Environmental and Technical Evaluation with Life Cycle Assessment

Hg-rid-LIFE
Mercury Decontamination of Dental Care facilities

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Preface

This report is part of the EU Life project Hg-Rid-LIFE with the LIFE project number LIFE15 ENV/SE/000465. The project was carried out between 01/09/2016 – 31/08/2019, by Praktikertjänst AB (PTJ), Sweden Recycling AB (SRAB) and the Swedish Environmental Research Institute (IVL).

The report covers the following project actions:

- C1.2. Evaluating Impacts in the dental care facilities.
- C1.5 Conclusions and recommendations for the environmental and technical parts.
- C1.6 Assessment of the technical system for Hg reduction.

and includes the following deliverables:

- C1.6.1 Life Cycle Assessment.
- C1.5.1 Final Results, Conclusions and Recommendations for the environmental and technical parts.

This report includes a technical evaluation of the performance of the Hg decontamination process and an environmental evaluation in a system perspective using Life Cycle Assessment (LCA) as the scientific tool for the evaluation. An overview presentation of the entire project can be found in the Final Report.

Gothenburg 26 August 2019

Håkan Stripple Michelle Nerentorp

SUMMARY

This report presents the results of the environmental and technical evaluation of amalgam/mercury decontamination (DC) activities of dental care facilities, using Life Cycle Assessment (LCA). This evaluation is part of the Hg-rid-LIFE project *Mercury Decontamination of Dental Care facilities,* which aims to reduce the emissions of mercury (Hg) from dental clinics in Sweden. The project was carried out between 01/09/2016 – 31/08/2019, by Praktikertjänst AB (PTJ), Sweden Recycling AB (SRAB) and the Swedish Environmental Research Institute (IVL), with financing via the EU LIFE Program - HG-RID-LIFE LIFE15 ENV/SE/000465.

Mercury has long been identified as an environmental problem that should be phased out and in Sweden this phase-out has been going on for a long time. Amalgam for dental treatments was left on dispensation for quite some time as alternatives were lacking. Today, there are good alternatives to amalgam for most dental treatments. The phasing out of amalgam is ongoing and has come quite a long way in Sweden and some other countries in Europe. However, in many parts of the world, also in Europe, amalgam is still used for dental treatments. Although most dental treatments with amalgam have ceased in Sweden, many patients still have amalgam fillings. If necessary, these amalgam fillings are replaced with other materials. This means that amalgam is still handled at Swedish dental clinics and can therefore pose an environmental problem.

At Swedish dental clinics, amalgam separators connected to the waste water collect amalgam waste from drilling activities and from other activities at the clinics such as cleaning of tools. Despite the amalgam separation, there is a certain discharge of amalgam, and thus Hg, from the dental clinic's drains. As part of the phase-out of amalgam, the dental clinics' drainage pipes are also cleaned from amalgam residues during a so-called decontamination process (DC). This can be done regularly or as there is a closure or a transfer of a dental clinic.

In this part of the project, an LCA model has been developed over the entire system of a dental clinic, the mercury cleaning process, and the final storage of collected mercury. A schematic picture of the technical system is shown below in Figure A.

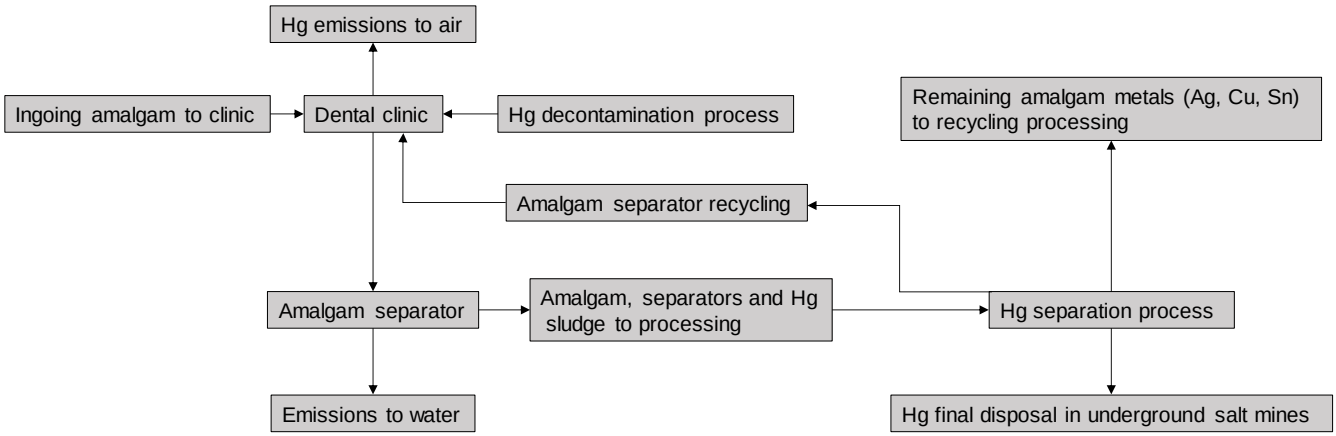

Figure A Schematic picture over the technical system for Hg separation at dental clinics in Sweden.

In addition, different forms of mercury have been analyzed in water samples at several dental clinics during the DC process. This information together with other process information has been used in the LCA model. Nine environmental impact categories have been evaluated in the study. The results are divided into the dental clinic, the Hg decontamination process, and the Hg sludge and final storage of Hg in closed underground salt mines. Three different scenarios have been evaluated:

- **Scenario 1:** Mercury handling with Hg decontamination, Hg processing and final Hg storage, representing the main handling system of today in Sweden.
- **Scenario 2:** Mercury handling with only amalgam separation and final storage of amalgam in Sweden.
- **Scenario 3:** Reference case with no mercury or amalgam handling. The amalgam from the dental clinics will go directly to the recipient.

All results are presented per functional unit.

The functional unit (FU) reflects the function that it intends to analyze. In order to make it possible to draw more general conclusions, and also to be able to transfer the result to corresponding activities in other countries, we have chosen to define the functional unit to: **one dental chair for one year of operation (226 working days)**.

In Figure B to Figure D, three different results from the LCA models are shown, namely Total Hg emissions, climate impact (measured as Global warming potential, GWP), and Terrestrial ecotoxicity. As shown in the figures, the Hg decontamination process is efficient and removes a large share of the mercury entering the clinic, see Figure B. However, the separation efficiency for the amalgam separator is about 98.6 % so some of the amalgam/Hg can spread further to the surrounding recipient. Global warming potential (GWP) includes an indication of other emissions than Hg from other processes, see Figure C. Only a moderate increase in GWP can be found for the Hg decontamination process. The elevated values for scenario 3, without Hg cleaning and separation, are due to the electrical energy consumption used at the

dental clinics during normal operation. However, the reduction in Terrestrial ecotoxicity is significant when having any kind of Hg cleaning in scenario 1 and 2 compared to the uncleaned case in scenario 3, see Figure D.

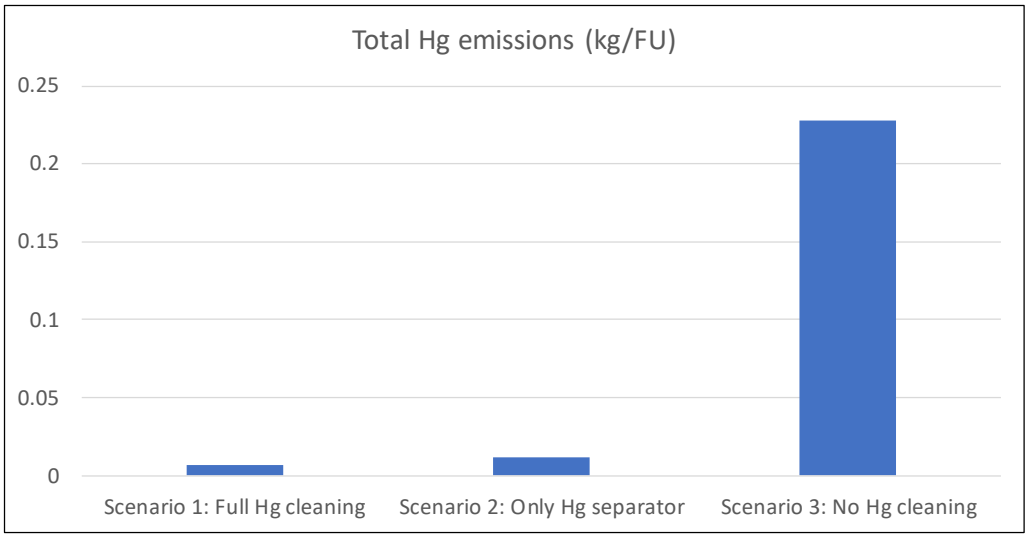

Figure B Scenario comparison of the total Hg emissions from the entire LCA model systems.

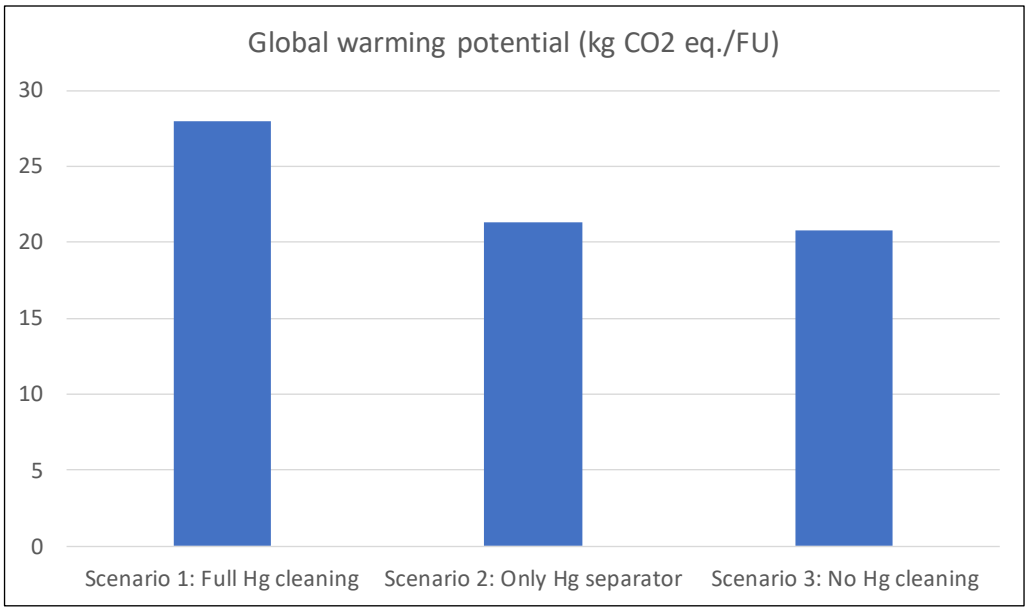

Figure C Scenario comparison of the Global warming potential (GWP100) for the entire LCA model systems.

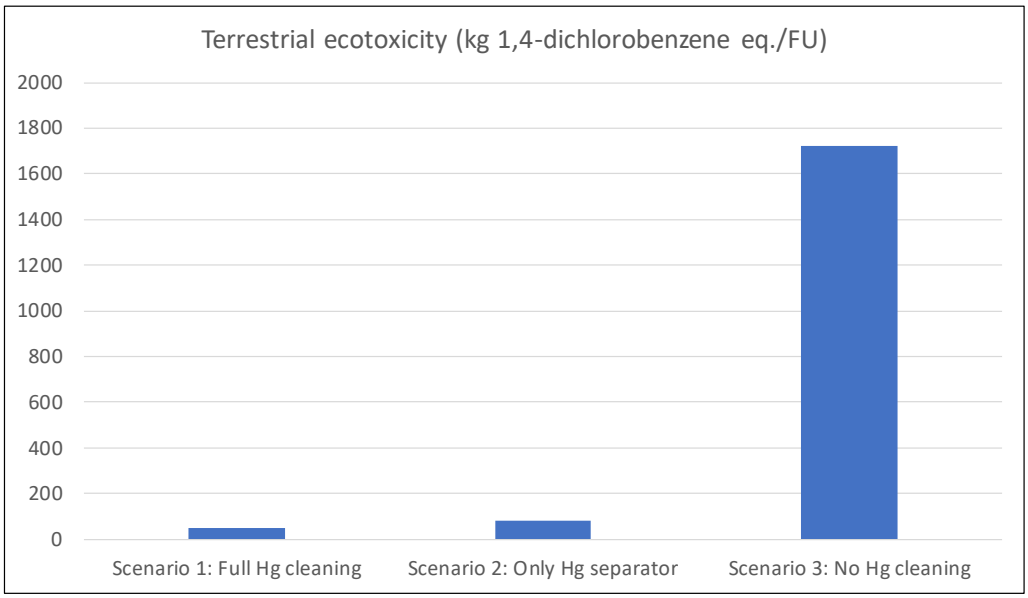

Figure D Scenario comparison of the Terrestrial ecotoxicity for the entire LCA model systems.

