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Environmental assessment of cleaning systems in connection with heat treatment

Master's thesis in the Industrial Ecology programme

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ABSTRACT

The cleaning processes before and after the heat treatment of steel are crucial of the quality of the final product. For the cleaning different systems based on alkaline detergents or solvents can be used. To analyse the environmental performance of those systems a process life cycle assessment was conducted with the aim to identify the cleaning system with the lowest environmental load. Furthermore it was of interest what kind of environmental impacts are caused and how they can be reduced. Therefore the results of the life cycle assessment were used to model possible improvement scenarios. In addition a literature study was conducted, where possible alternative cleaning systems were discussed theoretically.

It was found difficult to identify one cleaning system which has the lowest environmental load as there are different factors, like the utilisation and the cleaning efficiency, which influence the environmental performance of the cleaning systems considerably. However it could be discovered that the electricity consumption was the major cause of the environmental load within all impact categories. Thus measures to decrease the electricity consumption were developed. The final assessment of the improvement scenarios turned out that a new utilisation of the cleaning machines or the use of label certified electricity would be the most favourable solutions to reduce the environmental impacts of the cleaning systems connected with the steel heat treatment.

Key words: heat treatment, cleaning systems, life cycle assessment

Contents

Preface

This study was aiming to access the environmental loads of different cleaning systems in connection with steel heat treatment at one Bodycote International plc. plant in Sweden. The assessment was carried out from January 2014 until May 2014 at Swerea IVF in Mölndal, Sweden.

The study was supported by the supervision of Jutta Hildenbrand from the Environmental Systems Analysis department at Chalmers University of Technology.

For the great support during the study I would like to thank my supervisors Solmaz Sevim from Bodycote, Karin Wilson and Eva Troell from Swerea IVF and Jutta Hildenbrand from Chalmers. Without the strong involvement and commitment of all parties concerned, the study would not have been that meaningful.

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Nora Heling

1 Introduction

Heat treatment is an important processing step in manufacturing of steel parts. The properties of the material will be improved during the process, in regard to hardness, durability and strength. Those alterations in the properties are necessary to improve for example the wear resistance of machine parts or to reduce fatigue failures of load-bearing elements. The process is carried out in furnaces at temperatures above 500°C. However before the work pieces are heat treated and get their final properties the raw steel has to go through shape defining processes. Those processes encompass for instance casting, plastic forming, material removing or joining processes and determine the final design of the work pieces. During the shaping the steel surface is treated with different auxiliary agents like rust protection, cutting fluids or lubricants. If these substances remain on the surface, the thermal treatment might be impaired or partly inhibited. Also during the heat treatment itself, especially in the final quenching step to cool down the parts in a controlled manner, the work pieces are treated with different quenchants and thus are contaminated. Remaining quenching media on the steel's surface could also affect the quality of subsequent varnishing processes. Hence, it is necessary to perform a cleaning before and after the heat treatment (Holm et al., 2012).

As the cleaning processes before and after the heat treatment can considerably influence the quality of the finished work pieces, the main idea of the study was to assess the performance of different cleaning systems, including improvement concepts, in regard to environmental aspects, by using life cycle assessment.

1.1 Background

For removing residues on the steel surface a variety of cleaning methods are established in the market which are based on physical, thermal and chemical forces (Holm et al., 2012). In this study two systems, one based on alkaline detergents and one cleaning system which utilize solvents as cleaning media, were investigated. Both systems are applied at Bodycote and site specific process data was available for investigation.

The type of contamination, for instance grease, oil, or dust, designates the cleaning method in general. But also the type of heat treatment, or more precisely the temperature and atmosphere prevailing in the furnace, has a strong influence on the choice of the cleaning system as the different heat treatment processes have different quality requirements on the cleanness of the steel surface. The different demands emerge mainly due to a variance in the applied heat and process temperature during the treatment (Sevim, 2014).

The environmental burden of the cleaning processes is of great concern as the cleaning machines utilize chemicals, water and energy. This leads to resource consumption as well as emissions and waste.

Environmental commitment is crucial for Bodycote, the company actively works on improving the environmental performance of their processes (Bodycote, 2014), for example by a comprehensive monitoring of the electricity consumption of each machine used for heat treatment processes (Sevim, 2014). Hence, to assess the environmental loads of the different cleaning methods and to find possible alternatives to the existing processes, the study in cooperation with Swerea IVF was conducted.

The results of the study can be used for the decision support towards cleaner production technologies, as it provides insights for choosing suitable cleaning methods or for the optimisation of existing processes.

1.2 Plant description

1.2.1 Bodycote

The Bodycote Värmebehandling AB plant which was part of the study belongs to the parent company Bodycote International plc. In Sweden, Bodycote plc maintains nine plants for the heat treatment of different metals (Bodycote, 2014).

At the studied Bodycote site about 35 employees work fulltime and the production runs approximately 344 days per year in a two shift system, seven days per week (Sevim, 2014).

1.2.2 Plant outline

At the Bodycote plant of study, three heat treatment lines are installed. The different heat treatment processes which are carried out will be explained briefly in chapter 2.1.

In line 1, which was not part of the study, mostly tool steel is treated. In line 2 case hardening, carbonitriding and nitrocarburizing is conducted. The work pieces are cooled down (quenched) in oil after the heat treatment. Therefore a post-washer is installed in this line. In line 3 nitrocarburizing processes are performed. In this line the processed work pieces are quenched in gas, which means that the parts are almost clean when they leave the heat treatment process. Thus no post-washer is necessary in line 3 (Sevim, 2014).

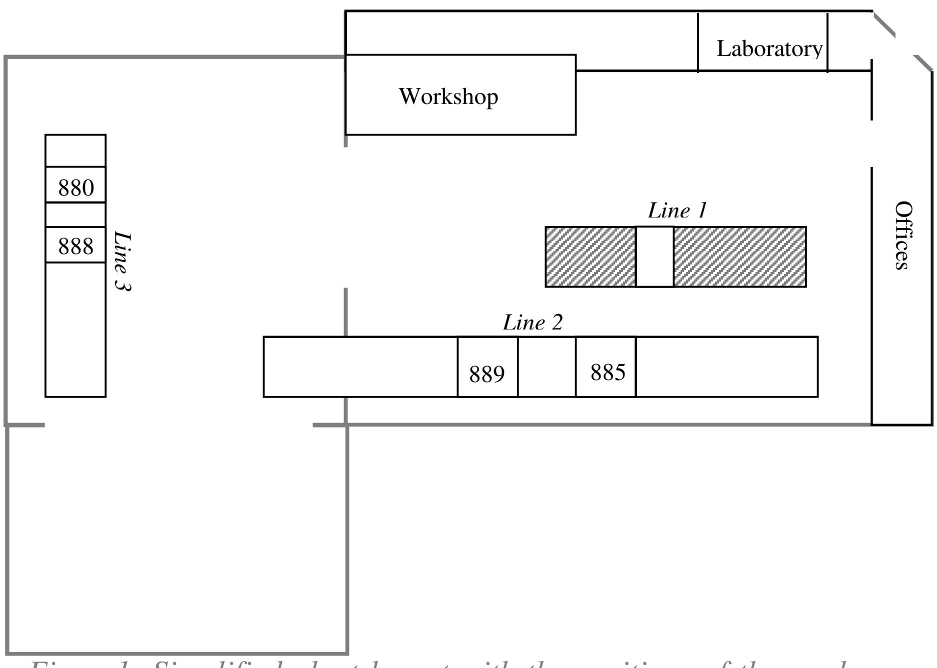

Figure1: Simplified plant layout with the positions of the washers considered in this study. 880 is the solvent cleaning machine. 885, 888 and 889 are alkaline washer. 885 is the only machine which is used for post-wash. Line 1 was not part of the study.

2 Theory and literature study

2.1 Thermo-chemical heat treatment and the role of cleaning processes

During the heat treatment the properties of the steel are modified through controlled heating and cooling (quenching) processes. Heat treatment processes can be divided into two main categories, thermo-chemical and thermal processes (Holm et al., 2012).

Thermo chemical processes are case hardening, carbonitriding and nitriding processes (nitriding and nitrocarburizing). They differ mainly in the applied temperatures and the utilized gases which are necessary to acquire the specific properties respectively different crystalline surface structures (Holm et al., 2012).

This study focused only on thermo-chemical processes which are used at Bodycote and will be further discussed in the following.

2.1.1 Case hardening

The work pieces are treated in a carburizing atmosphere, at temperatures between 850 to 950°C. That means carbon is applied as gas at atmospheric pressure. The atmosphere in the furnace mainly contains nitrogen and hydrogen as carrier gases and carbon monoxide as active gas, which is provided by adding methane or natural gas. During the heat treatment, the ambient carbon diffuses into the steel surface and thereby a carburized layer is formed. In the subsequent quenching the work pieces are cooled down and the crystallite surface structure of the steel changes. The crystalline structure or rather the carbon content on the steel surface determines the final properties of the steel. The main characteristics of case hardened work pieces are the very hard and wear resistant surface and a soft and tough core. Therefore case hardening is mostly applied to highly loaded machine or transmission parts like gear wheels or bearings (Holm et al., 2012).

2.1.2 Carbonitriding

Carbonitriding is based on the same process principles as case hardening but additionally to carbon also nitrogen, provided by establishing an ammonia atmosphere, is diffusing into the steel, during the process which is operated at 850°C. With the nitrogen content the hardenability of the steel increases (Holm et al., 2012).

2.1.3 Nitriding and nitrocarburizing

Nitriding and nitrocarburizing are both nitriding processes, where nitrogen is transferred into the surface of the steel and absorbed. The difference between the two processes is the carbon which is additionally transferred into the steel surface during the nitrocarburizing. The operation temperatures are between 550 to 580°C for nitrocarburizing, and 500 to 550°C for nitriding. Due to the lower temperatures applied there are no structural changes in the core of the steel. The formation of a compound layer on the steels surface and a diffusion zone below define the properties of the processed work piece. The advantages of the nitriding processes are the improved fatigue strength and load bearing capacity with only little distortion of the work piece (Holm et al., 2012).

Table 1: Overview of heat treatment methods applied at Bodycote (Bodycote, 2014).

Type of heat treatment	Process Temp. [°C]	Atmosphere	Properties	Application examples
Case hardening	850-950	Carburizing	• hard surfaces • resistant to wear • softer core	• transmission gears and shafts • wind turbine components • pump components
Carbo-nitriding	850	Carburizing + Ammonia	• hard surface • resistant to wear • improved fatigue strength • Improved hardenability of low alloyed steel	• gears and shafts • pistons • rollers and bearings
Nitriding	500-550	Nitrogen	• high surface hardness • increased fatigue strength • high resistance to: - wear - scuffing - galling - seizure - mainly	• gears • crankshafts • springs extrusion screws • die-cast tooling forging dies
Nitro-carburizing	550 580	Nitrogen + Carbon	• increased fatigue strength • resistant to wear • anti-scuffing minimal distortion	• spindles • cams • dies • hydraulic piston rods

2.1.4 The role of cleaning in heat treatment processes

Cleaning constitutes an important step during the processing of steel. The steel surface can be contaminated with different substances, for example cutting fluids or rust protection, during the processing (Troell, 2013).

Without cleaning prior to the heat treatment, the diffusion of carbon or nitrogen can be disturbed or inhibited by contaminants, and can accordingly lead to passive areas where no compound layer is build up or soft spots are formed (Holm et al., 2012).

After the heat treatment the work pieces are quenched in oil, gas or salt bathes (Holm et al., 2012). Especially for the oil-quenched parts the post-cleaning or degreasing is important for the further processing of the treated parts.

Without degreasing the quenching oil would remain on the steel surface and could cause for example problems with the adhesion of lacquer, if the parts will be varnished afterwards.

2.2 Cleaning systems

There are several cleaning systems established in the market, most commonly based on alkaline detergents or solvents (Troell, 2013). However there are different novel approaches which are already applied in other industry sectors and could be used in the steel processing industry. Some of those processes are not yet applied in the steel industry and thus discussed theoretically in the following only.

When it comes to the choice of a suitable cleaning process, several factors can have an influence on the decision. Costs, residues to be removed and the required degree of cleanness are decisive in the choice of the cleaning system (Lyman, 1961-1976).

Especially in the case of lower process temperatures (500 to 580°C), which are applied for e.g. nitriding and nitrocarburizing, the requirements regarding the cleanness of the steel surface are high. The reason is that residues on the surface would not burn off during the heat treatment. Case hardening, where temperatures up to 950°C are applied, does not have as high prerequisites on the pre-cleaning and the cleanness of the work pieces surface (Holm et al., 2012).

For the post-cleaning, the quenching media is the decisive factor for the choice of the cleaning method. Quenching media are in general quenching oils, different gases, polymer quenchants or salt baths (Holm et al., 2012). A thin layer of the quenchant will be formed on the surface of the processed parts after the quenching step is finished. This film has to be removed in the post-cleaning.

Bodycote

For the production at Bodycote, the choice of the cleaning method often depends not only on the heat treatment process respectively the application temperature, but also on financial decisions (Sevim, 2014). In many cases the customer decides on base of economic aspects which cleaning method is applied to clean the work pieces (Olsson, 2014).

2.2.1 Alkaline washer

The alkaline cleaning system comprises a variety of application techniques. The simplest method is soak cleaning, where the parts are immersed into the cleaning media and soaked for a certain time before they are rinsed with clean water. Another method is spray cleaning, here the cleaning media and the water for rinsing is sprayed via nozzles onto the work pieces. It is also possible to combine both methods. The choice of the design of the cleaning machine depends on the volume to be washed. For example spray cleaning is used for huge work volumes (Lyman, 1961-1976).

In the following only cleaning systems and methods relevant for the study are further discussed.

Bodycote

At Bodycote two different construction types of washers are in use, however the principle of function is the same for both. They are applied for pre- and post-wash equally (Grivander, 2014).

The washer consists of two respectively three tanks which contain the alkaline washing water and one chamber in which the actual washing is carried out. The parts to be cleaned are placed in a basket in which they remain during the whole processing cycle. The basket is placed in the washer's chamber. Then the chamber is flooded with the alkaline washing water from the first tank. After allowing the parts to soak for a short time the water is pumped off, back to the initial tank. Then the same water without any intermediate cleaning or filtration step is sprayed from the top of the washer onto the work pieces and pumped off again. This procedure is repeated with the content of all tanks. However, in the last tank only water and an additive to adjust the pH-value are used to rinse the work pieces, this is done to remove residues of alkaline detergents. Every washing step which includes soaking and spraying takes approximately 10 minutes. The complete washing procedure is finished after circa 35 minutes (Grivander, 2014).

The temperature of the washing bath has to be kept constantly at 70 - 80°C to provide the optimal cleaning conditions and also to avoid time losses and energy peaks while heating up the bath repeatedly (Sevim, 2014). Due to a constant warm environment in the chamber the work pieces dry in there after the washing (Olsson, 2014).

The oil separation takes place when the washing machine is idle, as high water levels and static conditions in the tanks are necessary for the separation process. The oil in the washing water has a lower specific density than water and rises to the surface where it is skimmed and pumped off. In addition, the washing water goes after the skimming through filters to reduce remaining oil and soil as much as possible before the next washing cycle starts. The separated oil from the pre- and post-wash, including soil and little amounts of washing water, is stored in a basement tank until it is transported to the waste disposal plant (Olsson, 2014).

The washing water has to be changed about four times per year respectively after approximately 500 washes. That means that the water is let off to containers and dispatched for treatment by an external company (Olsson, 2014).

Table 2: Alkaline washer and their function at Bodycote (Grivander, 2014).

Washer	Tanks	Cleaning intervals/ washer/ year	Function
888	2	3	Pre-wash
889	3	4	Pre-wash (If 885 breaks down also post-wash)
885	3	4	Post-wash

2.2.1.1 Ingredients of washing solution

Regular tap water constitutes the major part of the washing solution. It serves as a carrier and distributor for the detergent. In addition, the water is responsible for the heat transfer and lowers the viscosity of the contaminants and also flushes them away (Lyman, 1961-1976).

To improve the cleaning properties alkaline compounds are added. Those compounds are mainly builders and surfactants. Several builders can be used simultaneously. They provide the alkalinity and desired cleaning properties. Sodium compounds (carbonates, phosphates, silicates and hydroxides) are in general used in the bulk solutions. Surfactants are surface-active agents like soaps or synthetic detergents, which are used to lower the surface and interface tension to increase the cleaning properties (Lyman, 1961-1976).

2.2.1.2 Water hardness

Dissolved salts determine the hardness of water. The combination of salts, heat and alkalinity in water can lead to the formation of insoluble lime scale. This is particularly critical if the scale builds up in spray nozzles or aggregates on the surface of the heating coils in the tanks of the washer. Apart from the lower cleaning efficiency and the higher energy consumption as a result of the scale formation, the washing solution can be carried over to the rinse tank due to overspill caused by blocked nozzles or pipes. Moreover, scale could also build up on the work pieces because of the contamination of the rinsing water. Furthermore, corrosion can be accelerated by hard water (Ferguson, et al., 2011).

Bodycote

The use of deionised respectively softened water produced for example with ion exchangers could prolong the lifetime of the baths and also improve the cleaning properties as no chemical reaction can occur due to the absence of salts in the water (Kunz, 2012).

In the case of Bodycote the improvement potential of using softened water could be limited due to the low hardness of the tap water in Gothenburg. The tap water hardness was reported to be about 3 degrees dH (24 mg/L Ca) (Göteborg, 2014), which corresponds with low hardness. This could lower the expected effects of using softened water in the alkaline washers.

