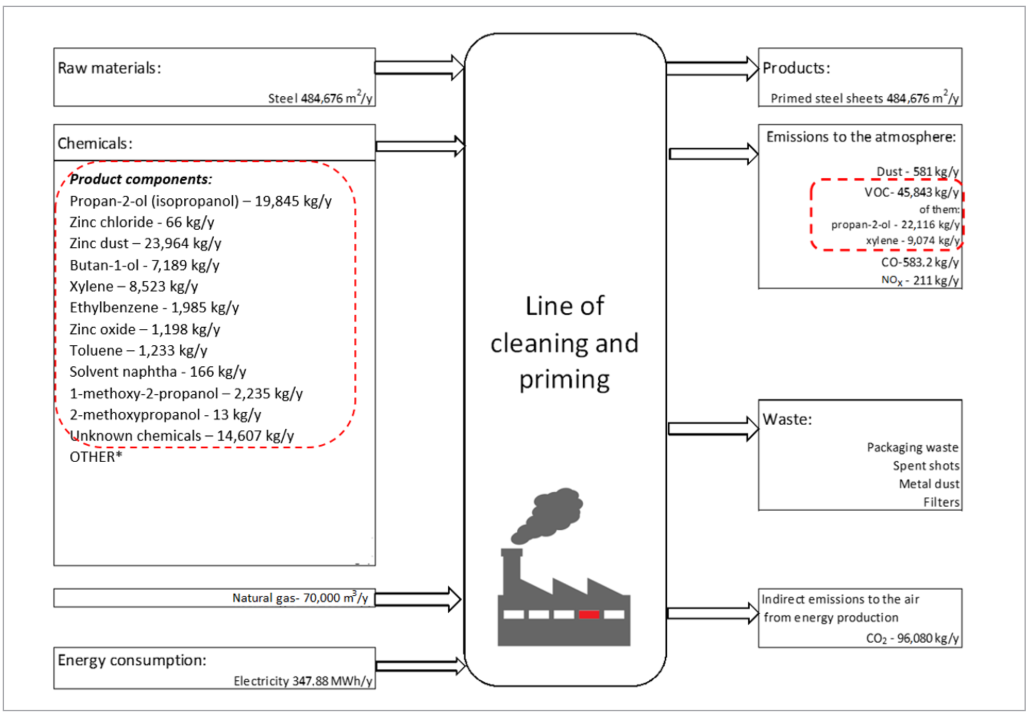


Fig. 4
Scope for the final situation after inventory analysis. Zeroth and some of the first tier processes are shown for the final situation. Not all the relevant background processes are shown, the node cut-off value is taken to be 1.9% for 'particulate matter formation' and tiers above first tier are excluded from this figure (but not from the study). Foreground processes are indicated with dashed lines



* The same for the initial and the final situation

Fig. 5
Input-output data of the priming process with Shopprimer A. Dashed boxes indicate the input/output that is different from the final situation

The company recognises that almost half of the chemicals used are emitted to the atmosphere as VOCs, the Propan-2-ol and Xylene being the major atmospheric emissions.

In contrast to Shopprimer A, Shopprimer B is a water-based product. This enables the use of water for thinning purposes instead of thinners, which are a major cause of VOC emissions. After the substitution of the primer paint to Shopprimer B, the input-output of the priming process is expected to be as in Fig. 6.

As our goal is to compare the environmental impact of 2 products, relative assessment can be conducted instead of an absolute assessment, meaning that not all the information in Figures 5 and 6 needs to be used in the impact assessment. The inputs-outputs that are not affected by the substitution will be excluded from the LCA inventory. By doing so, the background processes that supply these inputs are also excluded from the scope of the LCA.

After this exclusion, the input inventory can be described as in Tables 1 and 2 for the initial and the final situation, respectively.