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1 Background

This report presents the results of the environmental and technical evaluation of amalgam/mercury decontamination (DC) activities of dental care facilities, using Life Cycle Assessment (LCA). This evaluation is part of the Hg-rid-LIFE project *Mercury Decontamination of Dental Care facilities*, which aims to reduce the emissions of mercury (Hg) from dental clinics in Sweden. The project was carried out between 01/09/2016 – 31/08/2019, by Praktikertjänst AB (PTJ), Sweden Recycling AB (SRAB) and the Swedish Environmental Research Institute (IVL), with financing via the EU LIFE Program - HG-RID-LIFE LIFE15 ENV/SE/000465. The hypothesis of this project is that systematic DC of the pipe systems of dental care facilities lead to reduced impact of mercury to the environment. The LIFE project was carried out by decontaminating selected dental clinics in Sweden and evaluating the process from a socio-economic and environmental point of view. Other parts of the LIFE-project aimed to spread information about the project and the challenges with mercury, and to encourage training on maintenance routines through seminars, conferences, and web-platforms[1] in order to reduce mercury emissions from dental facilities. The objectives of Hg-rid-LIFE are further explained and assessed in the Final Report[2]. Further evaluation of the aims of this project are presented in the report "C1.5.1 Final Results, Conclusions and Recommendations".

1.1 Purpose and aim of the sub action C1.6.1 Environmental and technical evaluation with Life Cycle Assessment

The objective of the sub-action C1.6.1 *Environmental and technical evaluation with Life Cycle Assessment*, is to evaluate the DC process and the use of amalgam separators (AS) at dental care facilities from an environmental and technical point of view. The use of a system perspective, provided by using Life Cycle Assessment (LCA), was important to bring the whole life cycle of mercury into account when evaluating the role of DC and use of ASs to reduce mercury emissions.

To perform an LCA, an understanding of the system, along with input data of emissions to and from different receptors, is needed. Therefore, a close cooperation between IVL, SRAB, PTJ and Medentex was essential to share information, share experiences, make study visits and access sampling points for data collection.

1.2 Report's layout

In chapter 2, the project and the problems associated with the use of dental amalgam are introduced. Chapter 3 introduces mercury as an environmental toxic pollutant and its use within dental care. In chapter 4, a background to the method of Life Cycle Assessment is presented, followed by a technical background in chapter 5. The methods used for data collection are introduced in chapter 6 including all data results used as inputs to the LCA. The parameters and system boundaries used for the LCA

[1] See the developed web training tool: https://hg-rid.eu/en/home
[2] See website: https://www.praktikertjanst.se/om-oss/socialt-ansvarstagande/miljoprojektet-hg-rid-life/material-och-dokument-hg-rid/

are presented in chapter 7. Chapter 8 includes the results from the LCA model. This report ends with conclusions and recommendations in Chapter 9.

2 Introduction

Mercury has long been identified as an environmental problem that should be phased out and in Sweden this phase-out has been going on for a long time. Amalgam for dental treatments was left on dispensation for quite some time as alternatives were lacking. Today, there are good alternatives to amalgam for most dental treatments. The phasing out of amalgam is ongoing and has come quite a long way in Sweden and some other countries in Europe. However, in many parts of the world, also in Europe, amalgam is still used for dental treatments. Although most dental treatments with amalgam have ceased in Sweden, many patients still have amalgam fillings. If necessary, these amalgam fillings are replaced with other materials. This means that amalgam is still handled at Swedish dental clinics and can therefore pose an environmental problem.

At Swedish dental clinics, amalgam separators connected to the waste water collect amalgam waste from drilling activities and from other activities at the clinics such as cleaning of tools. Despite the amalgam separation, there is a certain discharge of amalgam, and thus Hg, from the dental clinic's drains. As part of the phase-out of amalgam, the dental clinics' drainage pipes are also cleaned from amalgam residues during a so-called decontamination process (DC). This can be done regularly or as there is a closure or a transfer of a dental clinic. This decontamination process is carried out in Sweden by, for example, SRAB. During the decontamination process, the waste water pipes from the dental chair and sinks are cleaned of sludge that may contain mercury. The Hg sludge is collected for removal of mercury, waste management and permanent storage of Hg in old salt mines.

In this part of the project which covers a technical and environmental evaluation of the overall decontamination process, the remediation of mercury from dental clinics has been investigated and evaluated. The evaluation is carried out by regarding several aspects such as methodology and technical function, decontamination efficiency with regards to Hg and environmental effects of the decontamination. In the entire evaluation of the decontamination of Hg in dental clinics, also economic and cost effectiveness and effects of supporting measures such as information and training of staff have been evaluated. The results from these analyses are presented in separate reports.
IVL's role in this project has been to monitor and evaluate the methods in its current form in Sweden. There is, of course, an interest from the EU to investigate whether existing methods works and are cost-effective. There are plans in the EU to introduce similar requirements that are now only available in some countries. It is then of great interest to investigate how the phase-out has worked in the countries that have the most ambitious Hg-reduction plans today. IVL will monitor and evaluate existing methods technically, examine its environmental effects with a system perspective

(LCA methodology), examine its financial effects mainly with CBA (cost benefit analysis) technology, and evaluate the supporting measures implemented in connection with phasing-out projects such as information and training efforts. The latter parts are presented in separate reports.

3 Mercury as a pollutant – an introduction

In this chapter mercury as a chemical element, a neurotoxin and an environmental pollutant is introduced. The use of mercury in dental amalgam is also explained.

3.1 Mercury as a toxic environmental pollutant

Mercury (Hg) is a chemical element belonging to the heavy metals in the periodic table, together with metals such as cadmium, arsenic, nickel and lead. Hg is unique due to that it's the only metal that is liquid in room temperature and exists as a stable monoatomic gas. A chemical element cannot break down in the environment, thus once released, Hg is only moving from different environmental compartments (air, soil, sea, lakes, biota) and cannot be destroyed (Lew, 2009).

Hg can be mined from the mineral cinnabar, that is often found in volcanic regions. Humans have increased the emissions and spread of Hg into the environment by about 30-50 %, from activities such as gold mining, coal combustion, metal production, cement factories, chlor-alkali production, waste incineration and emissions from the production and use of dental amalgam. Human activities thereby increase the emissions of Hg to the atmosphere by 2000-3000 tonnes per year (AMAP, 2011).

In the environment, Hg mainly exists in its elemental form (Hg(0)) or as oxidized in compounds as Hg(II). The predominant form of Hg in air is as Hg(0), gaseous elemental mercury (GEM). This semi stable gas is globally distributed, leading to a background concentration in the northern hemisphere of around 1.5 ng/m^3 (Sprovieri, 2016). Within the Swedish national environmental monitoring, IVL monitors Hg concentrations in air at three stations in Sweden and one in northern Finland, ranging from south to north with average annual concentrations in 2018 of 1.3-1.4 ng/m^3. Higher air concentrations in the south is explained by proximity to emission sources in more population dense areas of Europe (IVL, 2018). Hg in air can deposit into the environment and bio transform to methylmercury (MeHg, CH_3Hg^+), which poses a threat to living organisms.

All forms of Hg are toxic. Inorganic gaseous mercury (GEM, Hg(0)) is toxic when inhaled in high concentrations in combination with long-term exposure. It causes harm to the neurological system, lungs and kidneys, which could lead to death (WHO, 2005). However, since MeHg is bio accumulative, it is more likely to enter the ecosystem and cause harm to animals and top-predators such as humans. Organic forms of mercury pose a greater threat due to its ability to cross the blood-brain barrier. Their strong affinity for Sulphur atoms in cysteine residues makes it able to interfere with the functions and structure of proteins. MeHg poisoning can lead to

disturbed immune system, reproductive system and central nervous system, causing sense losses, mental disturbances, and in very high doses, death. Human exposure to MeHg is mainly depending on the diet. A tolerable intake of methylmercury via food was by the Joint FAO/WHO Expert Committee on Food Additives set to a weekly maximum intake of 1.6 µg methylmercury/kg bodyweight. The tolerable daily intake of total mercury was set to 2.0 µg/kg bodyweight (WHO, 2007). Pregnant women should take extra care due to the risk of the fetus developing intellectual disabilities or neurological damage. Hg poses similar threats to wildlife and is considered one of the most toxic environmental pollutants (AMAP, 2011).

3.2 Impacts of mercury used as dental amalgam

One of the main anthropogenic sources of mercury into water is from wastewater treatment plants (Swedish EPA, 2019). The main contributor to Hg monitored at Swedish municipal wastewater treatment plants originates from the discharge of Hg in dental amalgam which ends up in the sludge (Stockholm Stad, 2019). The use of dental amalgam in Sweden is prohibited since 2009. Though, older generations still have dental amalgam in their teeth, which eventually might get removed at a dental clinic, ending up in the municipal water. Policy development regarding the use of dental amalgam and ASs are further described in Hg-Rid-LIFE report C1.4.1 (Mellin and Yaramenka, 2019). One of the objectives with this study was to measure how much mercury and what kind of mercury species that leak into the sewage system from dental facilities, despite the use of ASs. Some mercury that is generated from the drilling of an amalgam filling is emitted as a gas into the air. The vacuum system used for suction during drilling operations, transports the suction air directly into the outdoor air via a ventilation system or similar. One aim of this study was to monitor the amount of mercury emitted to air from the exhaust gases from dental facilities.

The health effects of using dental amalgam have been widely debated for many years. An amalgam filling can release mercury through evaporation, electrochemical corrosion and released as amalgam particles, which can be taken up by the patient when inhaling. Some patients report hypersensitivity to amalgam and in other studies it has been suggested that long-term exposure to dental amalgam fillings could cause nephrotoxicity, autoimmune diseases, neurological damages and that there might be a link between low-exposure of mercury and the development of Alzheimer's disease and Multiple Sclerosis (Mutter, 2005). However, contradictory studies showed that the amount of Hg up taken by daily inhaling is not leading to Hg levels in urine exceeding WHO recommended threshold values (Mackert & Berglund, 1997). Also, it was shown that there was no elevated risk of mercury poisoning when working as a dental nurse in Sweden during the 1960s-1980s, the prime time of mercury amalgam use in Sweden (Vähäsarja et al., 2016).

Tests were performed, within this study, to see if unhealthy concentrations were reached during dental operations of amalgam fillings and handling of amalgam contaminated dental tools.

The main focus of this project assessment was to study the life cycle of dental amalgam and the environmental and health benefits of performing DC of dental pipes and the usage of ASs.

4 Life Cycle Assessment (LCA) – an overview

The use of different products, materials, or processes is often very complex and may involve many different activities in the society such as extraction of raw materials, operation of production plants, power generation and transportation etc. Due to this complexity, it can be difficult to calculate emissions and energy use in a relevant way for an entire process or production system. The complexity may increase when various process or production systems are compared, or when different process changes must be evaluated and assessed.