2.2.1.3 Maintenance of the cleaning bath

The lifetime of the alkaline cleaning systems can be influenced by many parameters. For instance, a higher concentration of contaminants in the wash water leads to lower cleaning properties. As explained above, also the water hardness plays an important role for the durability of the cleaning bath and the cleaning result. If too many dissolved minerals are contained in the cleaning solution, barrier layers or lime scale can build up on the work piece’s surface (Kunz, 2012).

Another important aspect to consider for the lifetime of the bath is the refilling of the washing water, which is lost during the washing process due to evaporation or draw outs. The refilling of water dilutes the active ingredients, and thus the cleaning properties are impaired and the lifetime is shortened (Lyman, 1961-1976).

For maintaining good cleaning properties and prolonging the lifetime of the cleaning bath, the addition of detergents is necessary on a regular basis. Therefore the composition of the bath has to be controlled periodically. The tests should include the measurement of the pH value and the conductivity of the bath to determine the alkalinity of the bath. How much of the compound has to be added can be investigated by titration with a standardised solution where the active alkalinity is measured. The frequency of replacing the bath depends on the soil contamination level and experiences gained from measuring the active alkalinity but also often on costs. The cleaning intervals can vary between one week and several weeks (Lyman, 1961-1976).

2.2.1.4 Cold alkaline cleaners

The major features of cold cleaners compared to conventional alkaline cleaning systems are:

1. No heating of the washing water is necessary
2. Based on different chemicals than conventional alkaline detergents

Silicates and phosphates are traditionally the active ingredients in the cleaning solution. They are responsible for the cleaning properties. For the cold washing system special purpose chemicals are added. These encompass borax, sodium tetra-borate and sodium nitrite for rust protection. Also the pH-value is 8,5-9,5, which is below the common system with 11-12,5 (Lyman, 1961-1976).

Table 3: Advantages and disadvantages of alkaline cold cleaning (Lyman, 1961-1976).

Pro	Contra
No heating required – saves energy	The production process of the detergent is more time consuming and difficult
	Slow drying after cleaning – depending on subsequent process, additional drying might be necessary
Requires less maintenance than conventional systems	Higher costs for cold cleaner
	Limitation to certain residues to remove

Bodycote

According to previously conducted studies at a Bodycote site in Denmark with similar operation processes the cold wash was successfully implemented. The energy savings were not measured, but the temperature in the washer could be reduced from 60 to 45°C. Also the lifetime of the cleaning bath could be prolonged considerably and thus the waste water production was reduced by 69%. In other case studies, carried out by the detergent supplier, energy savings for similar washing processes of approximately 30 to 40% could be achieved (DST-Kemi, 2014).

This promises also for the studied Bodycote site a good implementation potential. The total water consumption could be possibly reduced as well as the electricity consumption. However a higher demand on detergents is also likely according to the experiences from the site in Denmark (Sevim, 2014).

2.2.2 Solvent vapour degreasing

Solvents, mostly alcohols, are used as cleaning media in vapour degreasers. The solvents used today have the same cleaning properties as the previously used chlorinated hydrocarbons, but have less harmful properties, for example they do not contribute to stratospheric ozone depletion. The advantage of organic solvents is the high cleaning efficiency in regard to organic soil like oil, grease or waxes (Hubbard-hall, 2014).

For the technical implementation of the vapour degreasing there are different methods available. The most basic one is the exposure of the contaminated work pieces to a solvent vapour in a cleaning chamber. The hot vapour condenses on the steel's surface and dissolves the soil. The condensate trickles down the surface and takes away all contaminants. Depending on the degree of contamination, the vapour phase can be combined with spray or immersion cleaning. The final step is always a rinsing with pure solvent vapour which leads to clean and dry work pieces (Cormier, 1994).

For the efficiency of the process the chemical stability, or the purity of the solvent respectively, is decisive. The boiling point for example will rise if the solvent is highly contaminated with oil, which leads to less vaporisation and thus a lower cleaning efficiency (Cormier, 1994).

Bodycote

The solvent degreaser at Bodycote works with low pressure near vacuum, at 100mbar. This comes with several advantages. It enables the safe use of solvents with only minimal system losses. Due to the low pressure the boiling point of the solvents drops and the evaporation is accelerated and the cleaning can be performed at lower temperatures. Another advantage of operating under low pressure is the absence of a flash point at pressures below the minimum ignition pressure which is approximately between 25-100mbar, this also allows to operate on temperatures higher than the flash point, which improves the cleaning properties (Pawel and Brandes, 1998).

Manner of functioning:

The cleaning media in the vapour degreaser is stored in a 3000l tank from which it is further transported to the different functional parts in the machine.

In the first step the solvent is pumped into the washing chamber where the work pieces soak in it. Then it is pumped off, back to the storage tank, from which it goes to the vaporizer. The produced solvent vapour goes then again to the washing chamber, where it condenses on the steels surface and trickles with the remaining dirt down the surface. For the drying, the pressure is lowered from 100 to 1mbar so that the remaining solvent evaporates faster due to the lower boiling point of the solvent. Thus, no additional heating is necessary for drying the parts.

The condensate-soil mix is then pumped back to the storage tank, from which it is transported to the distillation unit for the oil separation. The whole cleaning process does not utilize any water or other detergents for the cleaning itself. However, for the cooling system water is needed.

The system has only few losses, around 300l solvent need to be refilled per year, owing to the internal distillation unit, which recycles the solvent continuously. The refill is part of the annual maintenance service. However, due to the continuous conditioning to purify the solvent, even when the machine is idle, huge amounts of electricity are necessary to run the process. (Kehr, 2014) In regard to optimisation possibilities the solvent washer is limited and could be considered as a black box. The only obvious possibility to improve the environmental performance of the washer could be the use of heat from the furnaces via heat exchange to warm up the solvent.

2.2.2.1 Choice of solvents

The choice of the right solvent for the vapour degreasing depends on different properties, the solvent has to provide:

- Non-flammability and non-explosiveness
- High solvency for oil, grease, and other contaminants
- Low evaporation temperature
- Boiling point (high enough to produce vapour but also low enough to enable oil separation via distillation)
- Low toxicity
- Vapour density
- Chemical stability
- Non-corrosiveness

(Cormier, 1994)

The most common solvents for the vapour degreasing are chlorinated hydrocarbons and hydrocarbons. The use of chlorinated hydrocarbons is only allowed in closed systems in strict accordance to the emission limit values, due to the risk of environmental pollution. Hydrocarbons including alcohols, esters and ketones are also in use. Here explosion safety regulations have to be kept in mind because of the low flammability (Habenicht, 2008).

2.2.2.2 Environmental and health hazards

In some cases there are still toxic chlorinated hydrocarbons in use. They constitute hazards to health and can cause for example fatigue, nausea, coughing if they are inhaled, and can ultimately be lethal (Cormier, 1994).

In modern vapour degreaser alcohols replace the traditionally used solvents (Kehr, 2014).

2.2.3 Ultrasonic cleaning

Ultrasonic cleaning systems are powerful enough to remove tough dirt, oil or grease from the steel surface without eroding it. They are based on the transformation of electrical energy into ultrasonic vibrations and operate at frequencies between 20 - 80kHz. Ultrasonic cleaning is often applied for small work pieces like printed circuit boards where conventional cleaning methods do not reach the requested cleanness (Cormier, 1994).

Ultrasonic cleaning can be combined with both systems applied at Bodycote, alkaline and solvent. However, as a standalone method it is not applicable for degreasing, as a thin film of oil remains on the steel surface. There is also the risk of the agglomeration of soil, at the lower part of the washer, which will not be washed out from the chamber. This leads to a blocking of the washer and its dysfunction in the worst case (Kehr, 2014).

For solvent immersion applications ultrasonic cleaning became more popular due to environmental restriction in the use of chlorinated hydrocarbons over the last years. Complex surface structures can be cleaned with the same efficiency as with vapor degreasing systems (Cormier, 1994).

Bodycote

An ultrasonic cleaning unit could theoretically be installed, however the cleaning properties of the conventional alkaline and the solvent system in regard to oil removal would probably not be considerably improved.

2.2.4 Ultrapure water

There are no references available that ultrapure water is already used in practice for cleaning processes in connection with steel heat treatment. However it is widely used in the pharmaceutical industry and in the semiconductor production due to high quality requirements (Lenntech, 1998 - 2009).

According to the definition ultrapure water contains only H_2O, H^+ and OH^- ions in equilibrium. The production steps include deionisation of tap or groundwater followed by reverse osmosis or ion exchange. The final conductivity will be approximately 0,054µS/cm at 25°C. The conductivity is a measurement for its impurity. The lower the conductivity of the water, the purer it is (Lenntech, 1998 - 2009).

The principle behind the cleaning properties of ultrapure water is the unsaturated state of it. The soil is better dissolved in unsaturated liquids. Thus, purer water has better cleaning properties. No additional cleaning agents or surfactants need to be added to the water (Ohmi, 1993).

However, demineralised water is highly aggressive. The unsaturated state of the water would lead to leaching of metals and other material from pipes and other plumbing materials in the washer (Lenntech, 1998 - 2009). Therefore special pipes would be necessary, also the accelerated corrosion of the work pieces could be an important aspect to consider when using ultrapure water for the cleaning of steel parts.

Bodycote

In general it would be possible to use ultrapure water in the alkaline washer, however it would be necessary to assess if the washing equipment is resistant to the aggressive water. Also additional equipment to produce the ultrapure water would have to be installed.

2.2.5 Cryoclean snow

Cryoclean snow was developed by Linde AG and represents a cleaning method which does not utilize solvents or water based detergents. It is based on dry-ice blasting, where ice crystals or pellets, which have the size of rice grains, are produced from frozen carbon dioxide in a snow chamber. The ice crystals can be produced on demand, thus no long preparation time or tempering of the cleaning media has to be performed ahead. The dry-ice pellets are shot onto the surface to be cleaned. They are transported and accelerated via compressed air through nozzles. Due to the low application temperature of -78°C the ice crystals cool down the surface and cause the residues to freeze and become brittle. The high velocity causes the pellets to vaporise (sublimation) on the steel surface, which removes the residues by small explosions and leaves a clean surface behind (Linde, 2005).

The advantages of the system are that no corrosive or aggressive solvents and detergents are used, which reduces stress on the steel surface due to the gentle cleaning process. Because of the pellet production on demand the energy consumption can be reduced, and this lowers also the operational costs (GlobalSpec Electronics, 2014).

Bodycote

The system does not seem to be applicable for the case of Bodycote and the mass production, as the parts are stacked in a box for the heat treatment and would not be sufficient cleaned. The nozzles are not able to reach all spaces, especially if the parts have a complex shape. This applies both for a stationary application unit or a manual control of the nozzle. The nozzles can only reach certain areas as the parts are packed tight in the box.

The cleaning process might be feasible for bigger sized individual parts, but then additional personnel would be needed for the manual control of the nozzle.

2.3 Comparison of alternative cleaning methods

In Table 5 the advantages and disadvantages of the alternative cleaning systems as well as the feasibility of implementation were summed up for a better overview. The evaluation was based on literature findings.

It becomes clear that only the change from the conventional alkaline system to the cold washing and the use of deionised water, both for cold and conventional alkaline washing, seems to be applicable and realistic in the foreseeable future.

Thus in the following life cycle assessment both possibilities were considered in the modelling to improve the environmental performance of the cleaning systems.

Table 5: Comparison of all above discussed cleaning systems and methods in regard to their advantages and disadvantages.

Cleaning method:	Water consumption:	Electricity consumption:	Cleaning properties:	Utilization of cleaning agent	Applicable:
Cyroclean snow	-	R	+++	No	No
Ultrasonic	S	S/ I	+	Yes/ No	Yes
Cold wash	R	R	++	Yes	Yes
Ultrapure water	?	?	+++	No	Yes
Deionised water	R	S	++	Yes	Yes

+++ very good, ++ good, + medium, R reduced, I increased, S same

3 Life Cycle Assessment (LCA)

Life cycle assessment is used as a tool to evaluate the environmental effects of products or services during their entire life cycle. This includes all phases, from the raw material extraction, processing, transportation, manufacturing and use phase to the final disposal (Baumann and Tillman, 2004).

Comparisons between different products as well as the evaluation of different stages of the life cycle are common practice. The results can be used for instance for the decision support or for the product improvement towards more environment friendly solutions (Baumann and Tillman, 2004).

The general life cycle assessment procedure, which is described in the international standards ISO 14040 and 14044, can be seen in figure 2.

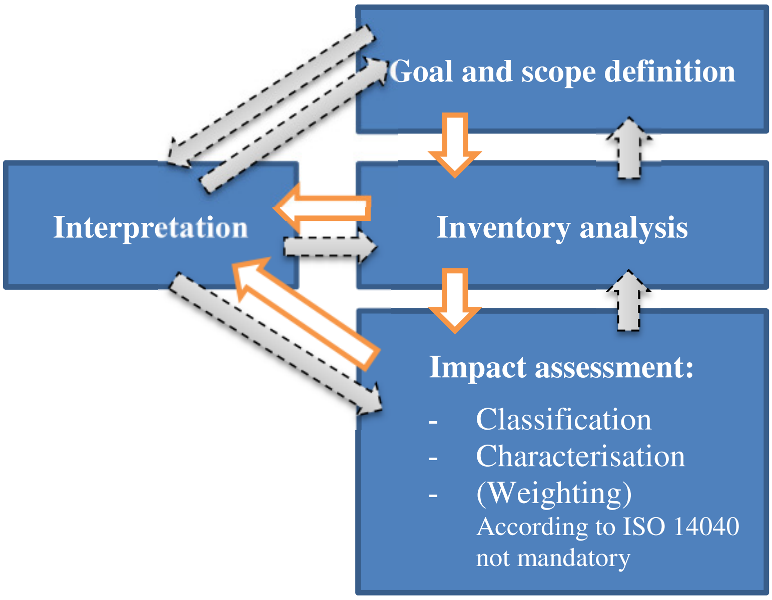

Figure 2: General life cycle assessment steps, the yellow arrows indicate the order in which each step has to be performed whereas the grey arrows show possible repetitions (Baumann and Tillman, 2004).

During the goal definition the intended purpose, the reason for carrying out the study and the audience to whom it is addressed need to be clearly defined and stated (ISO 14040, 2006).
In the scope definition, the modelling of the system is carried out. This comprises the determination of functional unit, system boundaries, impact categories, data quality requirements and the allocation principles (Baumann and Tillman, 2004).

Subsequently, the inventory analysis is performed. Here all life cycle relevant data are collected and documented, this includes for example the use of energy and resources, resulting products and emissions (ISO 14040, 2006). Also the construction of a flow model of the technical system and the calculations of the environmental loads related to the functional unit are accomplished in this phase (Baumann and Tillman, 2004).

The quantified results of the inventory phase are related to potential impacts on the environment, for example to global warming, eutrophication or resource depletion, and illustrate their magnitudes as a result of the impact assessment (ISO 14040, 2006).

For a better understanding of the result obtained in the previous steps the interpretation is conducted. Here the process components with the most significant environmental impact are identified (ISO 14040, 2006).

The aim of this study was to assess the environmental effects of the cleaning processes, including up- and down-stream processes, connected with steel heat treatment. This is a deviation from a product related LCA, which targets products. Adaptations were necessary, for example regarding the definition of the functional unit. The assessment was conducted with the SimaPro 8 software in compliance with the ISO 14040 series. Generic process data were included from the ecoinvent v3 database and complemented with specific data for the processes at Bodycote. The modelling of the three cleaning processes, the calculations for the inventory phase, the classification and the impact assessment were conducted with SimaPro 8.

3.1 Goal definition

Depending on the chosen system the steel cleaning process either utilizes large amounts of water in combination with alkaline detergents or solvents. But not only the consumption of consumables is high, also the fuel consumption is a critical point in the cleaning process as the machinery has to be kept at the operating temperature of 70°C continuously, even if it is idle, for the conditioning of the cleaning media to maintain good cleaning properties. Also the resulting wastes and by-products of the cleaning systems contribute to their environmental load.

To evaluate the environmental loads of different cleaning methods, the study was aiming to assess two different cleaning systems which are used in connection with the heat treatment of steel at Bodycote. One cleaning system was water based and the other system was solvent based. Additionally the assessment included changes in the cleaning systems to improve their environmental performance. Thus the study was focused on the examination of the cleaning process development and the evaluation of it from an environmental point of view.

With the examination of critical parameters in the cleaning processes, it was possible to find solutions which might reduce the environmental impacts of the existing processes along the process life cycle, including upstream and downstream processes. The results of the assessment will support decision makers in the choice of suitable cleaning systems in respect to their environmental impact or to improve their existing system towards cleaner production processes.

The study was mostly addressed to Swerea IVF, who commissioned the study and Bodycote, respectively the metal producing and processing industry.

In the assessment of the two cleaning systems, the central questions were:

- Which cleaning system has the lowest environmental load?
- What kind of environmental impacts will be caused during the cleaning process?
- How can the environmental load from the different cleaning systems be reduced?

The life cycle assessment was carried out with the cleaning processes before and after the heat treatment as a foreground. The foreground system included also all process chemicals, however without their production. The heat treatment itself was regarded as a black box, as only two production lines were considered, both using the same oil as quenching media. It was also assumed that the cleanness was as high as possible, and therefore no distinctions between the cleanness requirements for the different furnaces have to be made.

3.2 Scope

3.2.1 Process flow diagram

The major stages of the life cycle of the steel processing process are as following: material processing, cleaning, rust protection, packaging, waiting time, transport, waiting time, cleaning, heat treatment, cleaning, waiting time, further processing (e.g. coating). It is necessary to perform the cleaning before and after the heat treatment (Holm et al., 2012).