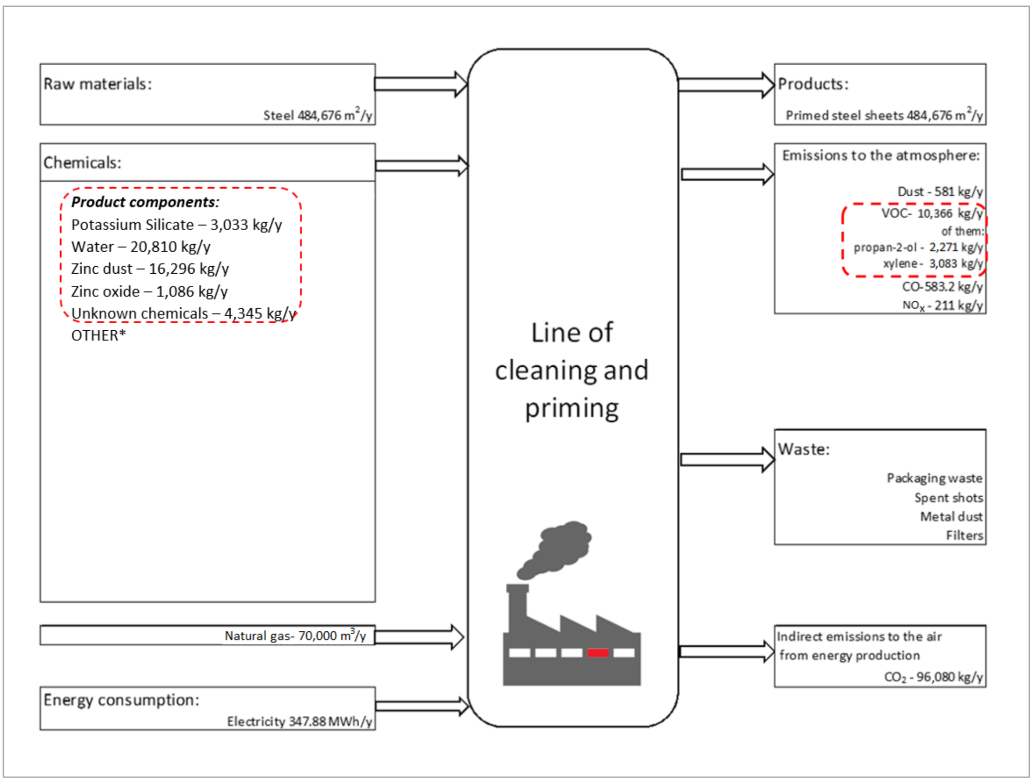
The old product is capable of covering 18.7 m^2/L (covered area per volume of primer used). The composition of inputs that are substituted is presented in Table 1.

The new product chosen as input is capable of covering a bigger (25m^2/L) area, hence less product is needed to cover the same area. A part of the composition of the product is not mentioned in the SDS or PDS; therefore, information from a similar product was used to fill in this data gap. The composition of the new input (Shopprimer B) is presented in Table 2.

This information is gathered from the safety data sheets and product data sheets of the products. As companies do not give the exact composition (as percentage of the total product) of their products in most cases, the Monte Carlo method could be used within the uncertainty range of product composition. Nevertheless, be-

Fig. 6

Expected input-output data of the priming process with Shopprimer B. Dashed boxes indicate the input/output that is different from the initial situation



* The same for the initial and the final situation

Table 1
Composition of substituted inputs; the initial situation (* VOC: Volatile organic compound)

Composition	CAS no.	Used amount (kg/year)	Normalised to functional unit (kg/m²)
1	2	3	4
Propan-2-ol (isopropanol)* [2]	67-63-0	19,845	0.04095
Zinc chloride[1]	7646-85-7	66	0.00014
Zinc dust [3]	7440-66-6	23,964	0.04944
Butan-1-ol*	71-36-3	7,189	0.01483
Xylene*	1330-20-7	5,991	0.01236
Ethylbenzene* [2]	100-41-4	1,438	0.00297
Zinc oxide	1314-13-2	1,198	0.00247
Propan-2-ol* [2]	67-63-0	1,166	0.00241
Toluene*	108-88-3	1,233	0.00254
Xylene*	1330-20-7	400	0.00083
Ethylbenzene* [2]	100-41-4	100	0.00021
Solvent naphtha* [3]	64742-95-6	166	0.00034
1-methoxy-2-propanol* [1 2]	107-98-2	2,235	0.00461
Xylene*	1330-20-7	2,132	0.00440
Ethylbenzene* [2]	100-41-4	447	0.00092
2-methoxypropanol*[1]	1589-47-5	13	0.00003
The rest (Unknown) [1]	-	14,607	0.03014
Total		82,190	0.16958