A system is a unit that consists of different parts interacting with each other. By applying a system perspective, i.e. taking the entire system into account, one can get a better and more accurate picture of a production system and one can for example avoid sub-optimization. For example, when evaluating a process in terms of energy and environmental aspects, it is important not to evaluate only the production process but also ensure that the environmental load does not increase due to e.g. increased upstream activities prior to the process or change in raw materials. The same applies when analyzing and evaluating gas or water treatment equipment. The overall efficiency of the treatment process must be good and the treatment process itself may not cause more environmental problems than those reduced by the treatment process, viewed from a system perspective. Analyzing production systems rather than individual production processes, demands more from a methodology and implementation perspective. A logical and structured methodology and a well-thought-out analysis are required. Computer-based calculations and models are also required.

For this type of system analysis, the most common method is Life Cycle Assessment (LCA). In this study, Life Cycle Assessment (LCA) methodology has been chosen as the base for the analysis of the Hg decontamination process for dental clinics.

A system analysis is a tool that allows a product to be analyzed through its entire life cycle, from raw material extraction and production, via use of the product/process, to waste handling and recycling. The LCA methodology is described in, for example, the standards EN ISO 14040:2006 and 14044:2006[3]. In a life cycle assessment, a mathematical model of the system is designed. This model is of course a representation of the real system, including various approximations and assumptions. The results from the model are, of course, also dependent on the input data and assumptions being applied. The LCA methodology allows us to study complex

[3] ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework. ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines.

systems, where interactions between different parts of the system exist, to provide as complete picture as possible of the environmental impacts of, for example, a product or a process.

An LCA is usually made in three steps with an additional interpretation step, see ISO 14044. In the *goal and scope* definition, the model and process layout are defined. The functional unit is also specified. The functional unit is the measure of performance that the system delivers. In this case, the functional unit has been defined by the operation of a dental clinic. This has been defined as using one dentist's chair for one year (226 working days) of operation.

In the *Life Cycle Inventory* analysis (LCI), materials, emissions and energy flows are quantified. Each sub-process has its own performance unit and several in- and out-flows. The processes are linked together to form the mathematical system being analyzed. The results of the model are the sum of all in- and out-flows calculated per functional unit for the entire system. The *life cycle impact assessment* (LCIA) is defined as the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product/process system throughout the life cycle of the product/process. The LCIA is performed in consecutive steps including classification, characterization, normalization, and weighting. The LCIA phase also provides information for the life cycle interpretation phase, where the final environmental interpretation is made. In this study, only classification and characterization have been included in the LCIA part. In this study, the following impact assessment categories and indicators are used:

1. Primary energy resource use - renewable and non-renewable, MJ/functional unit (FU), (using net calorific values)
2. Global Warming Potential (GWP 100), kg CO_2 eq./functional unit (FU)
3. Eutrophication Potential (EP), kg phosphate eq./functional unit (FU)
4. Acidification Potential (AP), kg SO_2 eq./functional unit (FU)
5. Photochemical Ozone Creation Potential (POCP), kg ethene eq. /functional unit (FU)
6. Human toxicity [kg 1,4-dichlorobenzene eq./functional unit (FU)]
7. Terrestrial ecotoxicity [kg 1,4-dichlorobenzene eq./functional unit (FU)]
8. Marine aquatic ecotoxicity [kg 1,4-dichlorobenzene eq./functional unit (FU)]
9. Freshwater aquatic ecotoxicity [kg 1,4-dichlorobenzene eq./functional unit (FU)]

The above-mentioned impact assessment categories and indicators are used to calculate the environmental performance of the Hg decontamination process and to evaluate the cleaning method. In this study, both conventional environmental parameters and toxicological parameters from specific substances need to be evaluated. The conventional environmental parameters emanate mainly from the decontamination process while the toxicological parameters are needed to evaluate the environmental impact of the specific emissions (e.g. Hg) emanating from the use of dental amalgam at the clinics. There is thus an environmental "cost" also for the decontamination process. This environmental treatment cost must be weighed against a reduced emission of contaminating substances (e.g. Hg) from the use of dental amalgam. The question is how these overall effects look like in a system perspective where all effects are handled simultaneously.

5 The technical system for Hg separation and storage for dental clinics

In Sweden, amalgam is no longer used for dental treatments. However, there are still many patients with amalgam dental implants that were inserted before the phase out. which will also be the case for many years to come. When these patients come to the dentist, amalgam fillings may need to be removed and replaced with repairs of other material. During these treatments, amalgam waste is generated which needs to be disposed of. Since generations of patients with amalgam fillings will continue going to the dentist during their lifetime, the need of systems for amalgam separation may be needed for many years to come.

Figure 1 shows a schematic illustration of a system for separating and handling amalgam from dental clinics. The ingoing amalgam to the clinic contains the amalgam that enters the clinic via patients. The exact amount of amalgam that enters a dentist's chair per day is impossible to specify exactly since it depends on many factors; e.g. age and number of patients, dental filling and necessary dental treatment. In this project, the amount of amalgam entering the dental clinic was estimated to be about 2 g per day and dentist's chair.

It is also important to estimate the metal composition of the included amalgam. In one study[4], researchers measured the metal content and composition of 10 teeth with amalgam fillings. There was no information about the age of the amalgam fillings, but the mean values of eight measurements per fill varied in copper content from 1.5 % to 18.2 %, with the majority between 8 and 10 %. Silver ranged from 20 to 35 %, tin from 7 to 16.5 % and mercury from 39.6 to 64.7 %. It is difficult to find any relation between the metal levels, but it is remarkable that the filling with 1.5 % copper had a mercury content of 64.7 %.

A typical composition of dental amalgam, which has been used in the LCA model, is suggested as follows. Estimated density for amalgam is about 11.5 g/cm^3:

Mercury, Hg: 50 %
Copper, Cu: 10 %
Silver, Ag: 28 %
Tin, Sn: 12 %

At the dental clinic, the amalgam is released when the dentist removes or drills the amalgam from the patients' teeth. During this treatment, drilling is producing larger and smaller pieces of amalgam as well as fine-grained amalgam dust. These particles are flushed out when the patient flushes the mouth with water and spits into the drain of the dentist's chair. A smaller part of the amalgam is washed off from the drill and other dental tools in a sink or washing machine that is connected to an amalgam separator. Every dental clinic has a suction system that sucks out air, water and small dust particles of amalgam. Both the outgoing air and water pass an amalgam separator located either in the dentist's chair (dry system) or in the basement where several separators sit jointly for the entire clinic (wet system). The amalgam separators are replaced every year. However, some of the amalgam gets stuck in the sewage pipes before they reach the amalgam separator. The amount of amalgam that gets stuck there depends, among other things, on the slope of the pipes, the water flow in the pipe systems and the inner surface of the pipes. To prevent growth in the pipe systems, the pipe systems are regularly disinfected with sodium hypochlorite (NaClO). The growth of residues in the pipe system could also give rise to environments where formation of methylmercury could occur. For these reasons, the drainage system is cleaned at different intervals (e.g. every ten years, after a shut-down of a clinic, when a clinic is transferred to another dentist) in a so-called "Hg decontamination process". In this process, high pressure water washes the pipe systems internally and the formed wash water (Hg sludge) is collected in barrels for further treatment.

Air and water that pass-through amalgam-containing pipes get contaminated when in contact with mercury that either evaporates or gets into the aqueous phase. Mercury and other metals are then transported to the sewer system and evaporated

[4] Tandvårdsskadeförbundet (tf), Sweden. http://www.tf.nu/nyhet/kvicksilver-fran-amalgam/

mercury in air is emitted to the surrounding air. In this study, analyses of different metals have been carried out in outgoing water and mercury has been measured in the air outlet. Analyses have also been conducted on the various forms of mercury available in water (Hg(0), Hg(II), methylmercury (MeHg) and total Hg (HgTot)).

The sludge from the Hg decontamination process and the replaced amalgam separators are sent by truck to Medentex processing plant in Bielefeld, Germany. Usually, to separate Hg from the sludge, the sludge is vacuum distilled at 398°C leaving a residue of waste and a mix of metals, which is further processed elsewhere to extract and recycle metals (mainly Ag, Cu, Sn). The process at Medentex includes dehydration (distillation), disinfection and demercurisation. The water is removed by filtration/centrifuge and distillation. The remaining residue is heated up to 750°C during 5 days in order to evaporate all Hg. The formed Hg gases are cooled to condense Hg into liquid form which is then collected for transport by truck to its final deposition in an old salt mine. The exhaust gases from this treatment are cleaned with carbon filters, which also go to final deposition after use. Some Hg is however still emitted to air and waste water from the process at Medentex. For this project, information about outgoing Hg concentrations have been received. However, it was not possible to get estimates of outgoing flows and therefore no total emissions could be calculated. The total emissions have thus been estimated based on estimated flows.

The remaining dry part from the heat treatment includes other metals in the amalgam (Ag, Cu, Sn). These are sent to metal recovery and further sold on the open market. The recovery processes of these metals have not been further included in this study of Hg decontamination.

The amalgam-separators sent to Medentex are cleaned for being sent back to the dental clinic for reuse. The average lifetime of a separator is approximately 10 years (used 10 times), which means that ~10 % of the separators are replaced by new produced separators.

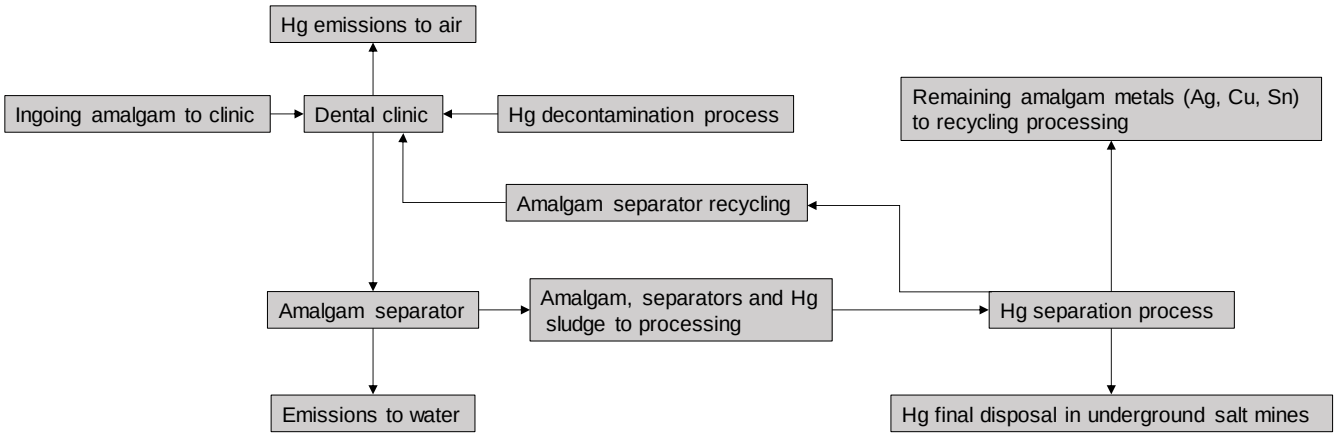

Figure 1 Schematic figure over the technical system for Hg separation at dental clinics in Sweden.

6 Data collection, measurements and system overview

An environmental and technical evaluation of the decontamination process (DC) was not possible without participating during the actual process. IVL was invited to participate during several DCs performed by SRAB. During the visits, IVL got acquainted with used methods of Hg removal and handling. By using a portable device for measuring gaseous mercury in air, IVL was able to monitor the release of Hg to air before, during and after the DC work. Hg in air was also measured in the premises of dental clinics during normal operation and at clinics after shutdown or in between hand-over to new owners. Complementing water samples were collected for comparisons and for speciation. For discretion, clinics are not presented by name or location.

6.1 Study visits

IVL did in total 15 study visits to 10 different dental clinics in Sweden and one visit to Medentex facilities in Bielefeld, Germany, where the collected Hg sludge is processed.

6.1.1 Dental clinics

A list of dental clinics visited by IVL is presented in Table 1. For discreation, the clinics are referred to as A-J. Concentrations of gaseous elemental mercury (GEM) in air was measured at all clinics and water samples were retrieved from eight clinics. Dental clinic D was visited three times for complementary measurements and tests. Clinics C, E and G were re-visited an extended time after DC for additional water sampling.