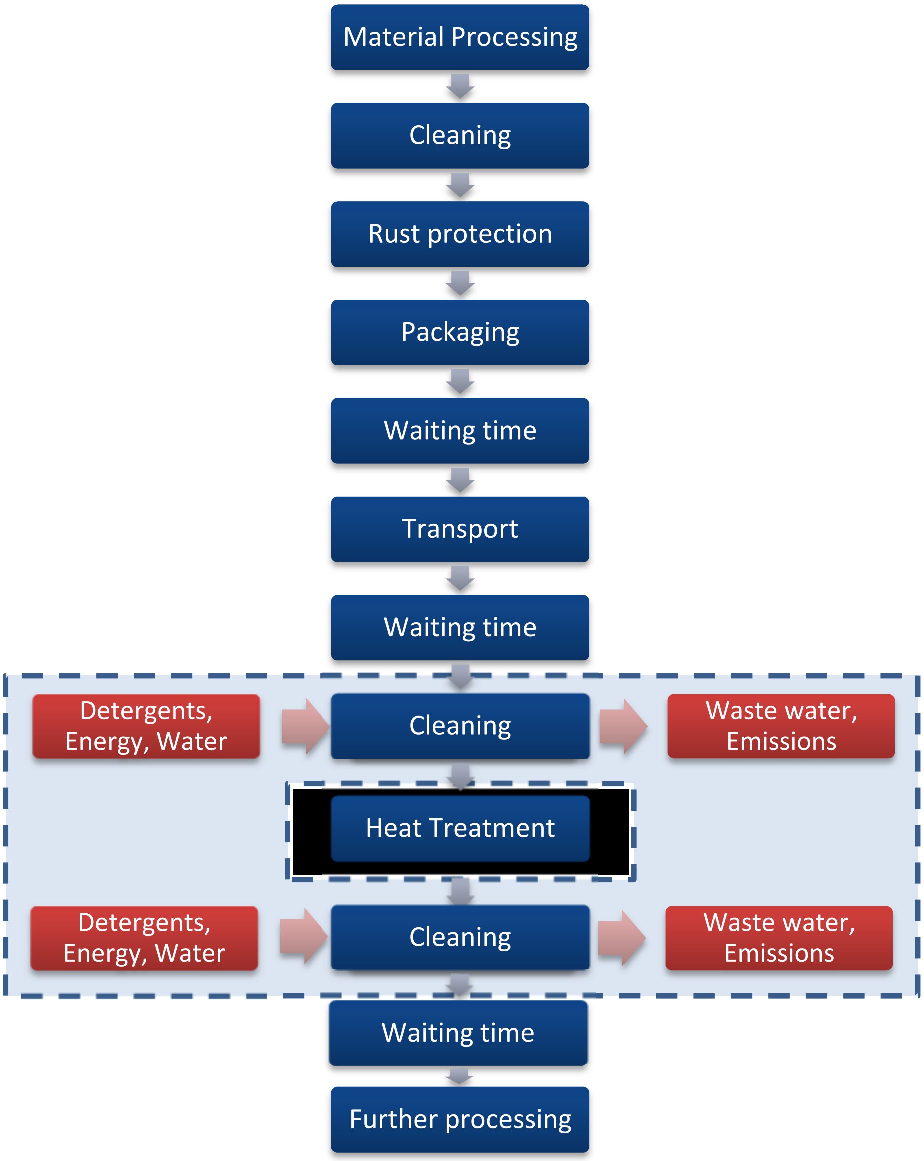

Figure 3: Steel processing flow including cleaning processes (Holm et al., 2012).

For the study only the different cleaning processes were examined, the heat treatment was not varied for the assessment. Generic requirements for the cleaning demands were assumed although the different atmospheres which are established in the furnaces to provide different steel properties also mean that there are different requirements for the cleanness.

3.2.2 Functional unit

To make the results of the different cleaning processes comparable and easy to communicate a functional unit has to be defined, this needs to be done in quantitative terms (Baumann and Tillman, 2004).

In this process life cycle assessment the most appropriate unit would have been the surface area of the work pieces, since hardening the surface is the purpose of the treatment. Like in other instances, the surface is not known and due to geometry also difficult to determine. The accounting between Bodycote and customers is based mostly on the weight of the treated parts, which can be used as a proxy unit. However, due to the high variance in the size and volume of the parts to be processed, it is also difficult to select a ‘typical part’, according to the weight or size, as a functional unit. Thus, different functional units for the comparison of the pre washer were chosen:

- *1 batch*: The cleaning of one batch, which is expressed by the weight of the processed parts.
- *1 kg oil*: The oil which was washed off from the work pieces. This is the common function of the cleaning. According to the current state of the art it was assumed that the parts need to be as clean as possible. Currently it is not known how clean the parts actually have to be for the heat treatment, thus further studies on the cleanness demands need to be carried out.

The post-wash was not considered in the life cycle assessment due to the lack of comparison possibilities. Only one machine carries out the post-wash in the two lines which were part of the study.

3.2.3 Impact assessment (LCIA)

The impact assessment aims to evaluate the potential environmental impacts of the quantified environmental loads gathered in the inventory phase. It addresses the impacts on the three major categories, human health, ecosystem and resources (endpoint categories). For the identification of cause-effect relationships, different subcategories can be introduced to show lower-order effects (Baumann and Tillman, 2004).

3.2.3.1 Choice of impact categories

Based on to the high fuel and water consumption and also the utilization of chemicals the following midpoint impact categories were chosen: climate change, freshwater eutrophication, human toxicity, freshwater and marine eco-toxicity, natural land transformation, resource (metal) depletion.

3.2.3.2 Method for the impact assessment - ReCiPe

For the interpretation of the inventory results, readily made interpretation methods are provided within the SimaPro 8 software.

The ReCiPe method was developed in the Netherlands by RIVM (Rijksinstituut voor Volksgezondheid en Milieu), CML (Centrum Milieukunde Leiden), PRé Consultants, and Radboud Universiteit Nijmegen. A special feature of the ReCiPe methods is the possibility of combining a mid-point and end-point approach (ReCiPe, 2012).

In the end-point method the results of the inventory are related only to the three end-point indicators. This aggregation makes the interpretation of the results easier as they are for non-specialist more understandable than various complex midpoint results, which might come with trade-offs. Thus a fast interpretation of the LCIA results is possible. However, the simplification bears the risk of high uncertainties due to modelling and assumptions which need to be done for the calculations (ReCiPe, 2012).

The mid-point approach offers 18 different subcategories. This allows a more detailed analysis of the environmental impacts of different products or processes and thereby reduces uncertainties. The disadvantages of having various subcategories are potential difficulties in the interpretation (ReCiPe, 2012).

Combining both methods enables the user to choose between different result levels. They are either connected to uncertainties in the end-point indicators or uncertainties in the correct interpretation of the mid-point indicators (ReCiPe, 2012).

To reduce uncertainties and to analyse each chosen impact category as precise as possible, the midpoint method, Europe ReCiPe Mid-point method H, version 1.09, was used.

This method refers to European normalisation values. The H in the methods stands for 'Hierarchist'. That means that the method is based on the most common policy principles using a medium time frame (100 years) for global warming, GWP100 (ReCiPe, 2012).

3.2.4 Type of LCA

The investigation aimed to assess the environmental load of different cleaning processes and possible changes to improve the environmental performance of the cleaning systems. Therefore a change oriented LCA was chosen.

3.2.5 System boundaries

Only the washing processes and their upstream and downstream processes were considered in this study. The heat treatment itself was treated as black box.

The upstream processes included the production of the detergents and solvents used in the cleaning process, as well as the electricity production. The transportation of the chemicals was not included in the inventory as not for all chemicals the production sites were known, and also because the purchased amounts were relatively small. The treatment of the resulting wastes and wastewater contributed to the downstream processes.

3.2.6 Data quality requirements

3.2.6.1 Data types and sources

The data for the foreground system were as far as possible site specific, collected on the site of Bodycote or requested from suppliers and contractors. However it was not always possible to collect primary data, especially for the upstream and downstream processes, as for example the detergent suppliers did not disclose the precise chemical composition of their products due to corporate secrecy. If primary data were not available or for the background system, average data from other conducted LCA studies, LCA databases (ecoinvent v3 and Swerea IVF database), scientific articles or interviews were used as information source.

3.2.6.2 Geographical boundaries

As Bodycote is situated in Sweden and the heat treatment process as well as most of the upstream and downstream processes are conducted in Sweden, the geographical boundaries for those processes were defined as local or regional. However for some processes, the boundaries needed to be expanded to Europe and to global, due to a lack of records in the databases. This concerned mostly the process chemicals.

3.2.6.3 Time horizon

For the future decision support the collected data should be as recent as possible. Therefore data which were not older than 5 years were collected. However, present data were preferably used for identifying the environmental hot-spots to make the results of the study as accurate as possible.

3.2.6.4 Allocation

For not directly assignable inventory flows, in particular for the water and detergent consumption, the allocation was done on base of physical relationships. The material flows of the shop floor, the tank volumes of the different washers including the cleaning intervals for the tanks as well as the detergent concentration in the single tanks were known. Also the operation times, energy consumption, and number of batches were documented in the production statistics. With the given information the inventory for each machine could be allocated.

3.2.7 Assumptions and limitations

Since not all production sites of the consumables were known it was assumed they were located in Europe. This was also applied for transportation distances. As the purchase of consumables during the observed time interval was relatively low, it was assumed that the transportation would not have a big effect on the final result.

Since the exact weight of each part respectively each batch was not measurable or documented, the weight of one batch was assumed to be 500kg.

Also the share of cooling water used in the solvent washer was assumed to be 10% of the total.

The study was limited to the production site of the studied Bodycote site, Sweden. All site specific data were collected there and thus were the only reference in this study. Other sites might operate under different conditions and thus the results may differ.

3.3 Life cycle inventory analysis

The major aims of the inventory analysis phase are to construct a simplified flow model of the technical system, to collect data for the relevant processes and to calculate their environmental load in accordance with the system boundaries and the functional unit, predefined in the goal and scope definition (Baumann and Tillman, 2004).

For the study all data were collected for the total annual production of the year 2013, and then related to the functional units. The numerical data were compared as far as possible with data from the purchase department, respectively with the disposal certificate, to check the correctness of the calculations.

3.3.1 Flowchart

To show the environmentally relevant processes (Baumann and Tillman, 2004) the washing processes of all three washers were subdivided into:

- Process chemicals
- Cleaning process
- Waste disposal

Only the cleaning process is performed at Bodycote. All other processes, upstream and downstream, are conducted by contractors and suppliers. The chemicals were produced in Europe, however not all locations were possible to spot and also the packaging producers and their location were unknown. The waste treatment was carried out by local operators. Therefore, the transportation for the extremely small amounts of chemicals and waste, per functional units, was not considered due to lack of data or the short distances.

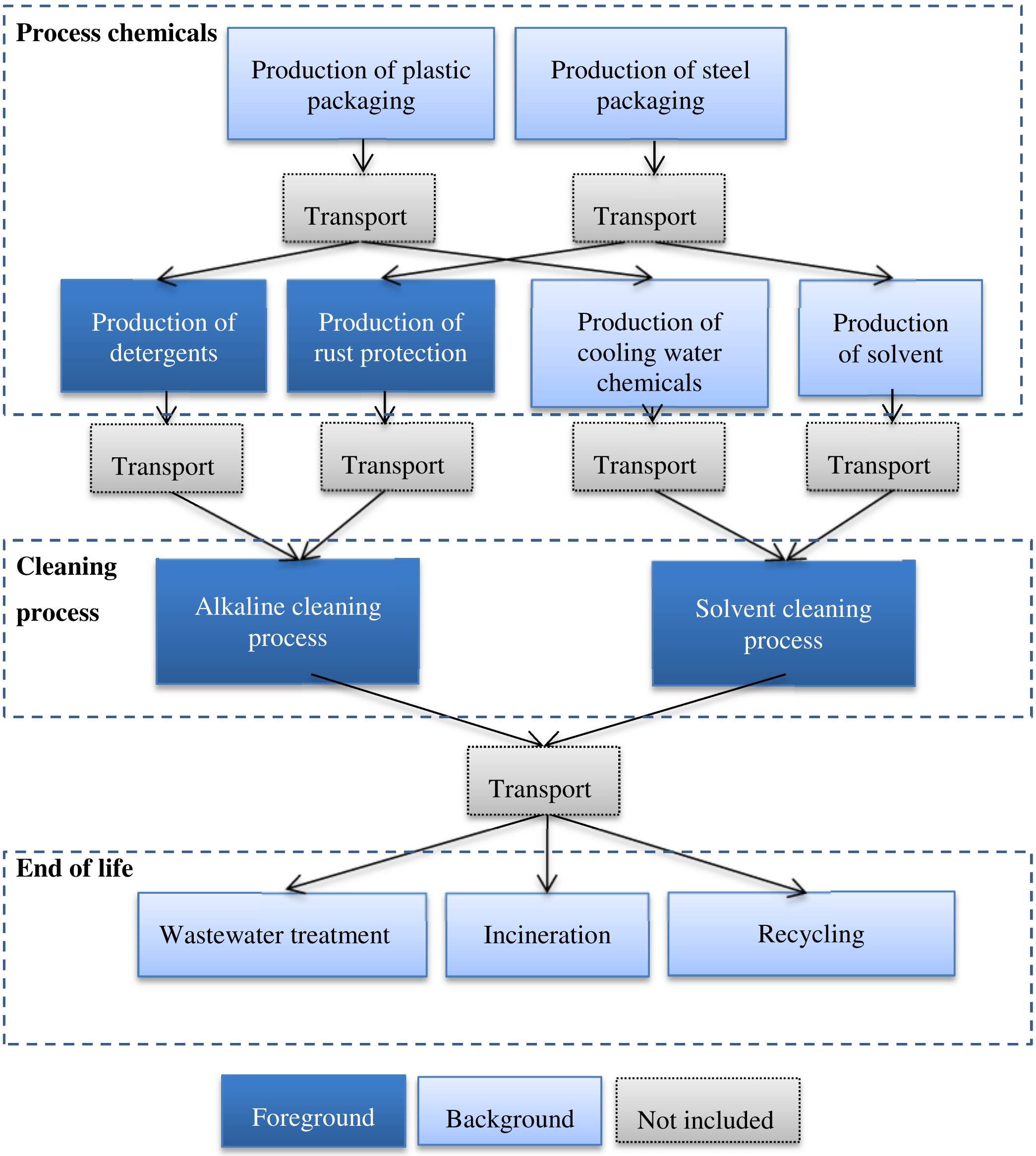

Figure 4: Flowchart of the cleaning processes at Bodycote. The flow for the alkaline cleaning process can be applied to the machines 888 and 889. The flow of the solvent cleaning represents the 880 washer.

3.3.2 Data collection and calculations

To facilitate the data collection and to get a better overview of the different flows, input-output charts for each machine type were generated. Those charts also served as a measure to compare and control incoming and outgoing flows according to the mass.

As the functional principle of the alkaline cleaning machines was similar, only one chart for both machines was used to show the flows of the alkaline cleaning system.

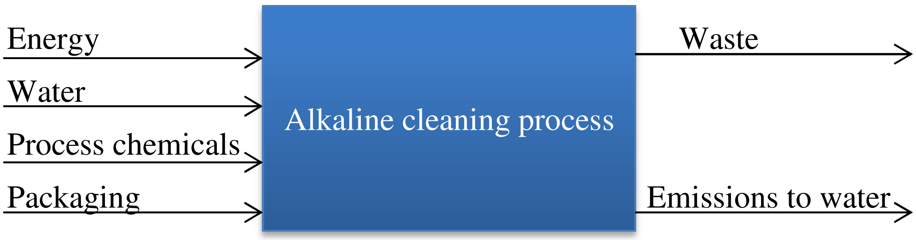

Figure 5: Simplified input-output chart for the numerical data collection for the alkaline washer (888 and 889).

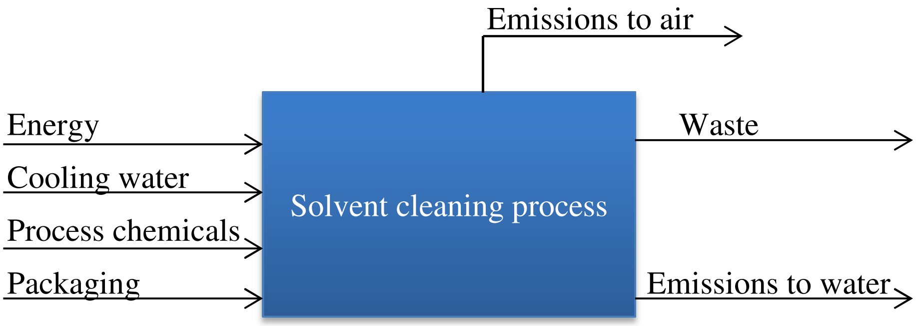

Figure 6: Simplified input-output chart for the numerical data collection for the solvent washer (880).

For further calculations it was necessary to calculate the functional unit. As already mentioned above, two functional units were chosen:

- *1 batch:* Environmental load for cleaning one batch
- *1kg oil:* Environmental load for removing 1kg of oil

Necessary information for the calculations was obtained by interviewing the production manager and by using production statistics from the year 2013. Hence it was possible to figure out the exact number of batches washed in each machine and the approximate amount of oil which was separated per machine.