[1] Missing in inputs; not in the LCI database
[2] Missing in air emissions - entered as general VOC
[3] Other substances are used in the LCI instead, which are assumed to be similar

Table 2
Composition of alternative product inputs; the final situation

Composition	CAS no.	Used amount (kg/year)	Normalised to functional unit (kg/m²)
1	2	3	4
Potassium Silicate [1]	1312-76-1	3,033	0.00626
Water	7732-18-5	14,810	0.03056
Zinc dust [3]	7440-66-6	16,296	0.03362
Zinc oxide	1314-13-2	1,086	0.00224
Water	7732-18-5	6,000	0.01238
The rest (Unknown) [1]	-	4,345	0.00897
Total		45,570	0.09402

[1] Missing in inputs; not in the LCI database
[3] Other substances are used in the LCI instead, which are assumed to be similar

cause the Monte Carlo analysis is not available in the Demo version of SimaPro 8.1 software, in this study the product composition is taken as in Table 1 and Table 2. All the chemicals in Tables 1 and 2, except 6,000 kg of water per year in Table 2, are transported from Denmark to Lithuania, which is approximately 1,700 km. As the origin of those materials is not known, it will be assumed that they are not recycled materials, and they are produced with world average technology unless there is information about the origin of the materials and services (e.g., tap water and transport is known to be from Europe). The transport process was accounted as an input to the priming process, as no separation of transport impacts is necessary for the purposes of this study. Allocation was set to the default system model, which is based on the economic allocation of the environmental impacts (Pre 2016). It will be assumed that all VOCs present in the primer will be emitted to the atmosphere during the application of the primer or in the drying stage.

Figures 7 and 8 show the input-output and emission data, present in the LCI databases, for foreground processes.

Fig. 7

Input-output data present in LCI databases for the overall foreground processes for the use case of Shopprimer A

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %
Shopprimer A	0.16958	kg	Mass	100 %
(Insert line here)				

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD
(Insert line here)				

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD
(Insert line here)					

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit
Isopropanol {GLO}| market for | Alloc Def, U	0.04095	kg
1-butanol {GLO}| market for | Alloc Def, U	0.01483	kg
Xylene {GLO}| market for | Alloc Def, U	0.01236	kg
Ethyl benzene {GLO}| market for | Alloc Def, U	0.00297	kg
Zinc oxide {GLO}| market for | Alloc Def, U	0.00247	kg
Isopropanol {GLO}| market for | Alloc Def, U	0.00241	kg
Toluene, liquid {GLO}| market for | Alloc Def, U	0.00254	kg
Xylene {GLO}| market for | Alloc Def, U	0.00083	kg
Ethyl benzene {GLO}| market for | Alloc Def, U	0.00092	kg
Naphtha {RER}| market for | Alloc Def, U	0.00034	kg
Xylene {GLO}| market for | Alloc Def, U	0.00440	kg
Ethyl benzene {GLO}| market for | Alloc Def, U	0.00092	kg
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	288.286	kgkm
Zinc {GLO}| market for | Alloc Def, U	0.04944	kg
(Insert line here)		

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD
(Insert line here)				

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD
1-Butanol	low. pop., long-tern	0.01483	kg	Undefined	
Xylene	low. pop., long-tern	0.01236	kg	Undefined	
Toluene	low. pop., long-tern	0.00254	kg	Undefined	
Xylene	low. pop., long-tern	0.00083	kg	Undefined	
Naphtha	low. pop., long-tern	0.00034	kg	Undefined	
Xylene	low. pop., long-tern	0.00440	kg	Undefined	
2-Methoxy-1-propanol	low. pop., long-tern	0.00003	kg	Undefined	
VOC, volatile organic compounds	low. pop., long-tern	0.05207	kg	Undefined	

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %
Shopprimer B	0.09402	kg	Mass	100 %
(Insert line here)				

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD
(Insert line here)				

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD
(Insert line here)					

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit
Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Def, U	138.788	kgkm
Water, completely softened, from decarbonised water, at user {RER}| production | Alloc Def, U	0.03056	kg
Zinc oxide {GLO}| market for | Alloc Def, U	0.00224	kg
Tap water {Europe without Switzerland}| market for | Alloc Def, U	0.01238	kg
Zinc {GLO}| market for | Alloc Def, U	0.03362	kg