6.1.2 Medentex

IVL visited Medentex 2019-06-18 in Bielefeld, Germany together with PTJ and SRAB. During the visit, Medentex presented their business and gave a tour around their premises. The visit was valuable for getting acquainted with the process of

recycling and storing of mercury after decontaminations. The visit gave insight information into the process chain and provided information for the Life Cycle Assessment and the Cost Benefit Analysis.

Table 1 IVL's study visits to dental clinics A-J. All clinics are located in Sweden. DC = Decontamination process

Dental Clinic ID	Description	Date of visit(s)
A	Measurements during normal operation	2018-10-18
B	Operations paused due to DC	2018-11-08
C	Operations paused due to DC	2018-11-21 2019-03-20
D	Measurements during normal operation	2017-05-10 2018-12-03 2019-05-07
E	Operations paused due to DC	2019-02-12 2019-03-19
F	Measurements during normal operation	2019-02-12
G	Operations paused due to DC	2019-02-13 2019-03-19
H	Operations paused due to DC	2019-02-14
I	DC due to shut down of clinic	2017-11-28
J	DC due to shut down of clinic	2018-09-18

6.2 Data collection

6.2.1 Air measurements of Hg at dental clinics

Measurements of gaseous elemental mercury (GEM) in air was performed using a Lumex RA-915+ instrument, which uses Zeeman atomic absorption spectroscopy technique for detection. Zero corrections for baseline determinations are performed automatically by the instrument, optimally every 20 minutes of measurements. A coal filter that filters the air from mercury was used for baseline calculations. The detection limit of the instrument is 0.5 ng/m^3 and measurements can be obtained down to once per second. The internal pump of the instrument pumps about 10 L/min of air through the system and the obtained values are re-calculated to ng/m^3. Equipment used for detecting Hg-gas in air and water is shown in Figure 2.

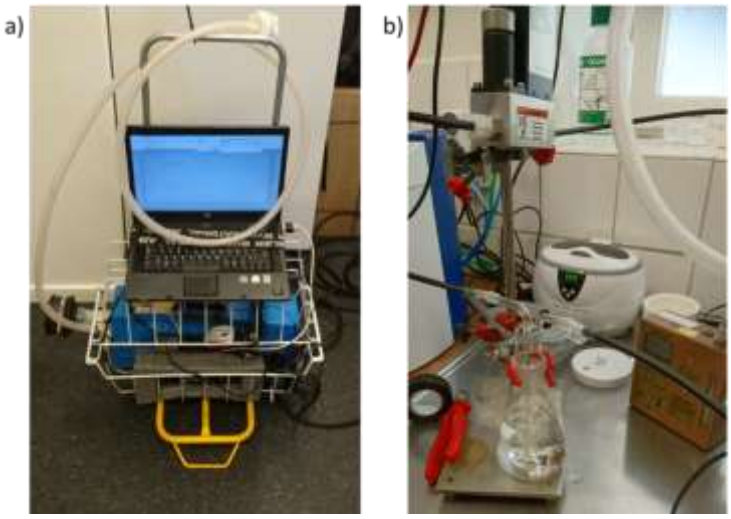

Figure 2 a) Lumex RA-915+ mercury analyzer with computer for data logging. b) Glass bottle with bubbler to measure dissolved gaseous elemental mercury in water samples.

6.2.2 Water sampling and analysis

A total of 29 water samples have been collected and analyzed for different forms of dissolved mercury in water. The motivation for water sampling is to evaluate if all kinds of mercury is filtered by the ASs or if there are forms of dissolved Hg that pass the filter to the outgoing wastewater. What has been analyzed is dissolved gaseous elemental mercury (DGM, Hg0), oxidized forms of mercury (Hg(II)), total mercury (all forms of dissolved mercury in the sample, HgTot) and methylated mercury (MeHg, $HgCH3^{+}$).

Water was sampled after the ASs either directly in the unit, if separator was installed in the dental chair (Figure 3a), or at the outlet to the wastewater system. Some clinics use a buffer tank which collects used water during a day of operation (Figure 3). At the end of the day, the vacuum system is shut down and collected water in the buffer tank is discharged to the sewage system. Water sampling at clinics using a buffer tank required a brief shut down of the vacuum system in order to obtain a water sample.

During DC, SRAB flush the pipes with high pressure water. The water is collected into 150 L barrels for further transport to SRAB's facilities in Växjö and further to Medentex in Germany for handling and Hg extraction. Mercury recovered from Swedish sludge is further transported to Herfa-Neurode in Germany for safe longtime storage. SRAB and/or Medentex normally take a water sample from the barrel for Hg analysis. For comparisons, IVL asked SRAB to take water samples from the barrel using the same method as for their analysis. The water samples collected by IVL were analyzed at the IVL laboratory in Gothenburg, Sweden.

The samples for analysis of Hg(II), HgTot and MeHg were collected in clean fluorinated bottles and transported in double zip-bags. All samples were handled and analyzed by IVL, according to the U.S. EPA standard reference methods 1630 and 1631 (EPA, 2001; EPA, 2002). Analysis methods are accredited by Swedac.

Figure 3 a) Water sampling point after an amalgam separator installed in a chair unit, b) Water sampling point after amalgam separators installed at the water outlet of a clinic.

6.2.2.1 Dissolved gaseous mercury (DGM)

Samples for DGM analysis were analyzed directly after sampling at the clinic. Water was sampled either directly into the analysis glass bottle, see Figure 1b, or into a clean fluorinated bottle for direct transfer to the analysis glass bottle. The analysis setup is shown in Figure 2b and Figure 4. The principle for DGM analysis was to purge air at 1 L/min through the water sample in the analysis bottle to degas the dissolved gaseous mercury into the outgoing air. The degassed Hg atoms from the sample were detected with the Lumex RA915+ instrument. The analysis result divided by the water sample volume obtained the DGM concentration in pg per litre sample. More information about the DGM analysis method can be found in e.g. Nerentorp Mastromonaco, 2016.

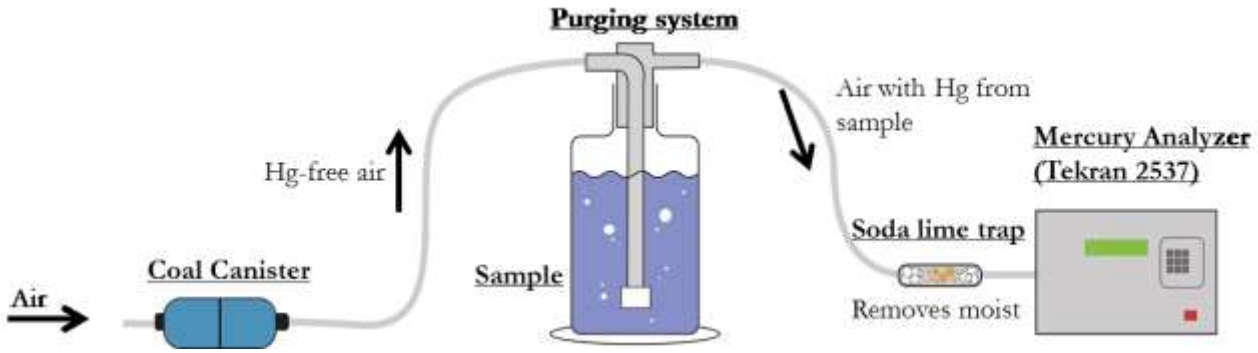

Figure 4 Principle of purging gaseous Hg(0), or DGM, in water samples for analysis. A Lumex RA-915+ mercury analyzer was used for analysis (not a Tekran 2537 as shown in this picture) (Nerentorp Mastromonaco, 2016).

Remaining samples for Hg speciation analysis were transported, divided and analyzed at the IVL laboratory for oxidized mercury species (Hg(II), for total mercury (HgTot) and for methylated mercury (MeHg).

6.2.2.2 Oxidised mercury, Hg(II)

For Hg(II) analysis, $SnCl_2$ was first added to the samples to reduce Hg(II) to Hg(0). The samples were then purged according to the principle presented in Figure 3. The degassed mercury was first preconcentrated on a gold trap, which was then heated up for analysis using a Tekran 2500 CVAFS (cold vapor atomic fluorescence spectrometer) mercury analyzer.

6.2.2.3 Total mercury, HgTot

All mercury in the water sample, including DGM, Hg(II), MeHg and Hg in amalgam particles were first oxidized by adding BrCl. In the oxidation process all forms of mercury are transferred to Hg(II). By adding $SnCl_2$, all now oxidized Hg in the sample reduces to Hg(0), which can be purged, preconcentrated on a gold trap and further analyzed with a Tekran 2500 Mercury detector CVAFS. The sample preparation and analysis were performed according to the EPA Method 1631 (EPA, 2002).

6.2.2.4 Methylated mercury, MeHg

Sample preparation and analysis were performed according to the EPA Method 1630 (EPA, 2001). At the IVL laboratory, the samples were separated through distillation, followed by ethylation in the water phase, separation through gas chromatography and analysis using a Brooks Rand model III CVAFS Mercury detector.

6.3 Analysis results

6.3.1 Air measurements

Gaseous elemental mercury (GEM) in air was often measured in all the premises of the dental clinics, including the entrance, reception, waiting room, toilet, staff premises, treatment rooms and in the pump and drainage room, which often was

located in the basement. Concentrations of GEM in air varied widely between different clinics and rooms, see Figure 5. For discretion, dental clinics are here referred to as clinic A-J. All measured GEM data are presented in Table 7 in Annex 1.

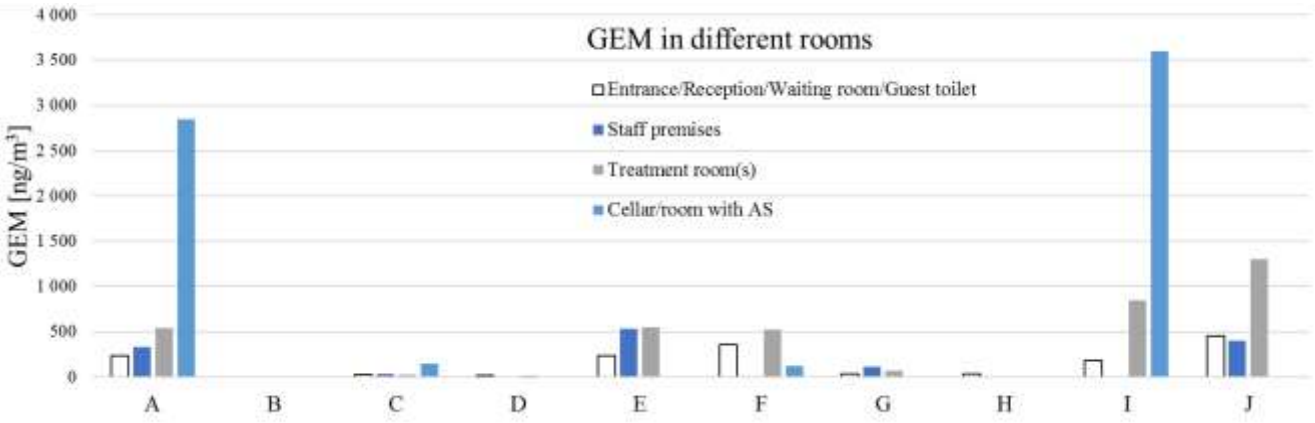

Figure 5 Average GEM (gaseous elemental mercury) concentrations in air measured at dental clinics A-J in different rooms of the premises before decontamination activities (DC). AS=Amalgam Separator.