To double check the amount of oil which was washed off, information from the purchase department were gathered. The results were also compared with the disposal certificate as the separated oil was collected and stored in a basement tank until disposal.

Table 6: Results of the calculations for the second functional unit (batches needed to remove 1kg oil from the work pieces).

Washer	Oil removed/ year [kg]	Batches/ year	Oil removed/ batch [kg]	**Batches to remove 1kg oil**
889	295,84	3801	0,078	**12,848**
888	29,58	1994	0,015	**67,401**
880	443,76	3915	0,113	**8,822**

3.3.2.1 Process chemicals

The allocation for the total amount of washing water and process chemicals was done according to physical relationships. That means that the tank volumes and the concentration of the process chemicals in each tank were known as well as the cleaning interval for each alkaline washer. With this on-site information it was possible to calculate the water and process chemical consumption for each alkaline washing machine.

To validate the calculations, the results were compared with information from the disposal certificate and the purchase numbers from 2013.

Data for the composition of the chemicals were either obtained directly from the chemical suppliers or from the respective material safety data sheets. Here it was difficult to get detailed information as the suppliers referred to confidentiality issues. Also the information from the safety data sheets might be incomplete or vague as only dangerous substances have to be listed and usually only approximate amounts are given. Thus average values were determined and used for the calculations.

In some cases the composition of the detergents and rust protection additives were modified as some of the components were not listed in the ecoinvent database v3. In those cases, chemicals with a similar chemical composition and properties were selected (see appendix A).

Information about the size and the material of the packaging for the process chemicals was collected at Bodycote via interviews and on-site visits. From generic technical data sheets, the weight of the packaging material was derived. As the content of each container was known and the consumption of chemicals was calculated, the amount of packaging material per washer and functional unit could be derived. The input-output tables 7, 8 and 9 show the inventory results per functional unit.

Water in the solvent washing machine 880 is not directly used for the cleaning itself, but it is utilized as cooling water for the internal distillation unit, which is responsible for the conditioning of the solvent. According to the production manager about 10% of the total cooling water used in the facility was utilized in the machine 880. Thus the additives for the cooling water were calculated also on base of this assumption.

The functioning of both alkaline cleaning machines was similar, however both machines used different rust protection agents. All other process chemicals were similar in case of the alkaline systems.

Table 7: Input-output table for the process chemicals used in the solvent washer 880, calculated per functional unit.

Washer 880: Material/ Process		1 batch [kg]	1kg oil [kg]
Detergent:			
Solvent	Propylen glycol methyl ether acetate	0,0613	0,541
Cooling water additives :			
Water	Tap water	5,00E-03	4,41E-02
Foam control	Sorbitan stearate	2,55E-07	2,25E-06
Anti-fouling	Sodium orleate	4,73E-05	4,17E-04
Scale and corrosion control	Sodium-methyl-benzotriazolide	7,66E-05	6,76E-04
Packaging for:			
Cooling water additives	HDPE	1,95E-04	1,72E-03
Solvent	Steel	7,05E-03	0,062

Table 8: Input-output table for the process chemicals used in the alkaline washer 888, calculated per functional unit.

Washer: 888 Material/ Process		1 batch [kg]	1kg oil [kg]
Detergent :			
Water	Tap water	0,113	7,646
Active ingredients	Alkanolamine	0,044	2,941
Surfactants	Alkanolamine	0,018	1,176
Rust protection 1, 888:			
Active ingredient	Alkanolamine	0,12	8,112
Packaging for:			
Detergent	HDPE	6,75E-03	0,455
Rust protection	Steel	0,011	0,746

Table 9: Input-output table for the process chemicals used in the alkaline washer 889, calculated per functional unit.

Washer 889: / Material/ Process		1 batch [kg]	1kg oil [kg]
Detergent :			
Water	Tap water	0,207	2,658
Active ingredients	Alkanolamine	0,08	1,022
Surfactants	Alkanolamine	0,032	0,409
Rust protection 2, 889:			
Water		0,0789	1,015
Active ingredient	Methyl-diethanolamine	0,023	0,292
Additive	Sodiumphospate	2,84E-03	0,037
Additive	Alcohols	2,84E-03	0,037
Additive	Polixetonium chlorid	5,68E-04	7,30E-03
Additive	Ethanediamine	2,84E-03	0,037
Packaging for:			
Detergent	HDPE	0,012	0,158
Rust protection	Steel	0,01	0,134

3.3.2.2 Cleaning process

The cleaning process was conducted at Bodycote. The cleaning respectively the equipment which performs the cleaning is fairly energy intensive. Also large amounts of water in case of the alkaline washers were utilized. The water consumption was allocated as mentioned above. Owing to the internal distillation unit in the solvent cleaning machine, the consumption of solvent it relatively low and only 240kg need to be refilled per year.

After consultation with Bodycote, the share of the cooling water for the solvent machine was estimated to be at 10% of the total, as also other machines in the facility utilised the cooling water.

Table 10: Inventory results for the water consumption per machine. 880 did not directly use the water for the cleaning process. It was used for the cooling water system.

Water consumption – Tap water [kg]		
Washer	1 batch	1kg oil
880	1,02	9,01
888	8,88	598,70
889	8,19	105,30

Due to comprehensive production documentations and statistics the exact electricity consumption per machine and the number of batches washed in each machine were documented, thus no allocation was necessary.

Table 11: Electricity consumption of each washing machine, calculated according to the functional units.

Electricity consumption - Swedish electricity mix [kWh]		
Washer	1 batch	1kg oil
880	88,31	779,04
888	61,00	4111,19
889	25,99	333,91

As the electricity consumption was quite high, the Swedish electricity mix taken from the database (ecoinvent v3) was further examined.

The information was taken directly from the ESU-services Ltd. (Energie-, Stoffe- und Umwelt Services), which was as mentioned as source in the database. Accordingly, the Swedish electricity mix is composed as follows.

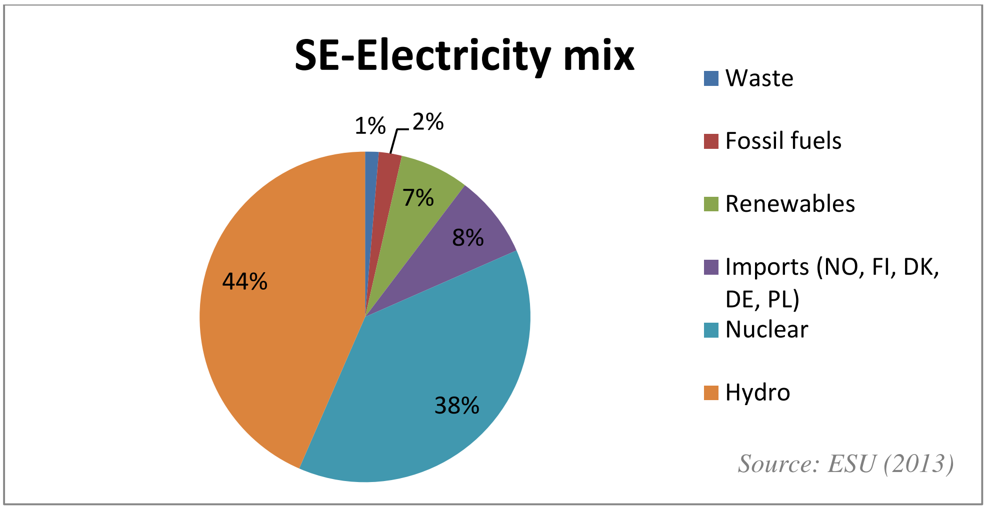

Figure 7: Composition of the Swedish electricity mix (ESU, 2013).

The data were collected in 2008 and were calculated including uncertainty adjustments to be state of the art for 2012 (SimaPro 8, 2013).

A closer look at the composition of the fossil fuels (figure 8) shows that peat has a relatively high share with 16% and that it was classified as fossil fuel (ESU, 2013). This was unexpected in two aspects. On the one hand, the harvesting of peat is in many countries restricted due to environmental concerns. On the other hand, peat has recovery abilities and therefore could be also considered as renewable energy source.

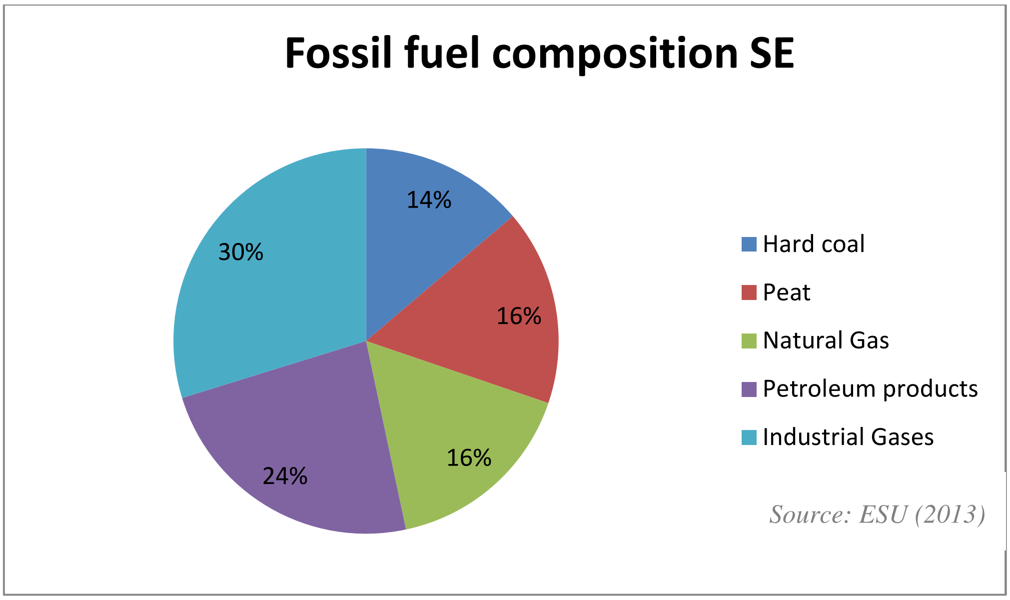

Figure 8: Swedish fossil fuel composition (ESU, 2013).

Historically the classification of peat as a non-renewable energy source was done by the International Panel for Climate Change (IPCC), because large amounts of peat for industrial purposes were harvested faster than the peat could regrow. Due to the fact that peat has recovery abilities, although they are slow, there was a disagreement between environmental organisations and the peat industry in regard to the classification as fossil fuel. In that case, all carbon dioxide emissions which are released during the combustion of peat for the electricity production are fully considered in calculations and the classification, the recovery is disregarded (IPS, 2001).

After extensive studies the IPCC decided in 2006 during the 25th session of IPCC to classify peat as own category, between renewable and non-renewable energy sources (World Energy Council, 2007). A separate consideration of peat in the ecoinvent database v3 could therefore be reasonable. It could be listed under an own category, ‘peat’ as the IPCC suggested.

The major environmental concerns in regard to peat are based on its global warming potential. Peat is an important natural carbon sink. During the extraction of peat the carbon which is usually under water is exposed to air, reacts with oxygen and emits as result carbon dioxide. Also during the combustion of it CO_2 is emitted. Additionally the release of large amounts of methane and nitrous oxides, which are greenhouse gases as well, is connected with the extraction of peat (Wetlands, 2014).

The total contribution of peat in the Swedish energy mix is relatively low with 0.4%. However some of the electricity mixes imported to Sweden are strongly based on fossil fuels (table 12) (ESU, 2013). This does also influence the environmental load of the SE-mix.

Table 12: Imports from the three major supply countries and their fossil fuel share (ESU, 2013).

Country	Share in SE-mix [%]	Fossil fuel share [%]	Peat share [%]
Norway	4,85	0,4	0
Denmark	0,87	50,61	0
Finland	1,96*	27,32	6,66

* Finland imports about 18% of their total electricity mix. For Finland 12% are imported from Russia whose electricity mix is based to 64% on fossil fuels and 2.5% are imported from Estonia. The Estonian electricity mix is based to 85% on fossil fuels where 79% is produced from peat (ESU, 2013).

3.3.2.3 End of life – Disposal

The amounts for the disposal were derived from the calculated input data and compared with the figures from the disposal certificate. How the waste was treated was directly obtained from the waste treatment facilities. Steel packaging was recycled, and the plastic packaging was disposed in the common waste container which went to the municipal waste incineration plant.

The waste water was collected by a local biological waste water treatment plant with physical and biological treatment. As no exact process for the waste water treatment for alkaline washers was documented in ecoinvent v3, a similar process from the database was selected referring to the process description obtained from the waste water treatment plant.

Table 13: Disposal figures for each washing machine, per functional unit.

Material/process	880		888		889	
	1 batch [kg]	1kg oil [kg]	1 batch [kg]	1kg oil [kg]	1 batch [kg]	1kg oil [kg]
Steel packaging to recycling	7,05E-03	0,062	0,011	0,746	0,01	0,134
HDPE packaging to municipal waste incineration	1,95E-04	1,72E-03	6,75E-03	0,455	0,012	0,158
Waste water treatment (physical + biological)	5,12E-03	4,52E-02	9,178	618,57	8,629	110,87
Solvent vapour (emissions to air)	0,0613	0,541	-	-	-	-

The amount of solvent which needs to be refilled per year was assumed to be lost via evaporation during machine stops or remaining solvent on the surface of the work pieces due to incomplete drying. Thereby the solvent is emitted to air and enters the environment thru the stack.

3.4 Life cycle impact assessment

For the impact assessment in SimaPro 8, the 'Hierarchist' ReCiPe midpoint method version 1.09 was applied. As described in section 3.2.3.2, this method allows a more detailed analysis of the impact categories. Thus it was used for the characterisation and normalisation, to analyse in more detail the type and source of the different environmental impacts and to reduce thereby uncertainties.

The classification of the inventory results was done in the SimaPro 8 Software. Here the emissions associated with the inventory result were related to the respective impact categories. This is necessary for the following characterisation calculations (Baumann and Tillman, 2004).

3.4.1 Characterisation results

Characterisation comprises the quantification of environmental impacts per category (Baumann and Tillman, 2004). Thereby the relative importance of each process component within the impact categories is calculated. For the calculations in SimaPro 8 equivalency factors were used, as applied in the ReCiPe method.

To visualise which process components of the respective cleaning system had a significant influence within the chosen impact categories, the washing process was subdivided into single components, only the waste treatment was summarised under the general term waste.

The calculation base for both functional units was the environmental load caused by cleaning one batch. For removing one kg of oil several batches were needed. As the characterisation results are expressed as percentage, in the individual consideration of the washers the graphs for both functional units were similar. Therefore only one graph per cleaning machine was generated. The detailed results of the characterisation can be seen in table 14.

Table 14: Characterisation results per functional unit.

Characterisation results - Basic		880	888	889	880	888	889
Impact category	Unit	1 batch			1kg oil		
Climate change	kg CO2 eq	6,231	4,663	2,25	54,96	314,32	28,927
Freshwater eutrophication	kg P eq	0,004	0,003	0,001	0,035	0,185	0,016
Human toxicity	kg 1,4-DB eq	7,916	5,524	2,44	69,83	372,34	31,436
Freshwater ecotoxicity	kg 1,4-DB eq	0,159	0,115	0,054	1,404	7,735	0,698
Marine ecotoxicity	kg 1,4-DB eq	0,166	0,119	0,056	1,464	8,035	0,72
Ionising radiation	kBq U235 eq	51,891	35,854	15,3	457,7	2416,6	196,57
Natural land transformation	m2	0,002	0,001	0,001	0,017	0,091	0,009
Metal depletion	kg Fe eq	2,051	1,515	0,736	18,09	102,08	9,457

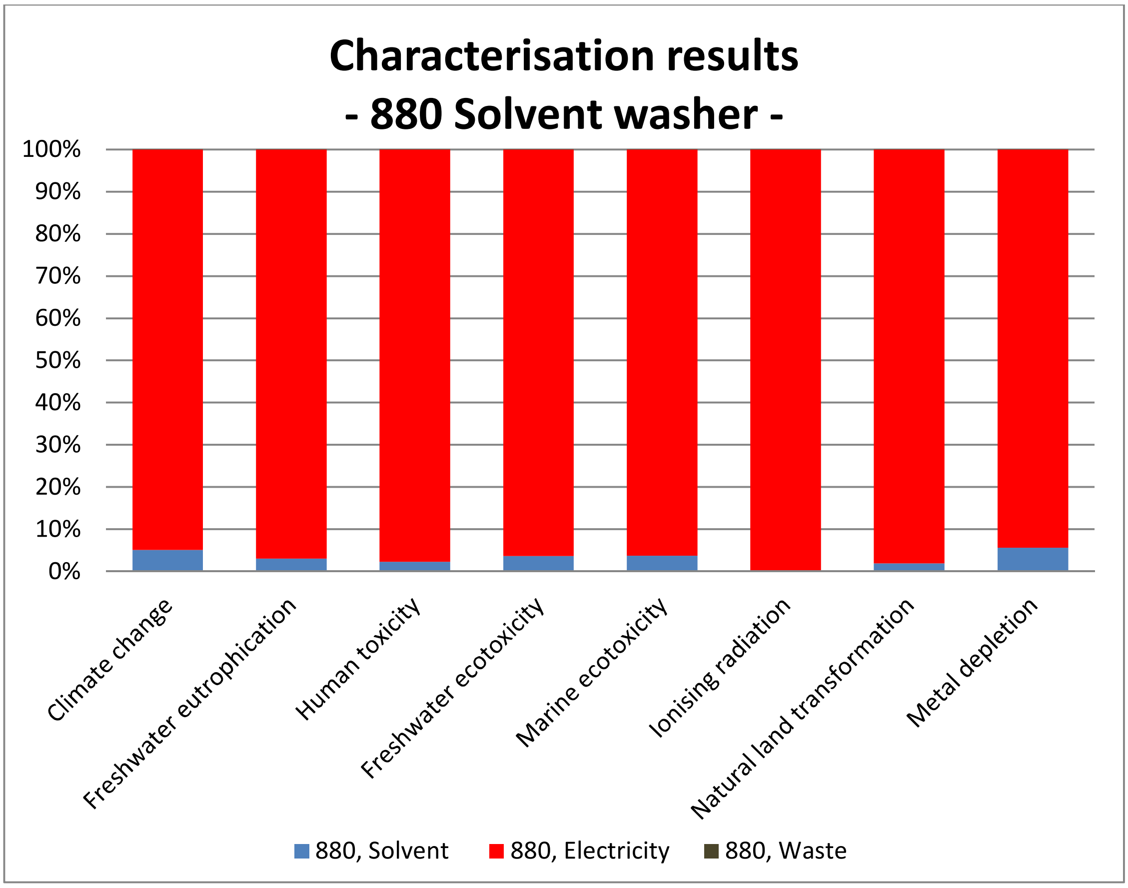

Figure 9: Characterisation results for the solvent washer 880.