Fig. 8
Input-output data present in LCI databases for the overall foreground processes for the use case of Shopprimer B

Impact assessment

There are various impact assessment methods that are available for LCA studies (EC 2010b). Among those, the ReCiPe 2008 method is a relatively new method that includes 16 midpoint and 3 endpoint impact categories. The method is developed to be consistent among midpoint and endpoint categories, meaning that midpoint categories are used to derive the endpoint impact categories (EC 2010b). The ReCiPe 2008 method will be used for the impact assessment in this paper. The selected version of the ReCiPe 2008 method is version 1.11 with normalisation values for Europe, and midpoint (egalitarian) impact assessment was chosen for implementation due to the relatively lower uncertainty in results compared with endpoint impact assessment (Goedkoop et al., 2013). The egalitarian option takes into account the long term impacts of disturbances, up to 500 years (Goedkoop et al., 2013). No cut-off is implemented for the impacts of the processes, and impacts of all processes are taken into account no matter how small they are.

Impact assessment results

The results are calculated to be as in Fig. 9 and Fig. 10.

Interpretation

The results (Fig. 9 and Fig. 10) of the impact assessment step suggest that the alternative product Shopprimer B is environmentally favourable, within the given scope, for all the impact categories. This is partly due to the fact that the water-based product is more efficient in covering an area per unit volume of the primer used, apart from the product composition. The normalisation step should be interpreted carefully because the normalisation is made by comparison to the environmental impact of an average European citizen in the year 2000 (Goedkoop et al., 2016), which is not necessarily sustainable.

Discussion

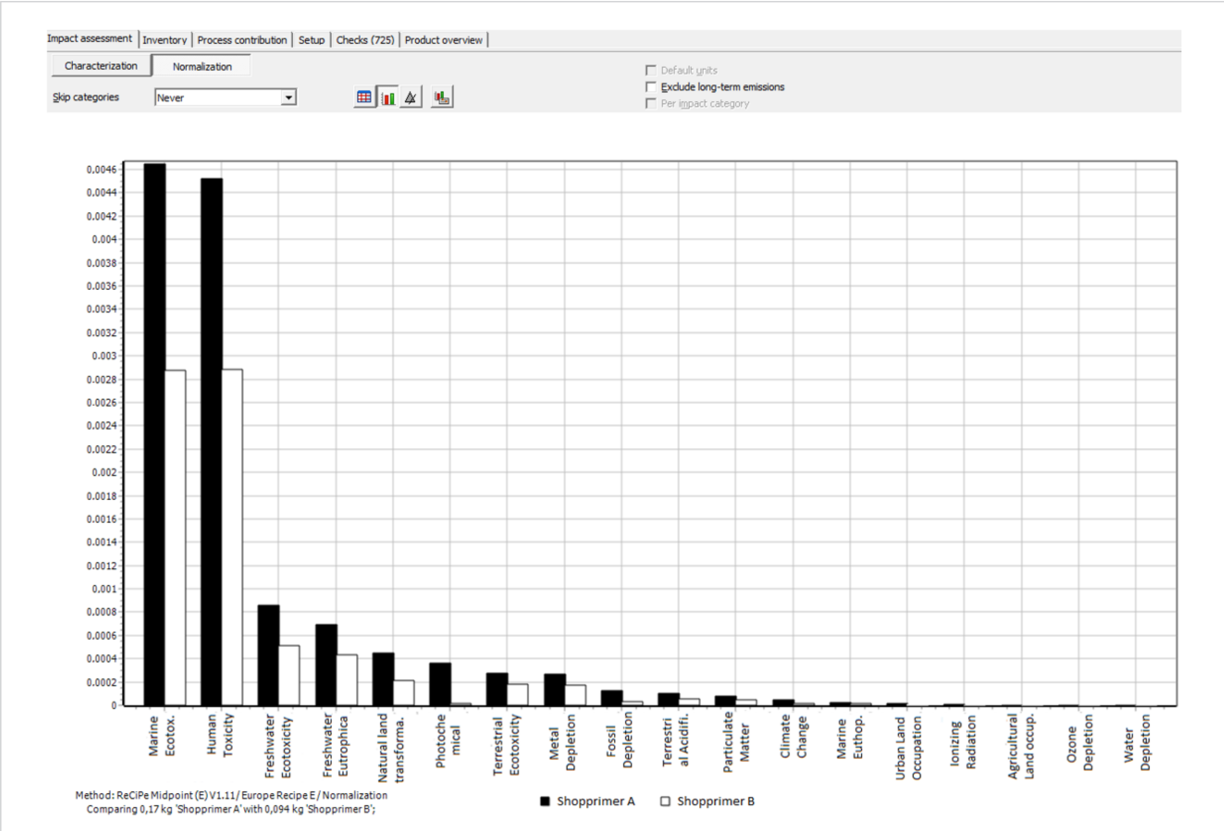
One surprising outcome of the results is that the water-based product contributes less to the depletion of the water resources when the life cycles of the products are taken into consideration (e.g., 1-butanol production, zinc production, xylene production, propylene production, etc.). This indicates the importance of life cycle thinking.