When a DC was planned, IVL measured GEM in air before, during and after the cleaning process. At clinic C and H, concentrations of GEM were measured in the entrance, reception, waiting room and toilet and at clinics I and J, GEM was measured in the treatment rooms. Average measured GEM concentrations are presented in Figure 6, showing concentrations in air before, during and after DC. When SRAB is flushing the pipes using high pressure water, amalgam attached to the inner surface of the pipes flushes out with the water. In the process, air in the pipes containing GEM is also flushed out which causes an temporal increase in air concentrations of GEM, see Figure 6. This phenomenon was observed at all clinics where a DC was performed. Generally, the air concentrations of GEM in the premises decreased a short time after the cleaning and went back to previous background concentrations within an hour after DC.

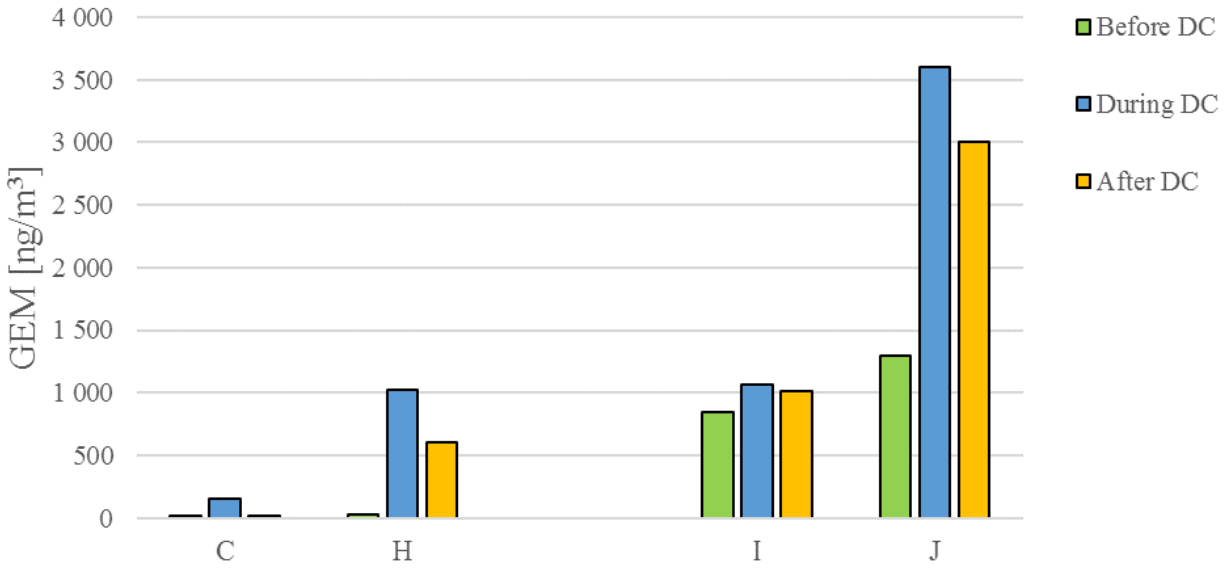

Figure 6 Average GEM concentrations measured in air before, during and after decontamination (DC) in the premises of dental clinics C and H (entrance, reception, waiting room, toilet) and clinics I and J (treatment rooms).

Air concentrations of GEM was measured at the outlet of the vacuum system to study how much mercury is emitted to the atmosphere from dental clinics. The results are presented in Figure 7.

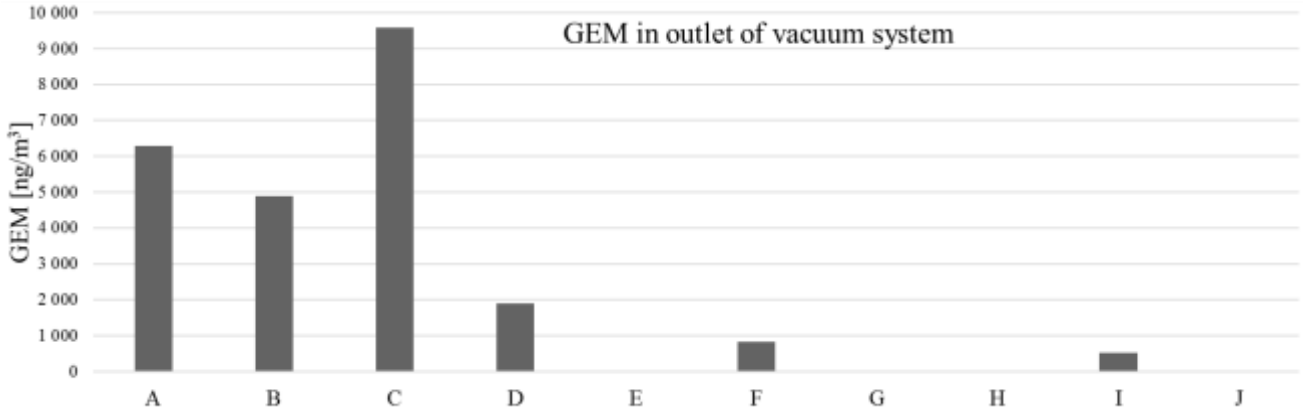

Figure 7 Average GEM concentrations measured at the outlet of the vacuum system, at dental clinic A, B, C, D, F and I, before decontamination.

6.3.2 Water samples

All collected samples are listed in Table 2. For discretion, dental clinics and samples are here referred to as ID numbers for clinics A-H. The laboratory results for all mercury analyses are presented in Table A1 in Annex 1 and in Figure 8.

Total mercury concentrations were highest due to that they represent all different kinds of mercury species present in the sample combined. In the waste barrels, all flushed water used to clean the pipes from mercury is collected, which resulted in the higher mercury concentrations found in samples B2, E4, F4 and H2 (Figure 5b).

Among the dissolved mercury species in water collected after ASs, Hg(II) showed the highest concentrations, especially true regarding samples collected from clinic C. In the waste barrels, Hg(II) concentrations were higher than the other dissolved mercury species at clinic B and H, however at clinic E4 and F4, methyl mercury was present in the highest concentrations.

This shows that methylation of oxidized mercury can occur in the pipe systems of a dental clinic. Methylation is partly a biologically mediated process, which is performed by certain bacteria. The reaction is more efficient in oxygen poor environments (Hu et al., 2013). The occurrence of methyl mercury in the samples indicate that methylation is possible somewhere in either the pipe system or in within the oxygen poor ASs.

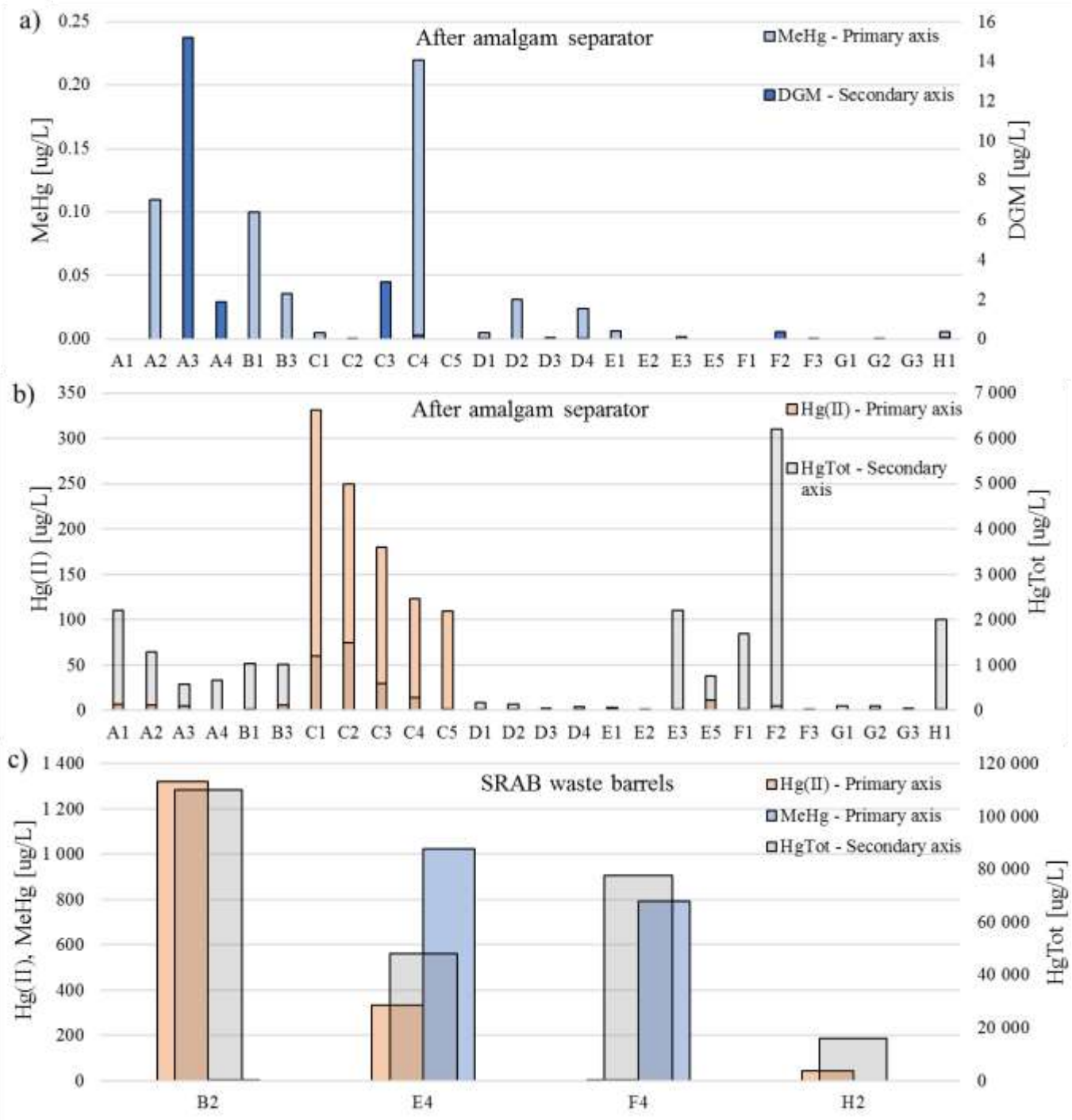

Figure 8 Analysis results of the 30 samples (Table 2) taken and analyzed by IVL. Samples were analyzed for dissolved gaseous mercury (DGM), oxidized mercury (Hg(II)), methylated mercury (MeHg) and total mercury (HgTot, secondary axis). In a) and b) the results of the samples taken after the amalgam separator (AS) are presented, in c) the samples taken by SRAB from the waste barrels and analyzed by IVL are presented.

Table 2 List of samples taken and analyzed by IVL from eight different clinics (A-H). DC = Decontamination, AS = Amalgam separator.

Sample ID.	Sample description
A1	After AS in chair
A2	Same but after flushing system a couple of times
A3	After AS in chair
A4	After AS in chair
B1	After AS in cellar, before DC
B2	From SRAB waste barrel. Sample taken by SRAB
B3	After AS in cellar, after DC
C1	After AS in cellar, before DC
C2	After AS in cellar, before DC
C3	After AS in cellar, during DC
C4	After AS in cellar, after DC
C5	After AS in cellar, 4 months after DC
D1	After AS in cellar, no DC
D2	After AS in cellar, no DC
D3	After AS in cellar, no DC
D4	After AS in cellar, no DC
E1	After AS in cellar, one day before DC
E2	After AS in sink, cold water
E3	After AS in sink, after flushing 1 L of cold water
E4	From SRAB waste barrel. Sample taken by SRAB
E5	After AS in cellar, 1 month after DC
F1	After AS in chair, room 1
F2	After AS in chair, room 2
F3	After AS in chair, room 3
F4	From SRAB waste barrel. Sample taken by SRAB
G1	After AS in cellar, before DC
G2	After AS in cellar, after DC
G3	After AS in cellar, 1 month after DC
H1	After AS in chair
H2	From SRAB waste barrel. Sample taken by SRAB

6.3.2.1 Before and after the decontamination process

For comparison, water samples for HgTot analysis were taken before, during and directly after DC at selected clinics, see Figure 9. Two clinics were revisited one month after the DC process and one clinic was visited four months after. At clinics B, C and G a clear reduction in HgTot concentrations was observed in water samples from before to after the DC process. At clinic C, the Hg concentrations showed a clear reduction from before to 4 months after DC. Sample E1 was not taken by IVL and cannot be directly compared with sample E5. This limited study indicates that removing Hg from the pipes at a dental clinic could have a positive impact of

reducing the amount of dissolved Hg in the water passing the AS to the wastewater and leaking into the environment.
SRAB performed separate water sampling and analysis of outcoming water after the AS before and after DC at 16 dental clinics. The sampling and analysis techniques used by IVL and SRAB differs and are not directly comparable. Although, in average the reduction of HgTot concentrations in water sampled before and after DC showed similar results with an average decrease of 80-100 % in concentration, see Table 3.