The characterisation results of the solvent washer 880 show that the electricity has a dominant contribution in all impact categories. In comparison the solvent has only a relative little influence on the environmental impacts. The contribution of the waste and cooling water was below one percent in all impact categories and thus are not indicated in the graph. The reason for that could be the small amount of produced waste and cooling water used in 880.

Also in the comparison of the alkaline washers 888 and 889, the contribution of the electricity is standing out in all categories. But here the detergent and the two rust protection agents contribute with up to 20% to the environmental load in the impact categories. The detailed percentage contribution can be seen in table 15.

Due to the higher utilisation of the washer 889 compared to 888, the washing bath needed to be more often replaced. That implies that the water consumption and thus the detergent and rust protection consumption were higher in this cleaning machine. That explains the higher potential impact of the process chemicals of 889.

The burden of the waste treatment within all categories was very low, probably due to the low waste generation and positive aspects connected with the waste treatment, e.g. energy recovery via incineration or recycling of the steel packaging.

Table 15: Percentage contribution to the environmental load of the process components, valid for characterisation, normalisation and both functional units.

Impact category	Unit	880 Solvent washer			888, Alkaline washer				889, Alkaline washer			
		Solvent	Electricity	Waste	Detergent	Rust protection 1	Electricity	Waste	Detergent	Rust protection 2	Electricity	Waste
Climate change	%	5,1	**94,9**	0	4,0	8,3	**87,6**	0,1	15,0	7,3	**77,4**	0,4
Freshwater eutrophication	%	3,0	**97,0**	0	1,2	2,9	**95,9**	0	4,7	4,0	**91,2**	0,1
Human toxicity	%	2,3	**97,7**	0	0,9	2,3	**96,7**	0,1	3,6	3,0	**93,1**	0,2
Freshwater ecotoxicity	%	3,7	**96,3**	0	1,1	5,8	**92,3**	0,9	4,2	9,3	**83,1**	3,4
Marine ecotoxicity	%	3,8	**96,2**	0	1,1	5,7	**92,5**	0,7	4,1	9,2	**83,9**	2,8
Ionising radiation	%	0,1	**99,9**		0,0	0,1	**99,9**	0	0,2	0,1	**99,7**	0
Natural land transformation	%	1,9	**98,1**	0	1,7	3,7	**94,6**	0	6,2	11,3	**82,5**	0
Metal depletion	%	5,6	**94,4**	0	0,6	11,1	**88,3**	0,1	2,1	20,3	**77,4**	0,1

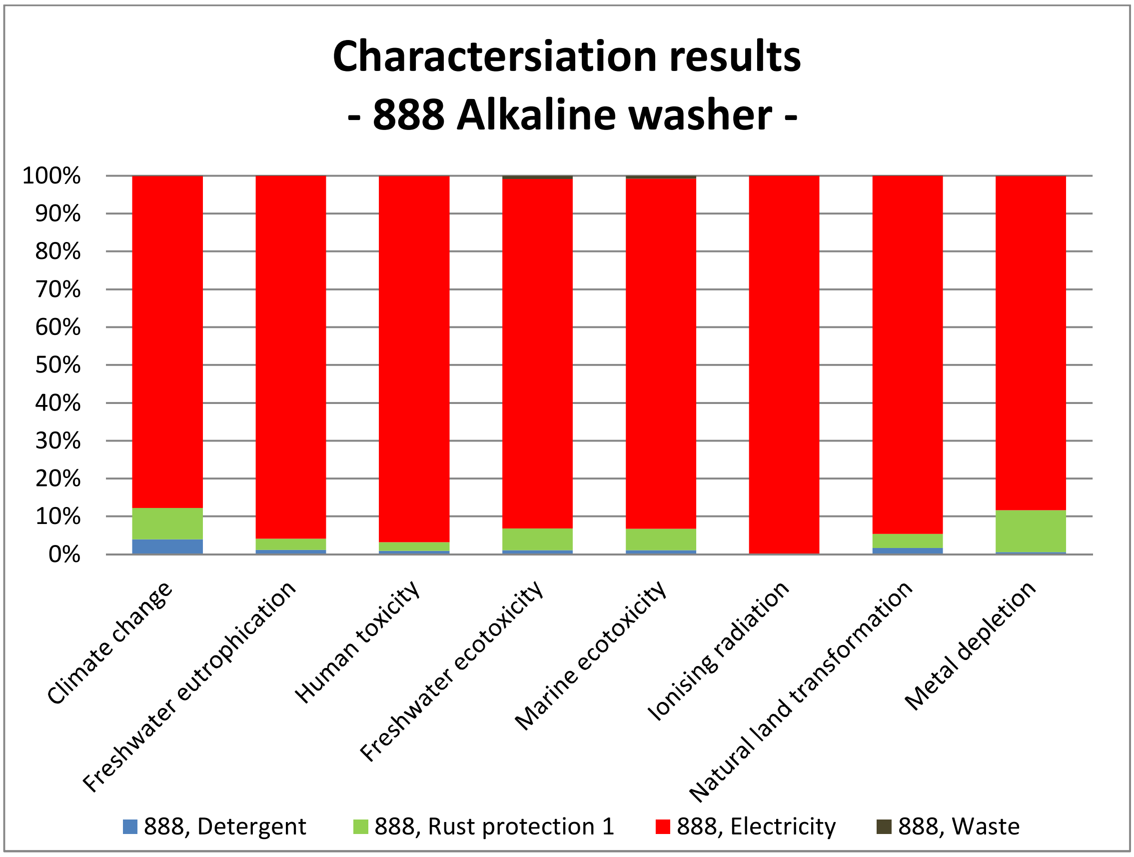

Figure 10: Characterisation results for the alkaline washer 888.

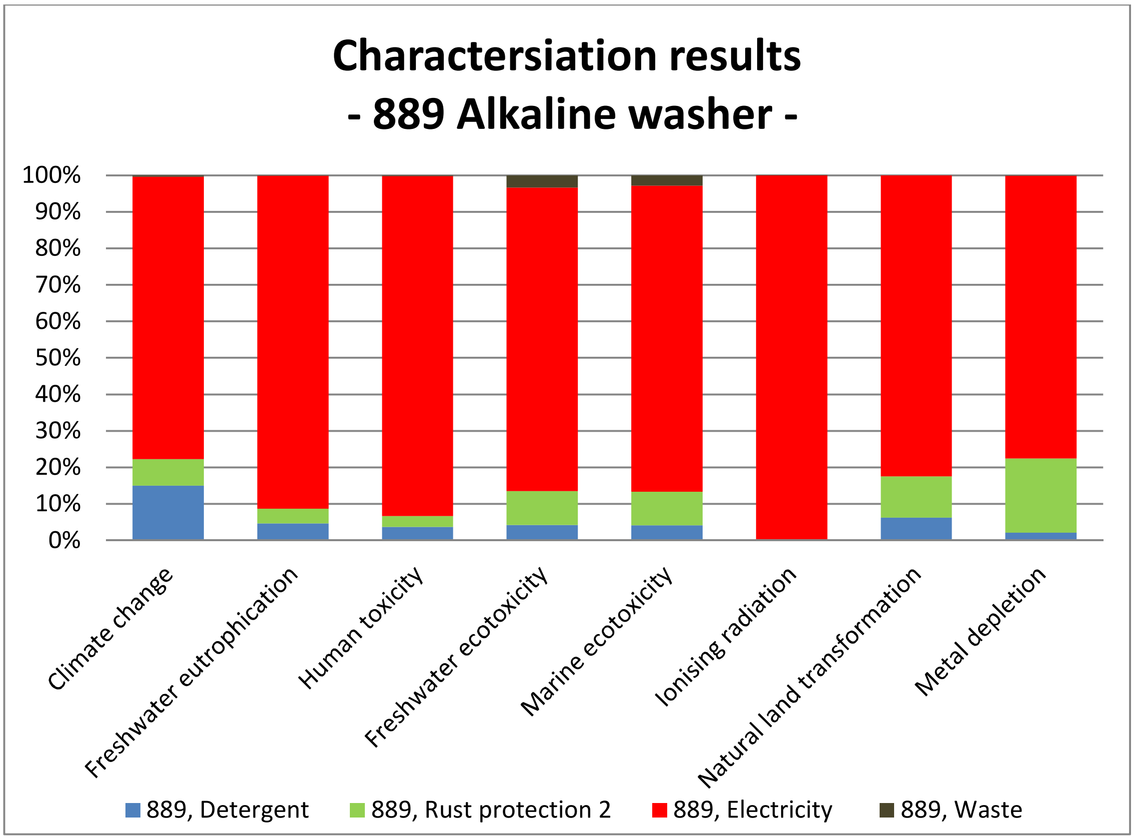

Figure 11: Characterisation results for the alkaline washer 889.

3.4.2 Normalisation results

To identify the environmental hot spots of each cleaning machine the quantified results of the impact assessment were related to European normalisation values (ReCiPe, 2012). This was done by using the normalisation function of the ReCiPe midpoint method.

The analysis of each machine showed that the electricity was dominant during the normalisation within all impact categories (table 15). For a better comparison of all washers, in the following the results for all washers were summarised in one graph. The subdivision of the cleaning process into the single components was omitted here but can be found in detail in table 15.

The ReCiPe midpoint method provided eighteen impact categories, for the assessment only the eight most relevant categories were chosen. Within those categories marine and freshwater ecotoxicity were of most concern, followed by human toxicity.

The comparison of the results per cleaned batch showed that the solvent washer 880 had the highest impacts in all categories. This was due to the higher electricity consumption per batch as seen in the inventory analysis.

Comparing both alkaline washers, the 889 performed considerably better than the 888. This was due to the higher utilisation of 889. With a higher utilisation the electricity consumption per batch decreases. From table 15 it can be seen that the electricity consumption was the major cause of the differences between the two alkaline washers.

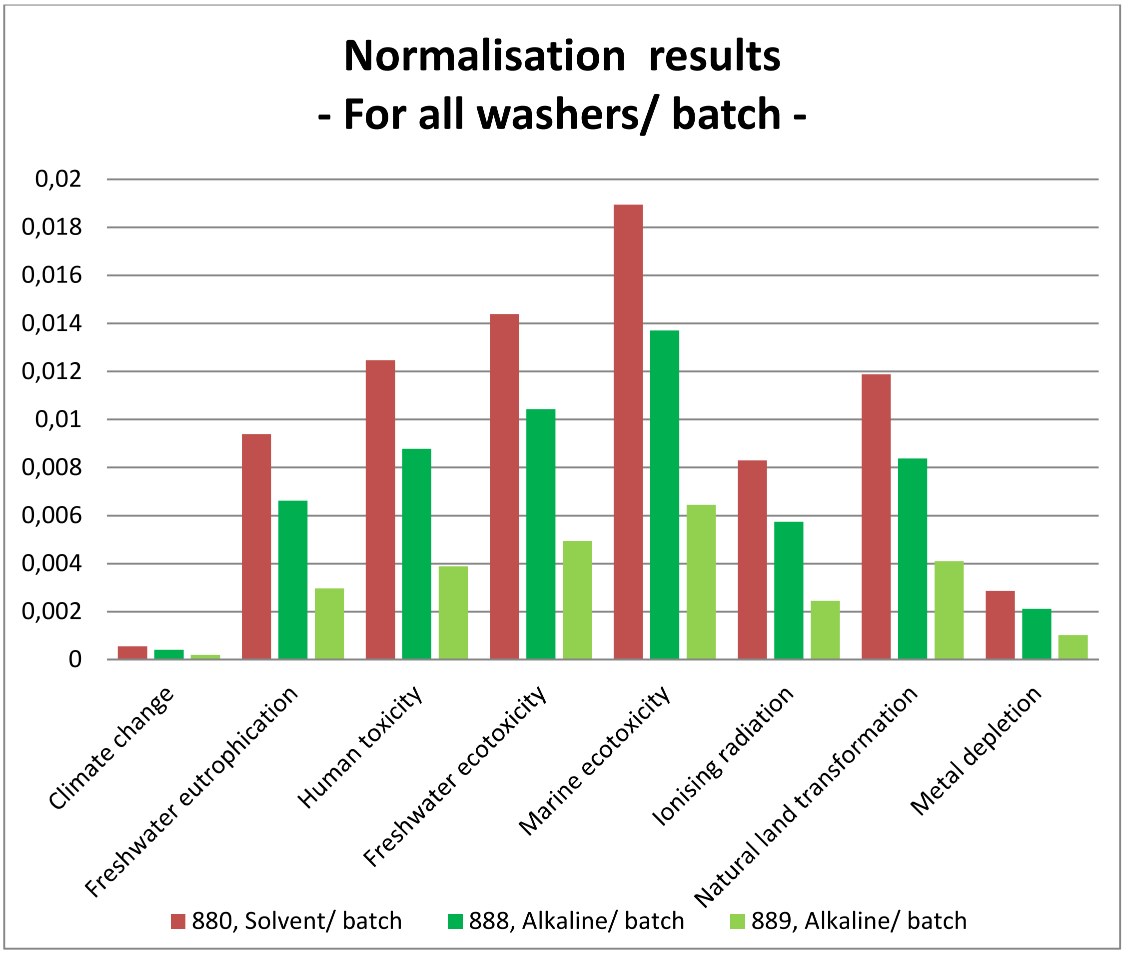

Figure 12: Comparison of the normalisations results per batch, for all cleaning machines.

The normalisation per 1kg removed oil, which reflects the actual function of the cleaning machine, showed different results. Here the alkaline washer 888 contributed more than the other cleaning machines to the environmental load in all impact categories. This can also be explained by the utilisation and the cleaning efficiency of the machine. A closer look at table 6 indicates that with 888 the least amount of oil was washed off per batch. Hence to wash off one kg of oil more batches were needed. The highest cleaning efficiency had the solvent washer 880, however here the electricity consumption was more than double as high, compared to 889.

Also the higher consumption of process chemicals per 1kg oil removed could have contributed to the worse performance of 888 in comparison to the other two washers.

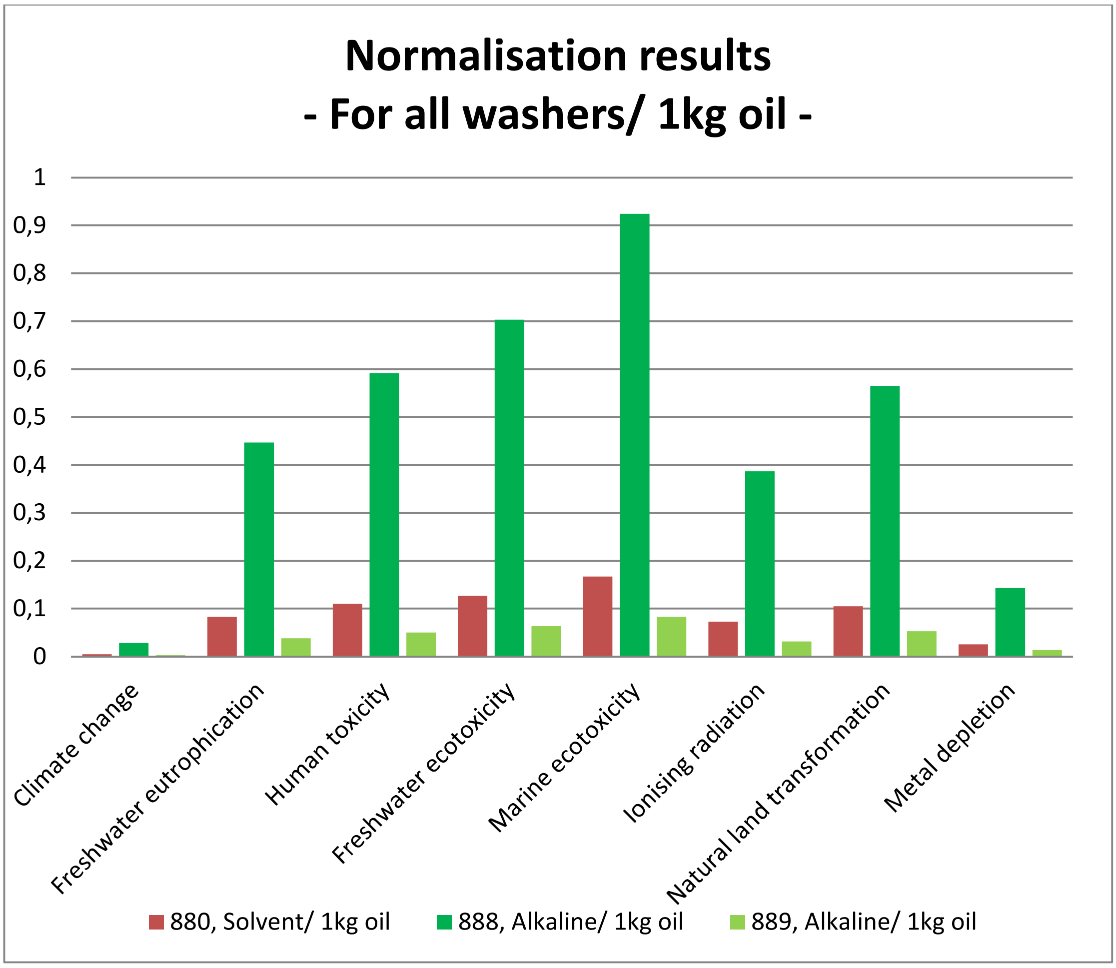

Figure 13: Comparison of the normalisation results per 1kg oil removed, for all cleaning machines.