Similar results have been concluded by a study on solvent-based and water-based coating products, for painting of buildings, conducted by the Duke University (Nitschke, 2014). Besides, LCA of water-based paints for road markings in Krakow (Poland) concluded the environmental benefits of substitution to water-based products and reductions in VOC emissions as a consequence (Burghardt, 2016).

The results should be interpreted carefully, keeping in mind that these results might be different for other primer types (e.g., with different efficiency of covering an

Fig. 9

Comparative impact assessment results without the normalisation step (Note: Impact categories cannot be compared with each other without a normalisation step)



area). For example, if the primers had the same efficiency of covering an area, then human toxicity, freshwater eutrophication and all categories of ecotoxicity would give higher impact results for the water-based primer.

One should also be very careful in making inferences based on a comparative LCA study. The results are comparative and based on exclusions of similar aspects and, hence, not for deducing absolute values.

The missing background processes due to the lack of data in LCI databases might necessitate the expansion of the scope of the LCI to include the missing processes into the foreground system. Another missing information, product composition (as a percentage of the total product), is caused by a totally different reason: to preserve company secrets. In the worst case, this problem can be eliminated by introducing harmonised encryption to the data from companies, which can only be decoded by the LCA software.

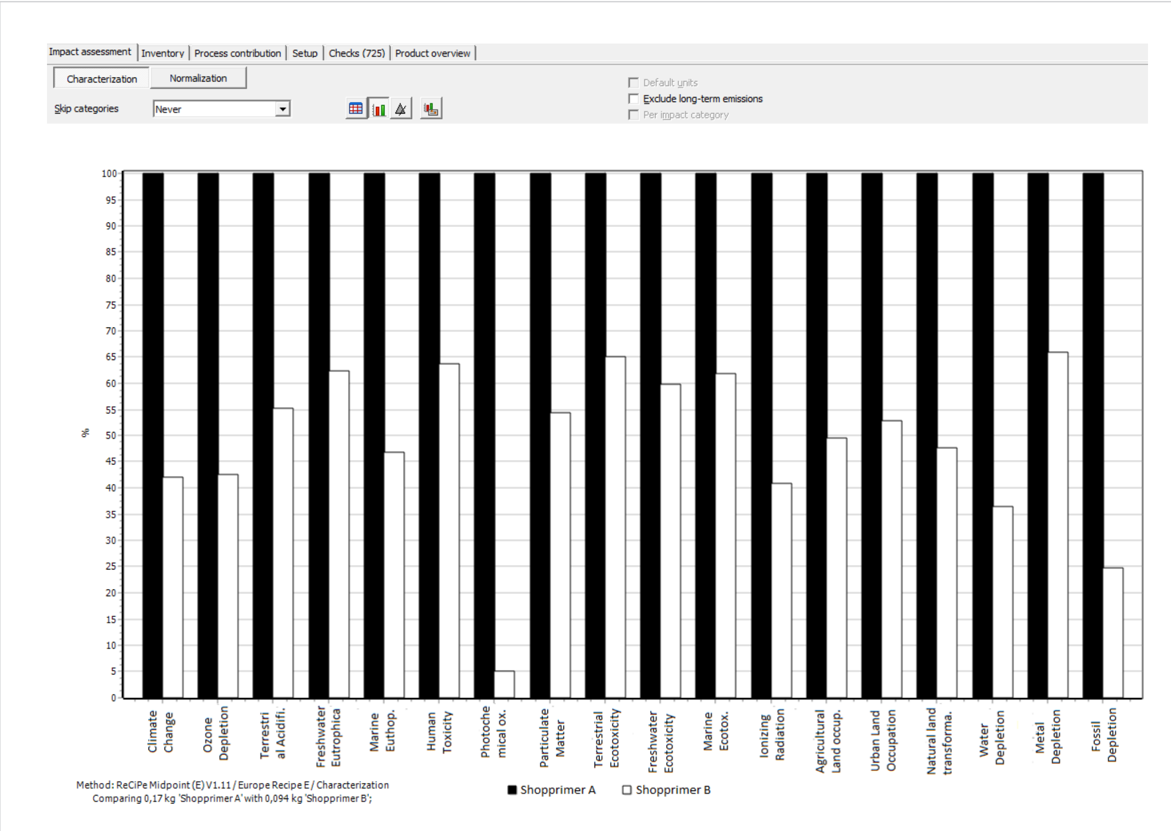
The waste treatment stage is also important to include. Nevertheless, for this study, it is not expected to change the conclusion because the alternative includes less amount of each of known substances that are currently being used. The importance of the waste treatment stage might be crucial if the efficiencies of the primer products for covering a given area were different than they are in this study.