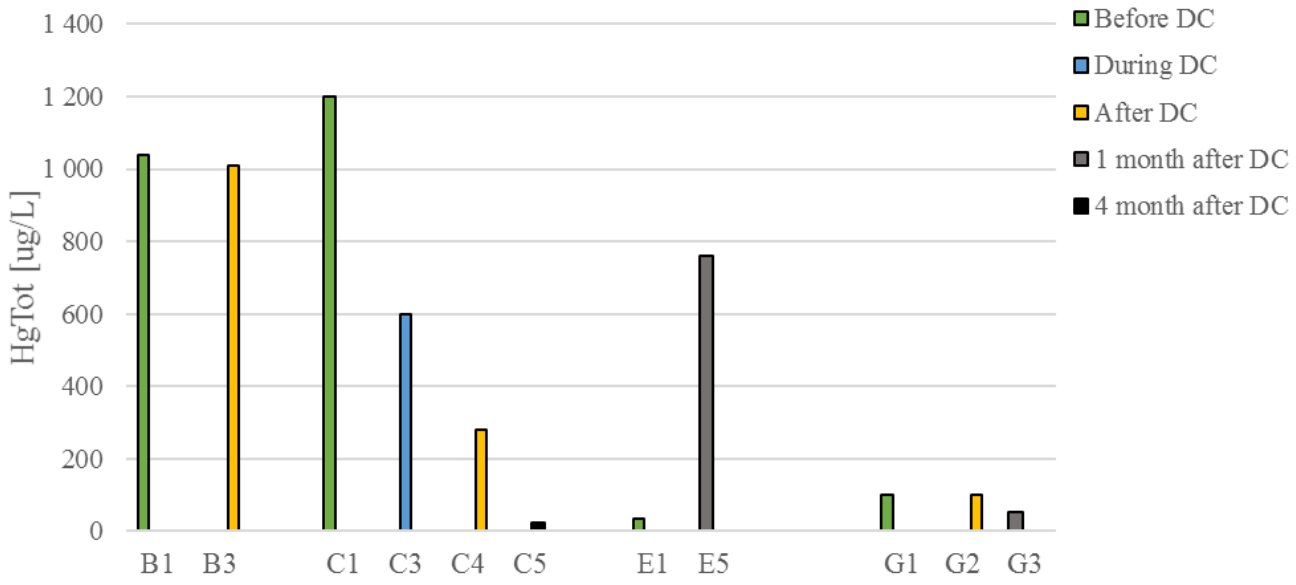

Figure 9 HgTot concentrations in IVL samples taken before, during and after the decontamination process (DC). Compared to Hg concentrations in water sampled one or four months after DC.

Table 3 Comparisons of average Hg concentrations in water samples before and after the decontamination process (DC). Average concentrations in samples from Sweden Recycling AB (SRAB) are calculated from samples from 16 different dental clinics. IVL samples are averaged from 3 dental clinics (clinic E is excluded).

	Before DC	After DC	Percentage difference
SRAB samples	3800	490	-87 %
IVL samples	780	30	-96 %

6.4 Potential environmental risks

The majority of Hg used within dentistry is expected to eventually leak into the environment (atmosphere, surface water, groundwater and soil), if not taken care of. When including the whole life cycle of dental amalgam, global total emissions of Hg to the environment was estimated to 180-240 tonnes/year (UNEP, 2016).

6.4.1 Emissions to air

The air concentrations of Hg (GEM) in the atmosphere is typically between 1-10 ng/m^3, with higher concentrations in urban areas, closer to emission sources. The global atmospheric emissions related to the use of dental amalgam was estimated to approximately 50-70 tonnes/year, including cremation (UNEP, 2016). In EU, the Hg pollution from dentistry is estimated to 16-23 tonnes/year (BIO Intelligence Service, 2012). In proportion, the total anthropogenic emissions of Hg to air was in 2015 estimated to around 2220 tonnes (GMA, 2019).

Cremation is expected to be the largest contributor to Hg emissions to air related to dentistry. However, handling of amalgam fillings at dental clinics should result in small contributions to Hg emissions to air. During study visits to dental clinics, IVL measured the Hg concentration in outgoing air from the vacuum system. A flow meter was used to measure the flowrate of ventilated air, in order to estimate the amount of total emissions of Hg from dental clinics. The air flow and outflow Hg concentrations varied significantly. The extreme values of measured flow and concentrations, and the estimated usage of dental vacuum systems in Sweden are summarized in Table 4 below.

Table 4 Average air concentrations of gaseous elemental mercury and estimated yearly emissions from dental clinics.

Measured air flow vacuum system [L/min]	760 - 1000
Measured Hg air concentrations outlet [ng/m^3]	830 - 9600
Number of dentists in Sweden	9000[5]
Estimated usage of vacuum system per clinic [hours/day]	0.1 - 8
Estimated emissions of Hg to air per dental chair per year [g/chair/year]	0.01 - 0.07
Estimated emissions of Hg to air from dental clinics in Sweden [kg/year]	**0.01 - 9.4**

By using the extreme values of measurements and estimations, the estimated Hg emissions to air from dental clinics in Sweden, is probably less than 10 kg/year.

[5] https://tandlakarforbundet.se/ny-statistik-om-tandlakare/

6.4.2 Emissions to water

Amalgam separators (ASs) have been in use in Sweden since 1979 and has been reported to have a Hg removal efficiency of 75-95% (Jacobsson-Hunt, 2007; Hylander et al., 2006; BIO Intelligence Service, 2012). ASs are mainly based on sedimentation (sometimes combined with a filter). The sedimentation principle bases on that larger heavier amalgam particles in the incoming water, sink to the bottom and are prevented to enter wastewater. Sometimes several ASs are installed in series to increase efficiency of capture. The weakness of this kind of separator is that they are sensitive to abrupt peaks in water flow passing through, that can flush out collected particles. Therefore, some dental clinics have a buffer tank that collects water during a working day and provides a steady low water flow (Hylander et al., 2006). ASs are efficient in collecting amalgam particles. However, no studies have yet presented the efficiency of collecting dissolved species of Hg in the waste water. In this study, the aim was to investigate how much Hg still leaks through the AS, and what kind of Hg species that are emitted from dental waste water.

Water sampling and analyses performed by IVL showed that some Hg from dental clinics is still discharged to wastewater, despite the use of ASs. Analyze results varied greatly from different clinics and time of sampling, which has also been observed in other studies (e.g. Gahnberg et al., 1993). The sampling technique used by IVL is therefore not representative to be used for calculating average Hg emissions from dental clinics to wastewater. Though for comparison, the extreme values of the IVL analyze results in water samples are summarized in Table 5.

Table 5 Average measured HgTot concentrations in water samples taken after the amalgam separators (ASs). Estimated Hg emissions from dental clinics per year.

Measured HgTot concentrations in water after AS [mg/L]	0.011 - 6.2
Estimated water use per dental chair [L/day]	40[6]
Estimated emissions of Hg to water per dental chair per year [g/chair/year]	0.1 - 56
Estimated emissions of Hg to water from dental clinics in Sweden [kg/year]	**0.9 - 500**

A rough estimate using the extreme values of acquired HgTot concentrations in outgoing water, the yearly emissions of Hg to water from dental clinics in Sweden, despite the use of ASs, could be as high as 0.5 tonnes/year.

The global emissions of Hg from dental clinics to surface water, groundwater and soil is approximately 35-45, 20-25 and 75-100 tonnes/year, respectively (UNEP, 2016). In relation to these numbers, the Hg emissions from Swedish dental facilities

[6] According to SRAB, Praktikertjänst and Medentex

are insignificant. However, the annual Swedish limit of allowed released amount of Hg from dental clinics is set to 5g Hg/chair/year (Hylander et al., 2006). During a test of the efficiency of four different brands of ASs by Hylander et al. (2006), the average outgoing HgTot concentration after the AS was measured to 1.5 mg/L. The calculated Hg emissions to water from the different ASs varied from 0,016 to 3,5 g/chair/year, which would result in a total yearly emission of 0,1 to 32 kg from Swedish dental clinics (Hylinder et al., 2006).

IVL's rough estimates from limited individual water samples are not representative enough to make an accurate national estimate of total Hg emissions to water from Swedish dental facilities. A development of a representative sampler that can account for the daily variations in water concentrations is needed.

6.5 Potential health risks

Mercury is a toxic pollutant and people handling Hg daily is at greater risk of getting poisoned. The overall risk is depending on the likelihood of exposure to high Hg levels and how fatal the consequences are if exposed.

6.5.1 Exposure to Hg in air

Hg concentrations in indoor air could be elevated in areas where Hg products are handled. This study shows that the average indoor GEM concentration in dental facilities during normal operation is about 200 ng/m^3, with higher average concentrations in the treatment rooms (~500 ng/m^3). Compared to outdoor background concentrations, the indoor Hg levels at dental clinics are on average about 100 times higher.

Gaseous elemental mercury is volatile and can, when inhaled, be absorbed via the lungs. When exposed to high concentrations, GEM could cause severe damage to several organs in the body, causing for example respiratory failure, cardiac arrest and could lead to death. GEM is also targeting the central nervous system and symptoms of Hg poisoning have been observed during all durations of exposure or/and due to an increase in concentration. Symptoms of GEM poisoning include insomnia, memory loss, headaches, tremors, neuromuscular changes, among others. When exposed to GEM in air during long-term, it may lead to changes in renal function (WHO, 2003).

Acute effects of inhaling elemental mercury in air has been observed at concentrations in the range of 50 000 to 350 000 ng/m^3 (WHO, 2005). If exposed to one to three million ng/m^3 during a few hours could cause irritation and destruction of lung tissue. Longtime exposure of GEM values above 100 000 ng/m^3 is expected to result in classical signs and symptoms of poisoning (WHO, 2005).

The occupational exposure limit for inhaling Hg(0) in air is set to 20 000 ng/m^3 by the World Health Organization (WHO). This number is determined by several studies showing that this average exposure, extrapolated from a 8h working day, 40h

working week, led to slight or non-clinically observed effects among exposed workers (WHO, 2003).

To test how high GEM concentrations employees and patients at a dental clinic occasionally can be exposed to, a test was performed by IVL during one of the study visits. The aim of the test was to study how high the GEM concentrations could be while drilling in an amalgam filling. The Lumex RA-915+ instrument was used for the measurements (Figure 2a). The test was carried out in a closed treatment room. The drilling in an amalgam filled extracted tooth was performed by a dentist, using conventional dental drills, see Figure 10. GEM measurements were performed by IVL before, during and after the drilling. The complete removal av the amalgam filling took approximately a minute and resulted in high occasional concentrations of over 35 000 ng/m^3, see Figure 11.

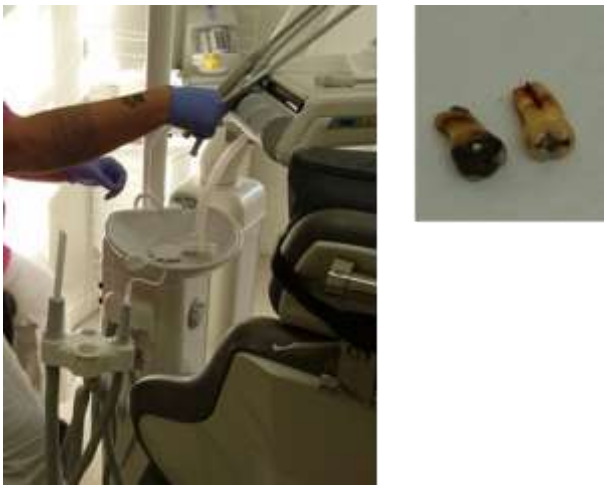

Figure 10 Test setup of drilling in an amalgam filling in an extracted tooth at a dental clinic.