To analyse closer the contribution of the single components of the cleaning systems the network function in SimaPro 8 was used. This function shows the percentage contribution to the environmental load of each component within the impact categories. The results are summarised in table 15 and apply for both functional units.

The waste caused in all impact categories almost no impact. The same applies for the cooling water and the wash water. Their contribution was below one percent and is therefore no longer listed in the tables and further examined.

The table shows that the major environmental load within all impact categories was caused by the electricity production. Also the steel packaging had a rather high contribution, especially in the categories metal depletion, and freshwater and marine ecotoxicity. The monoethanolamines contained in the rust protection of 888 and in the detergent add to almost all impact categories, but not to the same extent as the electricity does. Due to the higher process chemical consumption in the 889 all impact categories, apart from ionising radiation, were more burdened by the process chemicals in comparison with 888.

To further investigate the impact categories the analyses per substance function in SimaPro 8 was used. This function shows the major emissions which contribute to the respective impact categories.

Climate change:

In general the global warming potential compared to other impact categories was relatively low. The major emissions contributing to the global warming potential are carbon dioxide (fossil), dinitrogen oxide, methane (fossil and biogenic) and sulfur hexaflourid. Since the Swedish electricity mix is strongly based on nuclear and hydropower which do not emit CO_2, other fuels and their emissions have a stronger influence on this impact category.

During the combustion of fossil fuels and the waste incineration CO_2, N_2O and CH_4 are emitted. As explained in the inventory section possibly peat could influence here the results, because during the harvesting of peat huge amounts of greenhouse gases are released. SF_6, also a GHG, is used as insulation gas in switchgears and is directly emitted to air (SimaPro 8, 2013).

The alkaline detergent respectively the rust protection 1 had also a share in the global warming potential. Both were based on monoethanolamines, synthesised from ammonia and ethylene oxide (carcinogenic, toxic). During the production process also CO_2 and CH_4 are released (AkzoNobel, 2005).

Freshwater eutrophication:

Here the major causes were phosphate and phosphorus in water. Most of it originated also from the electricity production. For example, during mining activities phosphorus contained in rocks can be released to water.

Both substances are also used in fertilisers, which could be used to grow biomass and are thereby released to soil and water.

Monoethanolamines, contained in the rust protection and detergents, have also eutrophication potential as they contain nitrogen and phosphorus (AkzoNobel, 2005).

Human toxicity:

Heavy metals like manganese, barium, lead, arsenic, and zinc in water, and partly in air, were responsible for the environmental load in this impact category. They were almost entirely caused from the electricity production, for instance released during mining activities.

Freshwater and marine ecotoxicity:

Also here heavy metals like nickel, copper, manganese and zinc connected with the raw material extraction for the electricity production were the cause of the environmental load. The high severity of this two impact categories, especially in case of marine ecotoxicity, can be explained by the high importance of the category for the method developers. Their approach is considering the sea as final sink for toxic substances like heavy metals, which do not decompose in the sea and remain toxic for all organisms (ReCiPe, 2013).

Ionising radiation:

Radon 222 and Carbon-14 in air were here the cause, resulting from the electricity production. The share of nuclear power in the Swedish electricity mix is about 38%. Also during the extraction of raw materials radio nuclides are released to air.

Natural land transformation:

The transformation of forests, sea and ocean for the electricity production and the raw material extraction for the process chemicals, more precisely for the ethoxylated alcohols, contained in the rust protection 2, were here responsible for the environmental burden. Ethoxylated alcohols can be based on fossil fuels or natural feedstock like palm oil (Dean, 1995).

Positive impacts were caused by the waste treatment, where for example slag and other residues from incineration can be used for land reclamation purposes if treated properly.

Metal depletion:

Here also heavy metals like copper, iron, nickel, chromium and tin connected with the electricity production were also the origin of the environmental load. But also the steel packaging had a noteworthy contribution to the resource extraction.

3.5 Interpretation

In all three cleaning machines the most relevant process component was the electricity consumption. The process chemicals contributed also noticeable to the environmental load, however their relevance was not that high. The same applies for the packaging material, only the packaging made of steel had a minor influence. The water consumption in all three machines as well as the waste treatment had hardly any effect on the overall environmental profile of the cleaning systems.

Predominantly heavy metals released due to the electricity production were the major cause of most environmental impacts. They can be released for example during mining and land transformation activities.

Owing to this, in the first place the electricity and then the process chemical consumption should specifically be reduced in order to improve the environmental performance of the cleaning machines.

3.6 Improvement scenarios

As the electricity was identified to have the highest influence on the environmental load within all impact categories, different scenarios to reduce the electricity consumption were developed. Since the detergent and rust protection also added to the environmental impacts, even if considerably less, possibilities to decrease the water and thus the process chemical consumption were analysed as well.

Assumptions for the system improvements were derived from scientific articles or based on consultations with Bodycote. In the following the scenarios are explained shortly, including saving potentials and characterisation results per washer. Subsequently a comparison of all scenarios including normalisation results is presented.

3.6.1 Label certified “green” electricity

According to the impact assessment results of the basic scenario the electricity was the major cause of the environmental load within all impact categories. Origins were mostly heavy metals, released during mining activities or CO2 emissions resulting from combustion activities.

In order to reduce the emissions to air, water and soil, caused by the electricity production, the Swedish electricity mix was replaced by the Swiss label certified electricity system process from the database ecoinvent v3 in SimaPro 8.

As only the Swiss label certified electricity mix was available in the database uncertainties could arise, since the electricity composition may differ between both countries.

The aim of using certified electricity was to replace the electricity based on non-renewable energy sources like fossil fuel or nuclear power with renewable energy sources to reduce emissions to air, water and soil, caused by the electricity based non-renewable fuels.

Table 16: composition of the Swiss label certified electricity mix (ESU, 2013)

Type:	Composition of Swiss certified electricity [%]
Photovoltaic	0,66
Wind	0,83
Hydropower	97,78
Biomass	0,73

Characterisation results

In comparison with the results of the basic scenario (table 14), it can be seen that the characterisation result within all impact categories could considerably be reduced by using label certified electricity. The basic cause for this is a decline of heavy metals releases, connected with the extraction of fossil fuels.

As the label certified electricity is considered as carbon neutral, the change would lead to a clear reduction of the CO_2 emissions. Also in case of ionising radiation the impact potential could be reduced to a minimum, owing to the omission of nuclear power.

Table 17: Characterisation results for using certified electricity, for both functional units.

Characterisation - certified el.		880	888	889	880	888	889
Impact category	Unit	1 batch			1kg oil		
Climate change	kg CO2 eq	1,60	1,46	0,89	14,0	98,67	11,41
Freshwater eutrophication	kg P eq	0,00	0,00	0,00	0,02	0,11	0,01
Human toxicity	kg 1,4-DB eq	4,97	3,49	1,58	43,87	235,3	20,31
Freshwater ecotoxicity	kg 1,4-DB eq	0,13	0,10	0,05	1,16	6,47	0,60
Marine ecotoxicity	kg 1,4-DB eq	0,13	0,10	0,05	1,17	6,47	0,59
Ionising radiation	kBq U235 eq	0,13	0,10	0,07	1,18	7,00	0,87
Natural land transformation	m2	5,8E-04	4,5E-04	2,8E-04	0,01	0,03	0,00
Metal depletion	kg Fe eq	1,35	1,03	0,53	11,87	69,24	6,79

3.6.2 Use of deionised water

The use of deionised water only concerns the alkaline washers 888 and 889. The assumption was that the lifetime of the cleaning bath could be prolonged due to less scale formation, owing to the lower salt content in the softened water. If the salt concentration is high, the salts could react with the alkaline detergents and form scale. This would not only lower the lifetime of the washing bath but also impair the heat transfer if scale accumulates on the heating elements. Thereby the electricity consumption can possibly increase.

However, the hardness of the tap water in Gothenburg and surroundings is relatively low. Hence it was assumed that only the water consumption and subsequently the detergent and rust protection consumption could be reduced by 20%.

Table 18: Saving potentials due to the use of deionised water.

	Water consumption/ year [kg]	Detergent/ year [kg]	Rust protection/ year [kg]
Basic	83430	3350	1008
Deionised water	66834	2680	806
Savings	**16596**	**670**	**202**

<u>*Characterisation results*</u>

The biggest effects can be seen on those impact categories where the detergent and rust protection had a relatively high influence. That mostly concerns climate change, freshwater and marine ecotoxicity, natural land transformation and metal depletion. Whereby, in case of metal depletion the steel packaging from the detergent has the highest influence.

Table 19: Characterisation results for using deionised water, for both functional units.

Characterisation - Deionised water		888	889	888	889
Impact category	Unit	1 batch		1kg oil	
Climate change	kg CO2 eq	4,55	2,16	306,49	27,73
Freshwater eutrophication	kg P eq	0,00	0,00	0,18	0,02
Human toxicity	kg 1,4-DB eq	5,49	2,42	369,88	31,05
Freshwater ecotoxicity	kg 1,4-DB eq	0,11	0,05	7,61	0,68
Marine ecotoxicity	kg 1,4-DB eq	0,12	0,05	7,91	0,70
Ionising radiation	kBq U235 eq	35,84	15,29	24156	196,47
Natural land transformation	m2	0,001	0,001	0,09	0,01
Metal depletion	kg Fe eq	1,48	0,70	99,68	9,04

3.6.3 Heat exchanger

Furnaces for the heat treatment run continuously on high temperatures to avoid electricity peaks when switching them on and off. By installing heat exchangers the heat from the furnaces could be utilized to warm up the cleaning media in all washers. Thereby the electricity spent for heating and tempering in the washers could be saved.

For the calculations it was assumed that the heating constitutes about 30% of the total electricity consumption of each cleaning machine.

The use of heat exchanger would only reduce the electricity consumption other consumables would not be affected.

Table 20: Possible savings in the electricity consumption, per year.

Electricity consumption kWh/ year	
Basic	852624
Heat exchanger	596837
Savings	**255787**

<u>*Characterisation results*</u>

The environmental load would be notable reduced in all impact categories due a decrease of emissions caused by the electricity production.

Table 21: Characterisation results for installing heat exchanger, for both functional units.

Characterisation - Heat exchanger		880	888	889	880	888	889
Impact category	Unit	1 batch			1kg oil		
Climate change	kg CO2 eq	4,458	3,439	1,730	39,324	231,77	22,22
Freshwater eutrophication	kg P eq	0,003	0,002	0,001	0,025	0,132	0,012
Human toxicity	kg 1,4-DB eq	5,60	3,92	1,76	49,37	264,33	22,66
Freshwater ecotoxicity	kg 1,4-DB eq	0,113	0,083	0,041	0,998	5,595	0,524
Marine ecotoxicity	kg 1,4-DB eq	0,12	0,09	0,04	1,04	5,81	0,54
Ionising radiation	kBq U235 eq	36,34	25,11	10,72	320,6	1692,6	137,8
Natural land transformation	m2	0,001	0,001	0,000	0,012	0,065	0,006
Metal depletion	kg Fe eq	1,47	1,11	0,565	12,968	75,05	7,26

3.6.4 Cold wash

Another possibility to reduce the electricity consumption of the alkaline washer would be the utilisation of alkaline “cold wash” detergents. Their operation temperature is with about 35 to 40°C remarkably lower than with conventional detergents, which are handled at temperatures around 70°C. Therefore there is a realistic saving potential by using “cold wash” detergents.

According to data obtained from another Bodycote facility which implemented successfully the “cold wash” in their heat treatment processes and based on other conducted studies performed by the detergent supplier the following saving potentials were derived:

- 30% less electricity consumption
- 50% less water consumption

Not only the electricity consumption could be reduced, but also the water demand decreases, according to both sources.

However despite the reduced water consumption, the detergent consumption increased, according to the documentations obtained from Bodycote.

For the calculations it was assumed that the detergent and rust protection concentration was transferable from plant to plant. The new inventory results and the composition of the cold wash detergent can be found in annex B.

This measure would only affect the environmental load of the two alkaline cleaning machines.

Table 22: Saving potentials by using cold wash detergents.

	kWh/ year	Water/ year [kg]	Detergent/ year [kg]	Rust protection/ year [kg]
Basic	852624	83430	3350	1008
Cold wash	700553	41751	3948	316
Savings	**152072**	**41679**	**+598**	**692**

Characterisation results

The characterisation results for the both alkaline washers are similar to the heat exchanger scenario, as it was assumed, that the same amount of electricity per washing machine could be saved. The influence of the new process chemicals was marginal, but positive in regard to the environmental performance within all impact categories.

Table 23: Characterisation results for using cold wash detergents, for both functional units.

Characterisation – Cold wash		888	889	888	889
Impact category	Unit	1 batch		1kg oil	
Climate change	kg CO2 eq	3,41	1,65	230,01	21,23
Freshwater eutrophication	kg P eq	0,002	0,001	0,13	0,01
Human toxicity	kg 1,4-DB eq	3,92	1,73	264,30	22,22
Freshwater ecotoxicity	kg 1,4-DB eq	0,08	0,04	5,43	0,47
Marine ecotoxicity	kg 1,4-DB eq	0,08	0,04	5,64	0,49
Ionising radiation	kBq U235 eq	25,12	10,72	1693	137,69
Natural land transformation	m2	0,0010	0,0004	0,07	0,01
Metal depletion	kg Fe eq	1,02	0,46	69,07	5,86

3.6.5 Utilisation

During the impact assessment of the basic scenario, especially in the comparison of the two functional units, it became obvious that the utilisation and the cleaning efficiency of the washing machines play a major role in their environmental performance.

As the alkaline washing machine 888 removes relatively small amounts of oil and cleans only 1994 batches per year, it was decided to model al scenario in which that machine is turned off, to see how the environmental load would be affected.

Thus the workload and the oil which was washed off in 888 were evenly allocated to the other two cleaning machines. For the calculations it was assumed that for the extra work load, 50% more electricity per batch would be spent, as it was supposed that only the additional pumping and conditioning would cause the additional consumption. This theory was based on the fact that the cleaning media is kept on operation temperatures, even if the washers are idle, thus no additional electricity for heating up the cleaning media would be needed.

Apart from the electricity consumption the changes in the inventory mostly concerned the alkaline washer 889. For the extra workload one additional cleaning interval of the washer per year would be necessary and thus the water and process chemical consumption increases.

In the first instance the new utilisation would mean that the inventory results per batch of both remaining machines decreases (annex B) as the environmental load would be distributed between more batches, although the electricity and process chemical consumption slightly increases.

The consideration per removed kg of oil shows that the environmental load increased. This is due to the little amount of oil which was washed off in the 888, and distributed even between the other two cleaning machines. As a consequence less oil would be removed per batch and thus more batches would be necessary to collect one kg oil. This bears some uncertainties as the solvent washer has a higher cleaning efficiency than the alkaline washer. That means that theoretically the amount of oil washed off could increase and thereby the results per removed kg of oil would decrease.

Table 24: Saving potential connected with a new utilisation of the cleaning machines.

	kWh/ year	Water/ year [kg]	Detergent/ year [kg]	Rust protection/ year [kg]
Basic	852624	83430	3350	1008
New utilisation	787975	73620	3305	876
Savings	**64649**	**9810**	**45**	**132**

Characterisation results

The results of the characterisation reflect the result of the inventory, the load for both machines per batch decreased and partly increased for removing one kg of oil. However, it has to be considered that the machine 888 contributes no load at all. That means a significant improvement of the overall environmental performance of the shop floor.

Table 25: Characterisation results for the new utilisation of the cleaning machines, for both functional units.

Characterisation - Utilisation		880	889	880	889
Impact category	Unit	1 batch		1kg oil	
Climate change	kg CO2 eq	5,57	2,07	59,62	31,95
Freshwater eutrophication	kg P eq	0,004	0,001	0,04	0,02
Human toxicity	kg 1,4-DB eq	7,09	2,21	75,99	34,13
Freshwater ecotoxicity	kg 1,4-DB eq	0,14	0,05	1,53	0,77
Marine ecotoxicity	kg 1,4-DB eq	0,15	0,05	1,59	0,79
Ionising radiation	kBq U235 eq	46,62	13,71	499,39	211,84
Natural land transformation	m2	0,0017	0,0006	0,02	0,01
Metal depletion	kg Fe eq	1,83	0,68	19,61	10,43

3.6.6 Comparison of all scenarios

With the assembly function in SimaPro 8 all three cleaning machines were joined together, to calculate the overall environmental load for each scenario.