Improvements

Without Monte Carlo analysis, the results cannot be interpreted statistically. The Monte Carlo analysis is necessary to improve the validity of this assessment. Also, more data should be gathered about the omitted life cycle stages of the products and on the missing information in LCI databases. Assessment can be improved further by expanding the scope of the LCI by incorporating the missing processes in the LCI database to the scope of the LCI of the study itself. Besides, further comple-

Fig. 10

Comparative impact assessment results after the normalisation step (Note: Weighting step is not available for the midpoint categories)



mentary assessments (e.g., risk assessments, social assessments, etc.) should be implemented to reach a final conclusion. Such difficulties are discussed in another paper by the authors (Oguzcan 2016).

Conclusion

Life cycle assessment of 2 shop primer products showed, in this specific case, that the water-based shop primer was environmentally preferable for all the environmental impact categories, within the mentioned uncertainties. All the impact categories showed more than 34% decrease in environmental impact, which is a very good justification for the substitution in the company from an environmental perspective.

The results indicated the importance of conducting LCA for decision making and pointed out to the shortcomings of human intuition and local assessments (i.e., assessments that exclude the life cycle stages).

The study itself is not a standalone for decision-making, and further assessments should be done, such as risk assessment for the environment and for workers, social assessment, etc.

The study also underlined that 'company secret' information is problematic for LCA. It is stressed that, if keeping the 'company secret' is inevitable, the use of an appropriate encryption system will solve this problem.

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Vandens ir tirpiklio pagrindu pagamintų tarpinių gruntų, naudojamų plieno padengimui, palyginimas taikant būvio ciklo vertinimą

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Lakieji organiniai junginiai, pasižymintys pavojingumu aplinkai ir žmonių sveikatai, vis dar būna naudojami ir patenka į aplinką iš metalo dengimo procesų, pavyzdžiui, plieno gruntavimo. Pastaraisiais dešimtmečiais priimami vis griežtesni teisiniai reikalavai, kurie skatina naudoti mažesnio pavojingumo medžiagas. Tačiau tinkamai atlikti pavojingų cheminių medžiagų pakeitimą nėra paprasta, nes būtina įvertinti, ar pakeitimas tikrai sumažins neigiamą poveikį aplinkai ir žmonių sveikatai, ar jis nebus perkeltas kitur. Vienas iš būdų, leidžiančių įvertinti pakeitimo poveikį aplinkai, yra būvio ciklo vertinimas (BCV).

Būtent BCV pritaikytas straipsnyje pristatomame tyrime, skirtame pagrįsti metalo apdirbimo įmonėje planuojamą organinių tirpiklių pagrindu pagaminto grunto pakeitimą į vandens pagrindu pagamintą gruntą. Tyrimas parodė, kad pakeitimas bus naudingas visose nagrinėtose poveikio aplinkai kategorijose. Straipsnyje taip pat analizuojami duomenų pakankamumo ir kokybės klausimai, susiję su BCV taikymu cheminių medžiagų pakeitimo vertinimui.