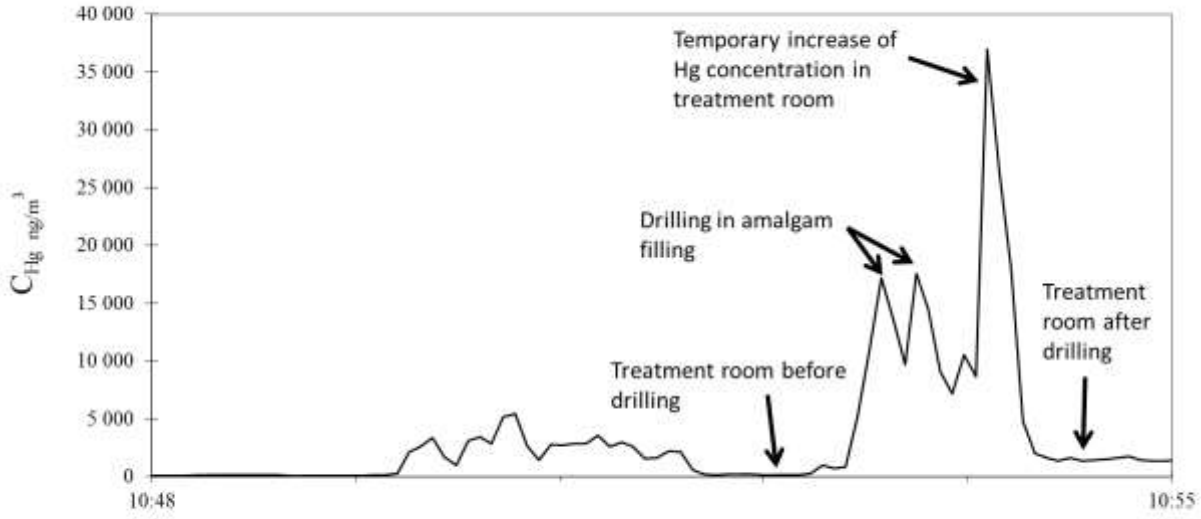

Figure 11 Hg(0) concentrations in air measured before, during and after drilling of an amalgam filling (not on a patient) measured with the Lumex RA-915+ instrument.

The test does not represent a real situation of drilling enclosed inside the mouth of a patient, where suction is working properly and emission to the surrounding air probably is limited. Though, the test shows that occasional high GEM concentrations can occur during handling of an amalgam filling. An evaluation of risk shows that staff and patients visiting the premises without being in contact with amalgam do not expose themselves to harmful concentrations of Hg in air. Although the likelihood of exposure is high during the visit, there were normally no harmful Hg levels in air in the premises. Patients visiting the dentist occasionally poses the lowest risk for harmful Hg exposure. There are no recordings of that these low Hg values pose any risk to people staying in the premises during longer periods of time.
The drilling test shows that during drilling of an amalgam filling, the air concentrations of Hg in the room occasionally can exceed the recommended threshold 8h-average value of 20 000 ng/m^3. However, Hg concentrations during the test did not exceeding the levels of observed effects, which means a probable low risk for patients. Though, complementary measurements during an 8 h working day are necessary to draw any conclusions about the risks for dentists handling several dental fillings per day. The same apply for workers performing DC at dental clinics who are exposed to high levels of elemental Hg in air which is released when flushing and cleaning the pipes.

6.5.2 Exposure to Hg in water

Ingesting inorganic mercury species may have toxic effects, affecting mainly the kidneys, but also the reproductive system. For total mercury in drinking water, the WHO guideline value is set to 1 µg/liter. The naturally occurring levels of mercury in the groundwater and surface water are typically less than 0.0005 mg/liter (WHO,

2005). The concentrations of Hg in water samples taken at several dental clinics show higher concentrations than the guideline value, see Table 8 in Annex 1. Though, the likeliness of Hg exposure is insignificant and pose no danger.

7 Life Cycle Assessment (LCA) information

In this chapter the LCA system used in this project is introduced.

7.1 LCA model and system boundaries

7.1.1 Overview

In the LCA model, a system model has been developed that includes all the parts of a decontamination process at a dental clinic. This project includes an investigation of the environmental consequences of decommissioning and decontamination of mercury at dental clinics. The LCA model thus includes those parts that directly relate to this settlement, including the dental clinic itself and its activities to continuously collect Hg (amalgam) during normal operations. Also included are the special activities that are performed to clean the clinic from Hg as well as the activities related to the final disposal of the Hg waste. Figure 12 presents the LCA model and its various parts. The entire model has been divided into three different parts which are;

- Dental clinic: including normal operations with normal handling of dental amalgam and mercury (blue).
- Hg decontamination process: containing the process of Hg remediation at the dental clinic and the use of amalgam separators (red).
- Cleaning sludge treatment and Hg storage: containing the reprocessing of amalgam sludge and final storage of Hg (green).

The LCA model is a dynamic and flexible model where different parts can be varied. To compare the above system for managing Hg at dental clinics, which is used in Sweden today, we have also used the model to analyze some other alternative systems. These systems are to use only amalgam separators and a final storage of amalgam in Sweden as well as a reference system without any mercury cleaning or amalgam separation where all Hg goes directly to the recipient.

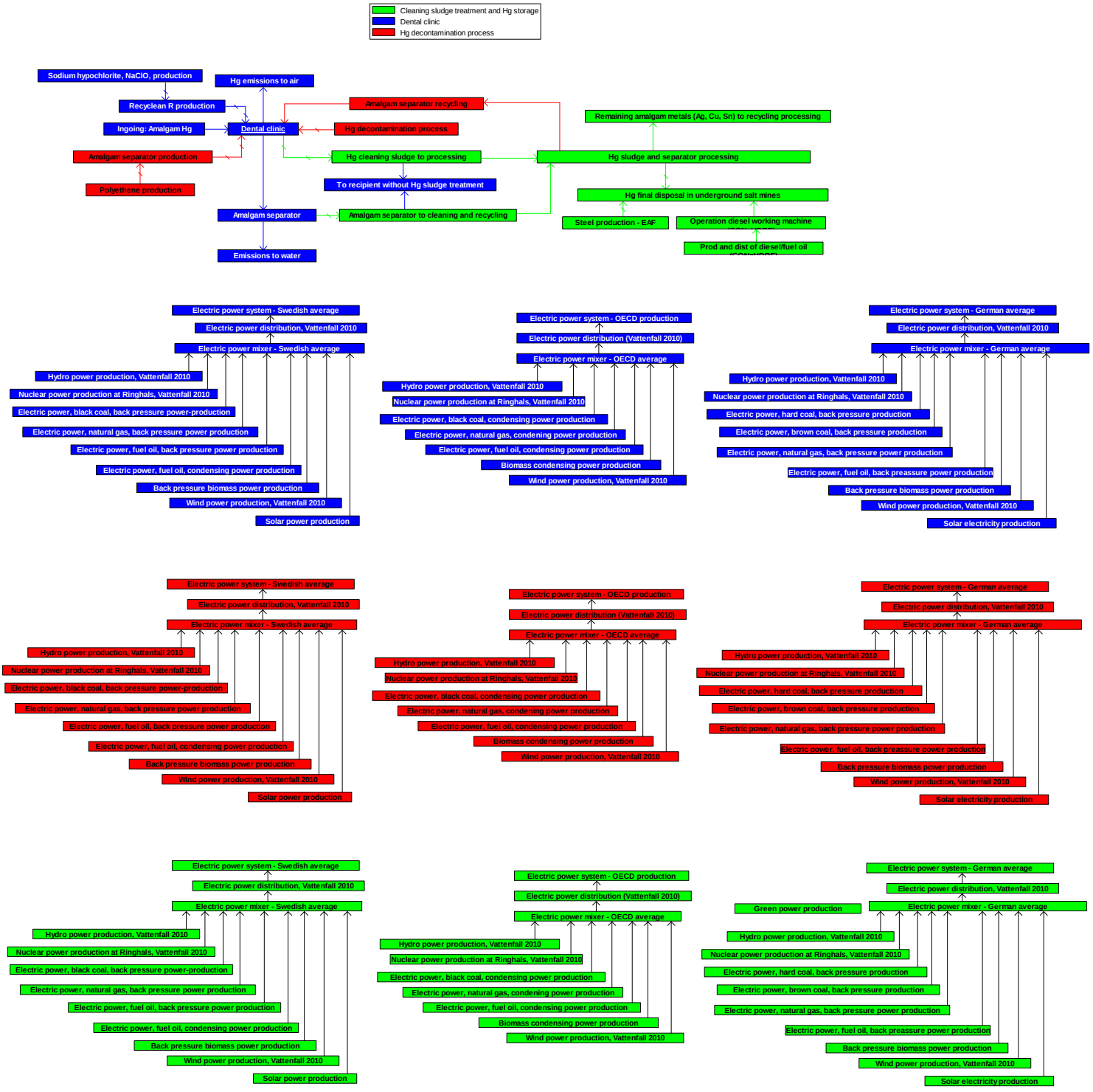

Figure 12 Life cycle assessment model of the amalgam and Hg decontamination system for a dental clinic. The figure can be difficult to read as a print-out but can easily be read enlarged at the screen. Dashes over the flow arrows indicate a transport in the flow.

Below, the different parts of the system are presented and described.

7.1.2 Dental clinic

The module "Dental clinic" with emission modules for air and water as well as the amalgam separator module, contains the information that has been used to model the activities at the clinic. The calculations are based on one dental chair used during one day of operation, having 12 patients per chair and day. The number of working days has been set to 226 per year and chair. Estimated amount of amalgam is 2g per chair and day. Hg cleaning with the Hg decontamination process has been set to each 10 years. The main energy use for Hg removal at the clinic is electricity to the dental suction system (used value is 17.28 MJ electricity for vacuum/filter for one day and one chair). The amount of sodium hypochlorite (NaClO) is estimated at 0.5 dl Recyclate R (5.23 % NaClO) per dentists' chair and workday and 0.25 dl Recyclate R per workday for tool cleaning separation. For the ASs, 10% are assumed to come from new production as injection molding of polyethene.

Measurements have also been conducted on the emissions to air and water of the various forms of mercury available (Hg(0), Hg(II), methylmercury and also total Hg(HgTot)). These emission values have been used in the LCA model. The emissions are thus average values of a limited number of specific measurements at dental clinics.

7.1.3 Production of amalgam separators

No specific data from amalgam separator production have been available for the project, therefore general data have been used. The amalgam separator production is modeled by combining injection molding and production of polyethene. The calculations assume an injection molding process of polyethene plastic. The injection molding machines are driven by electricity. An average electricity consumption for plastics and a low production rate (low efficiency) have been used for the estimation. An electricity use of 1.47 kWh/kg plastics (5.3 MJ/kg plastics) has been assumed[7]. For the polyethene production, general LCA data from Plastics Europe have been used. The LCA data for LDPE (Low Density Polyethylene) has been used, which contains the production of polyethylene plastics (LDPE). Recovered energy was calculated as a reduction of fuel oil use. Main gross raw material was used where data include production and feedstock energy. A truck transport of 500 km (one way) for both the transport of amalgam separators from the manufacturer to the dental clinic and for the transport from the polyethene producer to the manufacturer of amalgam separators.

[7] Elduque A., Elduque D., Pina C., Clavería I., Carlos Javierre C., Electricity Consumption Estimation of the Polymer Material Injection-Molding Manufacturing Process: Empirical Model and Application. Materials 2018, 11, 1740; doi:10.3390/ma11091740.