3.6.6.1 Characterisation results – Comparison of all scenarios

In the comparison of all scenarios it can be seen that a change to label certified electricity or the new utilisation of the cleaning machine would have the highest positive effect within all impact categories, for cleaning one batch. In regard to impact categories which are strongly influenced by the release of heavy metals, like human toxicity or marine ecotoxicity, the new utilisation would be the best choice.

Also all other scenarios have a positive influence on the environmental load, however in case of the deionised water the improvement possibilities are insignificant.

Table 26: Characterisation results for all scenarios per batch.

Impact category	Unit	Basic	Certified electricity	Cold wash	Deionised	Heat exchanger	Utilisation
Climate change	kg CO2 eq	13,15	3,95	11,30	12,94	9,63	7,63
Freshwater eutrophication	kg P eq	0,008	0,005	0,007	0,008	0,006	0,005
Human toxicity	kg 1,4-DB eq	15,89	10,045	13,57	15,82	11,28	9,30
Freshwater ecotoxicity	kg 1,4-DB eq	0,328	0,274	0,276	0,325	0,237	0,192
Marine ecotoxicity	kg 1,4-DB eq	0,341	0,274	0,288	0,338	0,246	0,200
Ionising radiation	kBq U235 eq	103,0	0,3	87,7	103,0	72,2	60,3
Natural land transformation	m2	0,004	0,001	0,003	0,004	0,003	0,002
Metal depletion	kg Fe eq	4,30	2,90	3,53	4,23	3,15	2,51

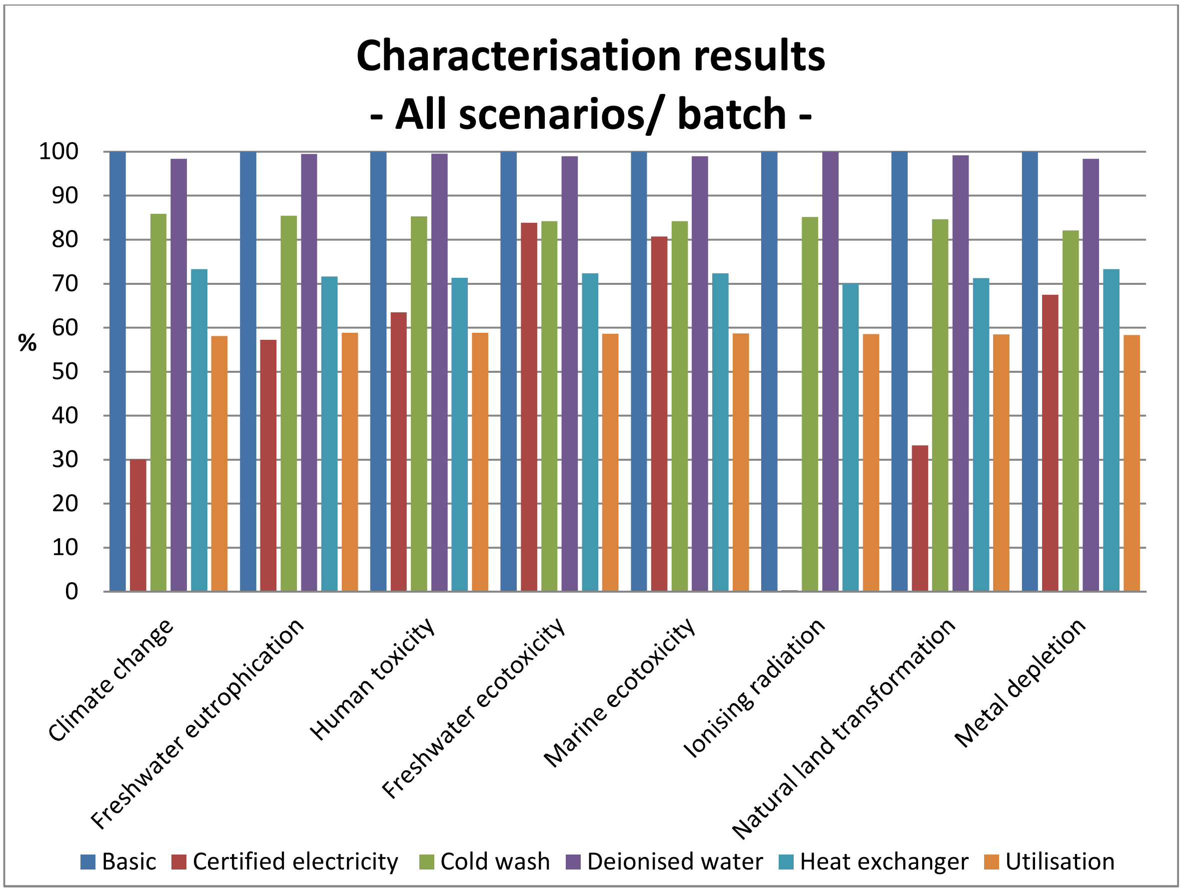

Figure 14: Comparison of the characterisation results per batch, for all scenarios.

Similar to the characterisation results per batch are the results for removing one kg of oil, but here the positive effect of the new utilisation in comparison with the label certified electricity becomes more evident. The impact could be reduced within all impact categories, apart from ionising radiation.

Table 27: Characterisation results for all scenarios per 1kg oil removed.

Impact category	Unit	Basic	Certified electricity	Cold wash	Deionised	Heat exchanger	Utilisation
Climate change	kg CO2 eq	398,2	124,2	306,21	389,19	293,32	91,57
Freshwater eutrophication	kg P eq	0,24	0,13	0,18	0,23	0,17	0,05
Human toxicity	kg 1,4-DB eq	473,6	299,51	356,36	470,77	336,37	110,13
Freshwater ecotoxicity	kg 1,4-DB eq	9,84	8,23	7,30	9,69	7,12	2,29
Marine ecotoxicity	kg 1,4-DB eq	10,22	8,23	7,59	10,08	7,39	2,38
Ionising radiation	kBq U235 eq	3071	9,04	2288	3070	2151	711,2
Natural land transformation	m2	0,12	0,04	0,09	0,12	0,08	0,03
Metal depletion	kg Fe eq	129,63	87,90	93,02	126,81	95,28	30,04

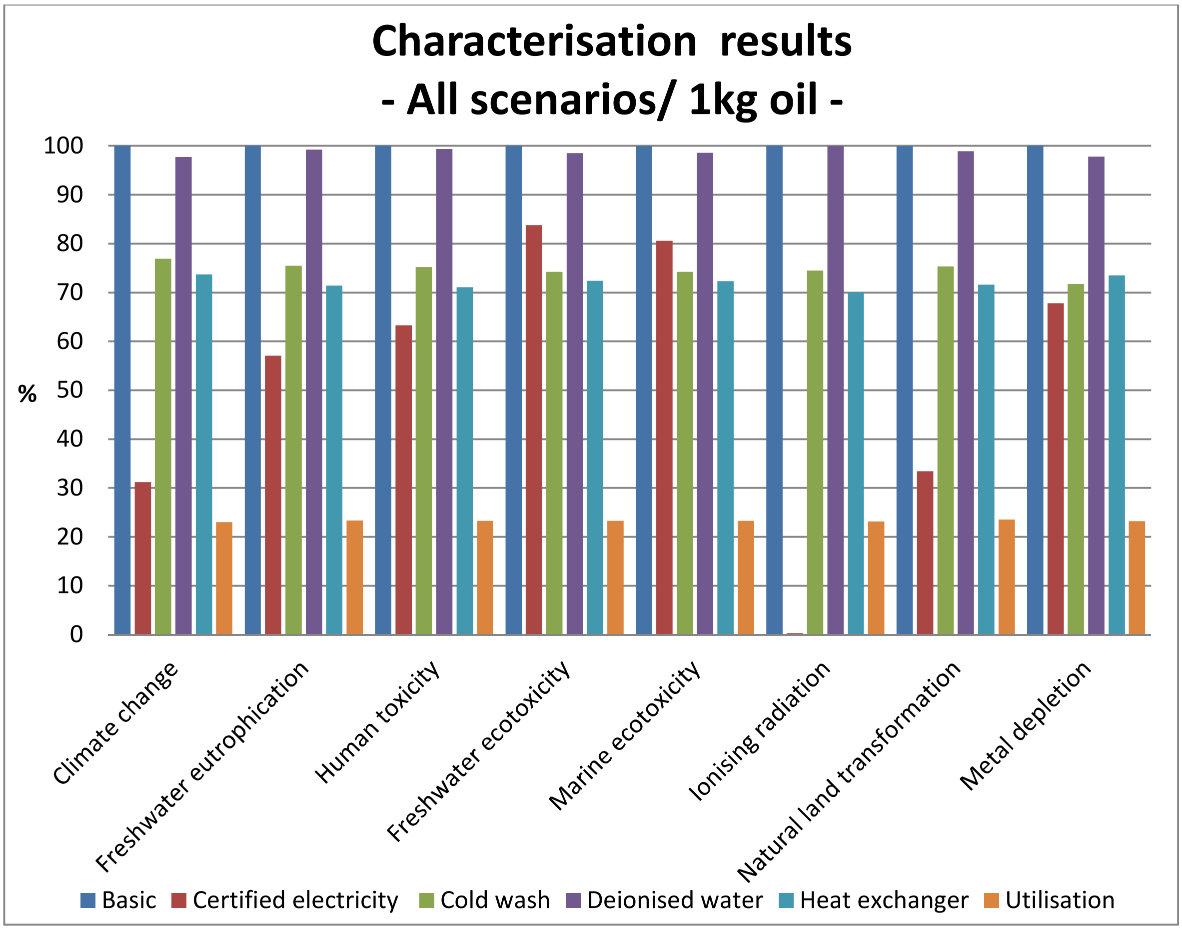

Figure 15: Comparison of the characterisation results per 1kg oil removed, for all scenarios.

3.6.6.2 Normalisation results – Comparison of all scenarios

Also the normalisation results show the same pattern identified during the characterisation. A new utilisation or the use of label certified electricity show in all impact categories the highest positive effect.

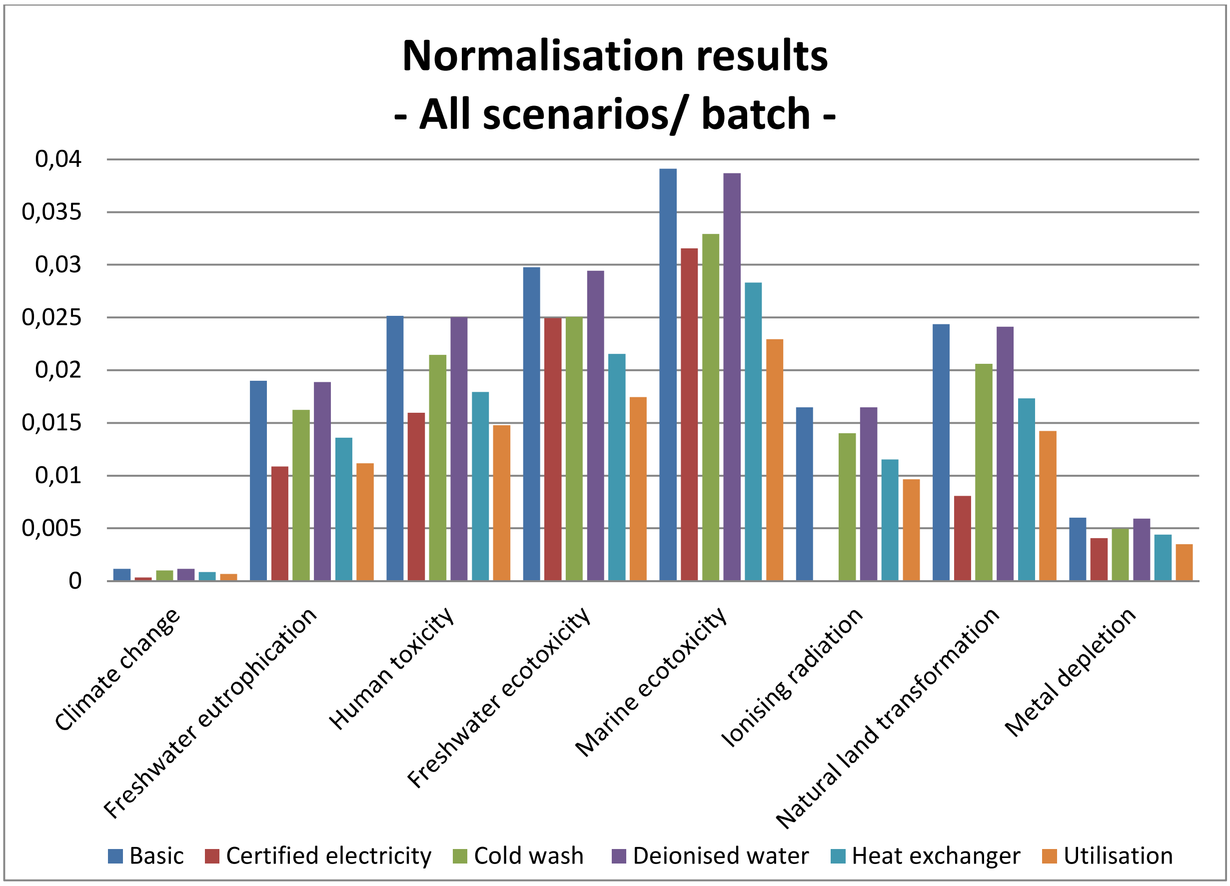

Figure 16: Comparison of the normalisation results per batch, for all scenarios.

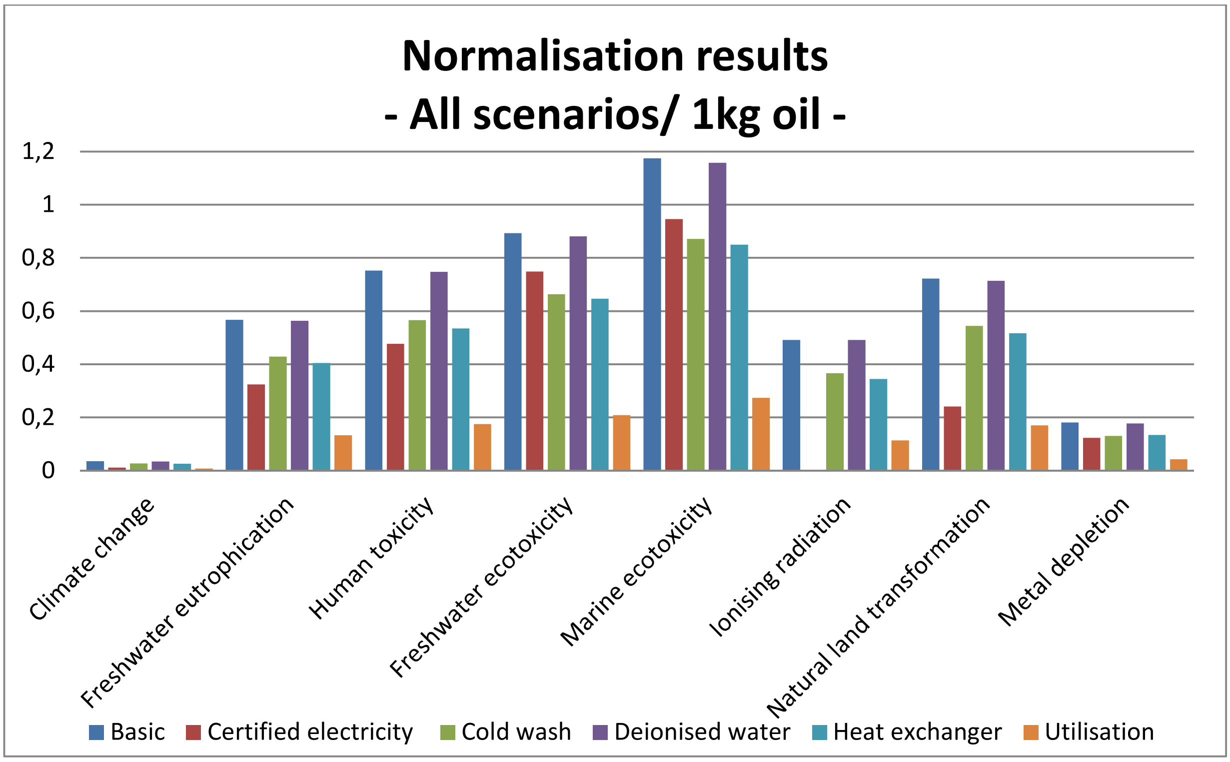

Figure 17: Comparison of the normalisation results per 1kg oil removed, for all scenarios.

3.6.6.3 Interpretation – Comparison of all scenarios

The comparison of the improvement scenarios with the basic scenario (current state), showed that by reducing the electricity consumption the environmental load of all cleaning systems could be reduced considerably. For improving the environmental performance, also the cleaning efficiency of the washing machines has to be considered. The best results could be achieved by a high utilisation of the most efficient washing machines.

Also the abandonment of non-renewable energy sources would improve the environmental performance of all cleaning systems significantly.

The decrease of process chemicals would also positively affect all impact categories, but only marginal. The impacts of water consumption and waste treatment were negligible, similar to the basic scenario.

3.7 Sensitivity analysis

During the impact assessment of the different improvement scenarios it became obvious that changes in the electricity consumption affect the environmental load within all impact categories. This backs the assumption that the electricity was the major cause of all environmental impacts.

A change of the electricity composition (label certified scenario) validated, that non-renewable energy sources or rather their respective emissions were the major cause of most of the environmental impacts.

Reducing the process chemical consumption (deionised water scenario) showed that their impact was compared to the electricity consumption not that remarkable, as investigated during the base line analysis. The same applies for the waste treatment which is directly connected to the water and process chemical consumption.

Another proof to validate the correctness of the impact assessment results is the comparison of the percentage contribution of the cleaning process components to each impact category. Table 28 shows, on the example of the alkaline washer 888, that by reducing the electricity consumption the impact of the process chemicals would rise, and the other way around, which is the logical consequence.

Table 28: Comparison of the percentage contribution of the process components within the impact categories, for reducing the detergents consumption (deionised water), and decreasing the electricity consumption (heat exchanger) with the base line conditions (basic).

		888, Basic			888, Deionised water			888, Heat exchanger		
Impact category	Unit	Detergent	Rust protection 1	Electricity	Detergent	Rust protection 1	Electricity	Detergent	Rust protection 1	Electricity
Climate change	%	4	8	**88**	3	6	**90**	5	10	**83**
Freshwater eutrophication	%	1	3	**96**	1	2	**97**	2	3	**94**
Human toxicity	%	1	2	**97**	1	1	**97**	1	2	**95**
Freshwater ecotoxicity	%	1	6	**92**	1	2	**94**	1	3	**89**
Marine ecotoxicity	%	1	6	**93**	1	2	**94**	1	3	**90**
Ionising radiation	%	0	0	**100**	0	0	**100**	0	0	**100**
Natural land transformation	%	2	4	**95**	1	3	**96**	2	5	**92**
Metal depletion	%	1	11	**88**	0	1	**90**	1	2	**84**

3.8 Uncertainty analysis

As it was rather difficult to define a functional unit for the cleaning processes, two functional units were chosen. Both based on cleaning one batch or rather several batches for removing one kg of oil. This bears some uncertainties as the weight, degree of contamination and surface area of the batches can vary greatly and could affect the final results as they depend on the cleaning efficiency of the washers. If for example some batches are more contaminated and thus more oil is washed off, the environmental load per removing one kg oil would decrease.

Also uncertainties in the composition of the process chemicals could affect the correctness of the final results as only the approximate chemical formulation was known and only dangerous substances have to be listed in the safety data sheets. Additionally, the availability of local or regional data in ecoinvent v3 limited the study. For instance only global data for the chemicals were available, that means that the data are based on global average process- and production data and thereby increase the uncertainty values. However the amount of process chemicals used in the cleaning machines was compared to the electricity consumption notably low, and thus it was assumed that the impact on the final results would be only marginal.

This also applies for the label certified electricity mix, which was only available for Switzerland. But as the Swiss label certified electricity mix is strongly based on hydro power, which is also predominant in the Swedish electricity mix it was assumed that a small variation in the composition of the label certified electricity would not have a high impact on the final results.

Another limitation of the study was a lack of transportation data, as the precise production sites for the process chemicals and the packaging materials were unknown. Since the chemicals only constituted a small fraction of the overall cleaning systems and the transport routes for the disposal were negligibly short, it was assumed that the transport would not have a noticeable influence on the final results.

3.9 Data quality analysis

For the correctness and the reliability of the life cycle assessment the data quality is vital (Baumann and Tillman, 2004). It is assumed that the modelled systems reflect the reality and are in accordance with the goal and scope definition. As the majority of the collected data was site specific and based on measurements and disposal figures, the quality of the inventory data can be considered as good. It is expected that some small gaps in the composition and the origin of the process chemicals had only minor impact on the final results. The data was as recent as possible due to the updated version of the ecoinvent v3 database, which was released in 2013 (Pré, 2013) and used in the assessment.

4 Recommendations

According to the results of the life cycle assessment the most effective measure for Bodycote international plc., would be to reconsider in a long term view a new utilisation of the cleaning machines to improve the environmental performance of the overall shop floor. The change of the electricity mix to a label certified electricity mix would also remarkably reduce the environmental load of the cleaning systems and could be fast implemented, without any changes in the cleaning processes or the production layout.

Also fast and easy to implement would be the use of cold wash detergents as only the process chemicals would need to be replaced. More efficient in regard to environmental aspects would be the use of heat exchanger to utilise the heat from the furnaces to heat up the cleaning media. However the installation could be difficult and strongly depends on the production layout.

The use of deionised water did not notably reduce the environmental load of the alkaline cleaning machines and therefore would not be the most preferable solution.

A combination of different scenarios could enhance the positive effects on the environment. Thus the use of label certified electricity in combination with a new utilisation of the washing machines could lead to a much higher improvement potential.

For future investment decisions it is recommended to examine carefully the electricity intensity and the cleaning efficiency of different cleaning systems. Also the production planning and thereby the utilisation of the cleaning machines should be reconsidered.

5 Conclusion

The results of the life cycle assessment of alkaline and solvent based cleaning systems in connection with heat treatment showed that the environmental performance of the cleaning systems strongly depends on the cleaning efficiency and the utilisation of the washing machines. Therefore it is difficult to make a clear statement about which cleaning systems caused actually the lowest environmental impact. However it was possible to identify the electricity consumption as major cause of the environmental load.

According to the results of the impact assessment, one of the two considered alkaline cleaning machines showed the best environmental performance for both functional units. This was due to the compared, by far lowest electricity consumption per batch and the relatively high cleaning efficiency. The solvent cleaning machine caused in comparison to this alkaline cleaning machine higher environmental impacts with approximately the same utilisation, however it has to be considered that on the one hand the machine consumes the highest amount of electricity, but on the other hand it has also the highest cleaning efficiency. The worse performance is based to the low utilisation of the solvent washer. If the utilisation would increase, the electricity consumption per batch would decrease and thereby the environmental load, caused by the cleaning machine.

A lower cleaning efficiency in case of the alkaline washers, which leave often a thin oil film on the steel surface after the cleaning, could increase the scrap rate as residues on the surface impair the quality of the heat treatment. Also if the post-wash was not sufficient, subsequent finishing processes could be impaired as well. That means that an additional cleaning would be necessary at the customers in order to reduce the scrap rate. This would increase the environmental load of the alkaline cleaning systems.

Therefore it would be necessary to assess how clean the steel surface has to be, in order to provide the optimal pre-conditions for the heat treatment and the subsequent processes, to evaluate which cleaning system would be the most appropriate.

The closer analyse of the environmental impact assessment figured out that the major cause of all impacts was the high electricity consumption of the washing machines. Of highest concern were there the impacts on freshwater and marine ecotoxicity, followed by human toxicity and natural land transformation. Apart from the natural land transformation, the origin for the environmental impacts were heavy metals released to air, soil and water, for example during mining activities for the fossil fuel extraction, from which also the impacts on the natural land transformation can be derived. Also for the installation of a hydropower plant, the landscape has to be altered, or for growing biomass the transformation of natural land to agricultural land is necessary and can influence therefore this impact category.

The process chemicals played only a minor role in the assessment, as their share within all impact categories was relatively low.

To reduce the environmental impacts of the cleaning systems within all impact categories it is necessary to reduce the electricity consumption of all cleaning machines. Therefore different improvement scenarios were developed not only to reduce the electricity but also the process chemical consumption. The comparison analysis of the different scenarios suggested the use of certified electricity or a new and higher utilisation of the cleaning machines. By replacing the non-renewable energy sources with renewable energy sources, all the impacts caused by the fossil fuel extraction and combustion would be reduces.

The new utilisation scenario included turning off the least efficient cleaning machine and the allocation of its work load to the other two machines. The result of the higher utilisation, of the other two cleaning machines, would lead to a decrease in the electricity consumption per batch. Also the overall process chemical and water consumption could be thereby reduced.

6 References

Literature:

AkzoNobel (2005): *Environmental Product Declaration - Ethylene amines*. Retrieved from: https://www.akzonobel.com/ea/system/images/AkzoNobel_EPD%20Ethylene%20amines%20_2__tcm53-30272.pdf, May 2014

Baumann, H. and Tillman, A.-M. (2004): *The Hitch Hiker's Guide to LCA - An orientation in life cycle assessment methodology and application*. Lund, Studentlitteratur AB, 2004

Bodycote (2014): *Heat treatment*. Retrieved from: http://www.bodycote.com, January 2014

Cormier, G.J. (1994): *Surface Engineering*, ASM Handbook. Vol. 5, ASM International, 1994

Dean, M. (1995): *Demonstration of Alternative Cleaning System*s. United States Environmental Protection Agency, August 1998

DST-Kemi (2014): *Cases*. Retrieved from: http://www.dstchemicals.com/cases, May 2014

ESU (2013): *Life Cycle Inventories of Electricity Mixes and Grid*. Retrieved from: http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf, May 2014

Ferguson, B., Jones, R., MacKenzie, D. (2011): *Heat Treating 2011: Proceedings of the 26th Conference*. ASM Heat Treating Society, Conference and Exposition, 2011

GlobalSpec Electronics (2014): *CRYOCLEAN® Blasting*. Retrieved from: http://www.globalspec.com/FeaturedProducts/Detail/LindeNorthAmerica/CRYOCLEANsnow_CO2_blasting_without_pellets/133129/0, May 2014

Göteborg (2014): *Vattenkvalitet distribuerat dricksvatten Göteborg 2013 (Jan-Dec)*, Retrieved from: http://goteborg.se/wps/wcm/connect/5fd21b52-8e5e-44f5-83ff-66c23c721e89/Dricksvatten+hos+brukare+2013.pdf?MOD=AJPERES, May 2014

Habenicht, G. (2008): *Kleben - erfolgreich und fehlerfrei: Handwerk, Praktiker, Ausbildung, Industrie*. Vol. 5, Vieweg + Teubner Verlag, 2008

Holm, T., Olsson, P. and Troell, E. (2012): *Steel and its Heat Treatment: A Handbook*. Swerea IVF, 2012

Hubbard-hall (2014): *Solvent & Aqueous Cleaning Chemicals*. Retrieved from: http://www.hubbardhall.com/chemical-apps-cleaning.htm, May 2014

IPS (2001): *Peat as an energy source*. Retrieved from: http://www.peatsociety.org/peatlands-and-peat/peat-energy-resource, May 2014

Kunz, U. (2012): *Sauber in die Wärmebehandlung*. JOT Journal für Oberflächentechnik, Vol. 52, Issue 10, pp 58-61, October 2012

Lenntech (1998-2009): *Ultrapure water*. Retrieved from: http://www.lenntech.com/applications/ultrapure/ultrapure-water.htm#ixzz2yZiuPeDq, May 2014

Linde (2005): *CRYOCLEAN® Dry Ice Blasting*. Retrieved from: https://secure1.linde.com/international/web/lg/com/like35lgcom.nsf/docbyalias/ind_dryiceblasting, May 2014

Lyman, T. (1961-1976): *Heat treating, cleaning and finishing.* Metals handbook, Vol. 2, ASM handbook committee, 1961-1976

Ohmi, T. (1993): *Ultra-Clean Technology Handbook: Volume 1: Ultra-Pure Water*. Marcel Dekker Inc., June 1993

Pawel, D., Brandes, E. (1998*): Abhängigkeit sicherheitstechnischer Kenngrößen vom Druck unterhalb des atmosphärischen Druckes*. Physikalisch-Technische Bundesanstalt Braunschweig und Berlin, PTB, September 1998

Pré (2013): *ecoinvent v3*. Retrieved from: http://www.pre-sustainability.com/ecoinvent-v3-what-is-new, May 2014

ReCiPe (2012): *Methodology*. Retrieved from: http://www.lcia-recipe.net/characterisation-and-normalisation-factors, May 2014

ReCiPe (2013): *ReCiPe 2008*, main report, Version 1.08, updated May 2013. Retrieved from: http://www.lcia-recipe.net/file-cabinet, May 2014

SimaPro 8 (2013): LCA-software, PRé Consultants bv, October 2013

Swerea IVF (2014): *Areas of Expertise*. Retrieved from: http://swerea.se/en/Start2/Working-Areas/, January 2014

Troell E. (2013): Master thesis description: *Environmental assessment of cleaning systems in connection with heat treatment*. Swerea IVF, July 2013

Wetlands (2014): *Carbon emissions from peatlands.* Retrieved from: http://www.wetlands.org/Whatarewetlands/Peatlands/Carbonemissionsfrompeatlands/tabid/2738/Default.aspx, May 2014

World Energy Council (2007): *Survey of Energy Resources.* Retrieved from: www.worldenergy.org/documents/ser2007_final_online_version_1.pdf, May 2014

ISO 14040 (2006): *Environmental Management – Life Cycle Assessment – Principles and framework.* International Organization for Standardization, Geneva Switzerland, July 2006

ISO 14044 (2006): *Environmental Management – Life Cycle Assessment – Requirements and guidelines.* International Organization for Standardization, Geneva Switzerland, July 2006

Interviews:

Grivander, T. Platschef. Bodycote Värmebehandling AB, 2014

Kehr, V. Service Technician. EMO Oberflächentechnik GmbH, 2014

Olsson, M. Maintenance Manager. Bodycote Värmebehandling AB, 2014

Sevim, S. Heat Treatment Engineer. Bodycote Värmebehandling AB, 2014

Svensson, D. Purchase Manager. Bodycote Värmebehandling AB, 2014

Appendix A – Changes in the inventory

Table I: Changes in the inventory for the modelling in SimaPro 8.

Process/ material:	Changed to:
Process chemicals:	
Surfactants, rust protection 1	Monoethanolamine
Surfactants, rust protection 2	Monoethanolamine
Polixetonium chloride, rust protection 2	Ethylenedichlorid
Waste treatment:	
Physical and biological waste water treatment	Treatment, pig iron production effluent, to wastewater treatment, class 3/CH S

Appendix B – Inventory of improvement scenarios

Table I: Inventory results for the process chemicals, per scenario.

		Basic		Deionised water		Utilisation	
Washer: 888		Batch	1kg oil	Batch	1kg oil	Batch	1kg oil
Material/ Process		[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
Detergent :							
Water	Tap water	0,113	7,646	0,091	6,117		
Active ingredients	Monoethanolamine	0,044	2,941	0,035	2,353		
Surfactants	Monoethanolamine	0,018	1,176	0,014	0,941		
Rust protection 1:							
Active ingredient	Monoethanolamine	0,120	8,112	0,096	6,490		
Packaging for:							
Detergent	HDPE	0,007	0,455	0,005	0,364		
Rust protection	Steel	0,011	0,746	0,009	0,597		
Washer 889:							
Detergent :							
Water	Tap water	0,207	2,658	0,166	2,127	0,204	3,165
Active ingredients	Monoethanolamine	0,080	1,022	0,064	0,818	0,079	1,217
Surfactants	Monoethanolamine	0,032	0,409	0,025	0,327	0,032	0,487
Rust protection 2:							
Water		0,079	1,015	0,049	0,631	0,078	1,208
Active ingredient	Monoethanolamine	0,023	0,292	0,014	0,181	0,022	0,348
Additive	Sodiumphospate	0,003	0,037	0,002	0,023	0,003	0,043
Additive	Ethoxylated Alcohols	0,003	0,037	0,002	0,023	0,003	0,043
Additive	Polixetonium chlorid	0,001	0,007	0,000	0,005	0,001	0,009
Additive	Ethanediamine	0,003	0,037	0,002	0,023	0,003	0,043
Packaging for:							
Detergent	HDPE	0,012	0,158	0,010	0,126	0,012	0,188
Rust protection	Steel	0,010	0,134	0,008	0,107	0,010	0,160

Table II: Inventory results for the cold wash scenario.

Cold wash		Washer: 888		Washer: 889	
Material/ Process		[kg]	[kg]	[kg]	[kg]
		Batch	1kg oil	Batch	1kg oil
Detergent:					
Water	Tap water	0,295	19,895	0,249	3,203
Active ingredients	Monoethanolamine	0,114	7,652	0,096	1,232
Surfactants	Monoethanolamine	0,045	3,061	0,038	0,493
Rust protection 3					
Water	Tap water	0,036	2,434	0,021	0,274
Active ingredient	Monoethanolamine	0,012	0,811	0,007	0,091
Packaging for:					
Detergent	HDPE	0,008	0,284	0,080	0,101
Rust protection	Steel	0,004	0,298	0,003	0,034

Table III: Inventory results for the cleaning process (electricity and water consumption), per scenario.

	Basic		Deionised water		Heat exchanger		Cold wash		Utilisation	
	Batch	1kg oil	Batch	1kg oil	Batch	1kg oil	Batch	1kg oil	Batch	1kg oil
880										
Electricity [kWh]	88,3	779			61,8	545			79,3	823
888										
Electricity [kWh]	61	4111			42,7	2878	42,7	2878		
Water [kg]	8,9	599	7,1	479			4,4	299		
889										
Electricity [kWh]	26	334			18,2	234	18,2	27,1	23,3	343
Water [kg]	8,2	105	6,5	84			4,3	55,4	8,1	125

Table IV: Inventory results for the waste, per scenario

	Basic		Deionised water		Cold wash		Utilisation	
	Batch	1kg oil	Batch	1kg oil	Batch	1kg oil	Batch	1kg oil
888								
Waste water [kg]	9,2	618,6	7,4	494,9	4,9	332,5		
HDPE to incineration [kg]	0,007	0,455	0,005	0,364	0,008	0,284		
Steel to recycling [kg]	0,011	0,746	0,009	0,597	0,004	0,298		
889								
Waste water [kg]	8,6	110,8	6,9	88,4	4,7	60,7	8,5	131,9
HDPE to incineration [kg]	0,012	0,158	0,010	0,126	0,080	0,101	0,012	0,2
Steel to recycling [kg]	0,010	0,134	0,008	0,107	0,003	0,034	0,010	0,2