7.1.4 Production of sodium hypochlorite (NaClO)

Sodium hypochlorite is often used in ordinary cleaning/disinfection products and is prepared from chlorine gas (Cl_2) and sodium hydroxide (NaOH), which in turn is electrochemically prepared from electrolysis of NaCl. Sodium hypochlorite can be prepared by absorbing chlorine gas in a hot solution of sodium hydroxide in water according to the formula:

$Cl_2 + 2NaOH \rightarrow NaCl + NaClO + H_2O$

The data for the electrolysis is obtained from the BREF Best Available Techniques (BAT) Reference Document[8]. Data for the membrane technique was used. Electricity used for the Cl_2/NaOH production was estimated to 2.650 kWh/kg Chlorine and 10 MJ electricity/kg NaClO. A truck transport of 500 km (one way) for both transport of NaClO from the manufacturer to the producer of Recyclean R and for the transport from the producer of Recyclean R to the dental clinic.

7.1.5 Hg decontamination process

The DC process is a high water pressure cleaning of the drain pipes at the dental clinic, usually from the chair to the amalgam separator in the basement, at least for the wet separation processes. The electricity use for the cleaning process has been estimated to 3.6 MJ per cleaning process at a dental clinic. The washing water from the pipe cleaning is collected in plastic barrels for further transport to Hg processing in Germany. There is also a truck transport connected to each cleaning. These transports are from Växjö in Sweden to each individual dental clinic anywhere in Sweden. Sometimes, the decontamination actions are combined for several dental clinics in proximity of each other. An average transport distance (one way) has been estimated to 100 km.

7.1.6 Amalgam separator recycling

The amalgam separators are recycled back to the dental clinics from the cleaning process at Medentex in Bielefeld, Germany. The return transport for the Hg sludge transport is used, so there is no extra transport.

7.1.7 Hg sludge and separator processing

The collected Hg sludge from the decontamination process and the used amalgam separators are transported by truck to the mercury reprocessing plant in Germany. A truck transport of 808 km (one way) is included in the LCA model. This transport is carried out between Växjö in Sweden and the Medentex facility in Bielefeld, Germany. This transport is carried out about once a month. The process is described in Chapter 5. The total energy use for this process is 0.29 kWh electricity/kg amalgam (1.044 MJ electricity/kg amalgam). The electricity is generated by solar cells and

[8] BREF Best Available Techniques (BAT) Reference Document for the Production of Chlor-alkali (2014).

geothermal heat by a heat pump. A substantial amount of electricity is used for the production of solar cells and that energy is, in this case, assumed to be covered by wind power, which can be an underestimation of the real emissions. The Hg concentration in outgoing water has been obtained as 0.01 mg/litre and in outgoing air to 0.02 μg/m^3.

7.1.8 Hg final disposal in underground salt mines (e.g. Herfa-Neurode, Kassel, Germany)

The obtained metallic mercury from the Hg process is stored for all future in an old salt mine in Germany (in this case Herfa-Neurode, Kassel, Germany). The materials to be stored are transported by truck from Bielefeld to Kassel, a distance of 137 km (one way). Steel containers are assumed to be used for the storage. There are also internal transports in the mine e.g. elevators and forklifts. Both electric and diesel driven vehicles are used. A 50% / 50% transport case is assumed. The internal transport in the mine is estimated to 2 km+loading+elevator. The energy use for the internal transports has been set to 0.006 MJ electricity/kg Hg and 0.011 MJ diesel/kg Hg based on theoretical calculations. German average electric power production has been assumed for the mine. The mine will be closed when full, so no future energy consumption is expected.

7.1.9 Remaining amalgam metals (Ag, Cu, Sn) to recycling processing

When the mercury is removed from the amalgam, there will be a residue consisting of the remaining metals (Ag, Cu and Sn). There are several processes, both hot and wet, to separate these metals to recover the pure metals. These processes are complex and require energy and other resources. The question is how the energy and environmental performance is for these processes compared to virgin metal production from ore or recycling production from collected pure metals. Today, there is a metal recovery process that recover the pure metals from the residue for resale on the open market. However, there is no available information about this process. These processes are also outside the scope of this project and this project has therefore not further analyzed these processes.

7.1.10 Transport data used

Life cycle inventory data have been calculated for a heavy truck used for the transports. Data from the NTM database[9] have been used. Data for pre-combustion of the fuel has also been included in this module. In Table 6, the inventory data for the transports are presented.

[9] NTM (Nätverket för Trafik och Miljö) database and calculator.

Table 6 Inventory data for the truck transports used in the LCA model. The data include also pre-combustion emission (e.g. production of the diesel fuel).

Inputs			**Outputs**		
Primary energy resources - non renewable			**Emissions to air**		
Crude oil	0.57	MJ/(km*tonne)	CO (air)	6.50E-05	kg/(km*tonne)
			CO_2 fossil (air)	0.041	kg/(km*tonne)
			HC (air)	8.00E-05	kg/(km*tonne)
			NO_X (air)	0.0007	kg/(km*tonne)
			Particles (air)	1.60E-05	kg/(km*tonne)
			SO_2 (air)	1.00E-05	kg/(km*tonne)

7.1.11 Electricity production data

In the LCA model, there are three different electricity production data which are used to supply the different modules with a specific electricity:

- Swedish average production mix from the grid (mix for year 2017).
- OECD average production mix (mix for year 2016).
- German average production mix from the grid (mix for year 2018).

The electricity supply is divided and presented in the different process areas (different colors). The use of electricity production for the different processes are shown below:

Process module	**Electric power production mix**
Scenario 1	
Amalgam separator production	OECD average production mix
Hg decontamination process	Swedish average production mix
NaClO production	Swedish average production mix
Dental clinic	Swedish average production mix
Hg sludge and separator processing	Specific green power production
Salt mine storage	German average production mix
Scenario 2	
Dental clinic	Swedish average production mix
Amalgam separator production	OECD average production mix
Swedish storage	Swedish average production mix
Scenario 3	
Dental clinic	Swedish average production mix

The main electricity LCA data are from Vattenfall LCA/EPD[10] covering hydro power, nuclear power and wind power. Remaining electricity data are from combustion data for the national reporting (coal, oil and natural gas combustion).

7.1.12 Model modifications for scenario 2 – only amalgam separator

In this scenario, only an amalgam separator is used to remove the amalgam from the wastewater. The amalgam separator is changed every year in the same way as in scenario 1, and the life expectancy is also here about 10 years, after which it is replaced with a new one. When replacing amalgam separators, these are washed in place and separated amalgam is taken care of and shipped to a final repository in Sweden. A truck transport of 500 km one way with no return transport has been used for this transport. From the chemical analyzes performed in this project, it could be concluded that there is a certain risk of formation of methylmercury in the separator that could be released during washing. This is an aspect that needs to be investigated in more detail in a technical application.

7.1.13 Model modifications for scenario 3 – no amalgam or Hg cleaning

In the model, there is also a module "To recipient without Hg sludge treatment" which is used for a reference base case to compare a situation without Hg cleaning. In this scenario, no amalgam separator or Hg decontamination process exist. No cleaning sludge treatment or Hg storage exist either, but the amalgam waste goes directly to the recipient. Eventually, it can be trapped in the wastewater treatment plant and found in the sludge as a toxic pollutant that can leak out to the recipient if the sludge is used or stored in an improperly way.

7.2 Functional unit for the LCA model

The functional unit (FU) should reflect the function that it intends to analyze. In order to make it possible to draw more general conclusions and be able to transfer the result to corresponding activities in other countries, we have chosen to define the functional unit as: **one dental chair for one year of operation (226 working days)**.

[10] Vattenfall AB GENERATION NORDIC Certified Environmental Product Declaration, EPD® of electricity from Vattenfall´s Nordic Hydropower, UNCPC Code 17, Group 171 – Electrical energy, EPD S-P-00088 2008-10-31, version 1.1 revised 2010-02-15.
Vattenfall AB Nuclear Power, Certified Environmental Product Declaration EPD of Electricity from Ringhals Nuclear Power Plant, S-P 00026, 2010-12-16, UNCPC Code 17, Group 171 - Electrical energy
Vattenfall wind power, Certified Environmental Product Declaration EPD® of electricity from vattenfall´s wind FARMs, UNCPC Code 17, Group 171 – Electrical energy, S-P-00183, 2010-02-01.

8 Results from the LCA model scenarios

All results are presented per functional unit i.e.: **one dental chair for one year of operation (226 working days)**.

8.1 Scenarios used for the analyses and applied by the LCA models

In order to analyze the results of the LCA models, one needs to determine the conditions that will apply to the model runs. This study primarily analyzes how the current system for managing Hg at dental clinics works in Sweden. To set this function in relation to other alternative management methods, additional reference scenarios are also needed as a comparison. In this case, we have chosen to compare with a reference system completely without Hg cleaning or amalgam separation. In addition, we have chosen a further alternative that represents a simplified amalgam separation and final deposition alternative. The technical details and conditions are described in the technical description of the report. The selected scenarios are:

- **Scenario 1:** Mercury handling with Hg decontamination, Hg processing and final Hg storage representing the main handling system of today in Sweden.
- **Scenario 2:** Mercury handling with only amalgam separation and final storage of amalgam in Sweden.
- **Scenario 3:** Reference case with no mercury or amalgam handling. The amalgam from the dental clinics will go directly to the recipient.

8.2 Scenario 1: LCA results with Hg decontamination, Hg processing and final Hg storage (today's system in Sweden)

Most of the processes used in the system include the use of electricity and transport by diesel vehicles. These constitute an important aspect together with the emissions from the amalgam, and especially the emissions of mercury in its various forms. The result presentation shows the results of the different impact categories from the entire system, broken down by the different process parts and certain specific emissions. The metal emissions and their effects are mainly shown by the results of the toxicity calculations.

Figure 13 shows the emissions of mercury from the various parts of the system. As the figure shows, most of the emissions come from the dental clinic itself. Here, these are mostly emitted as particulate mercury to water and only minor amounts of dissolved gaseous mercury (DGM), Hg(II) and methyl mercury. Emissions to air is mainly as elemental mercury, Hg(0).

Figure 14 shows the use of primary energy resources in the system. As can be seen, it is the dental clinic's suction system that constitutes the largest energy use. This

entails a consumption of electricity and in this case, Swedish average production mix has been used, which is largely composed of hydropower, nuclear power and wind power, which has low greenhouse gas emissions such as fossil-based CO_2.

This also explains the results for the Global warming potential (GWP) shown in Figure 15. As can be seen, the contributions from the dental clinic are relatively low, while the relative importance for "Hg decontamination process" and "Cleaning sludge treatment and Hg storage" has increased. This is mainly due to higher use of fossil fuels for e.g. trucking.

The eutrophication and acidification potential shown in Figure 16 and Figure 17 also exhibits the same emission pattern, as emissions are often formed from a combustion process of some kind. The emissions here are mostly NO_X, SO_2 and COD (chemical oxygen demand).

For Photochemical ozone creation potentials (POCP), shown in Figure 18, the formation is more complex as POCP is formed from hydrocarbons, NO_X and sunlight in combination. The result is based on a model calculation, which then also represents a specific uncertainty. Since the exact formation of POCP depends on ambient conditions, the formation cannot be calculated precisely. However, the relative relationship between different processes compared with the same POCP method would appear to be significantly less uncertain and give a relatively good picture of reality.

Figure 19 to Figure 22 show the values of Human toxicity, Terrestrial ecotoxicity, Marine aquatic ecotoxicity and Freshwater aquatic ecotoxicity. The results are shown in kg 1,4-dichlorobenzene equivalents per functional unit. As can be seen from the figures, it is mainly the metal emissions from the amalgam and especially mercury in its various forms that contribute. It should be noted that we used toxicity factors intended for Hg(II) also to Hg(0) when elemental mercury is converted in nature to preferably Hg(II). This can eventually cause some overestimation of the toxicity.

Figure 23 shows an overview of all analyzed impact categories. Here you can see the percentage contributions of the different process parts to the respective impact category.

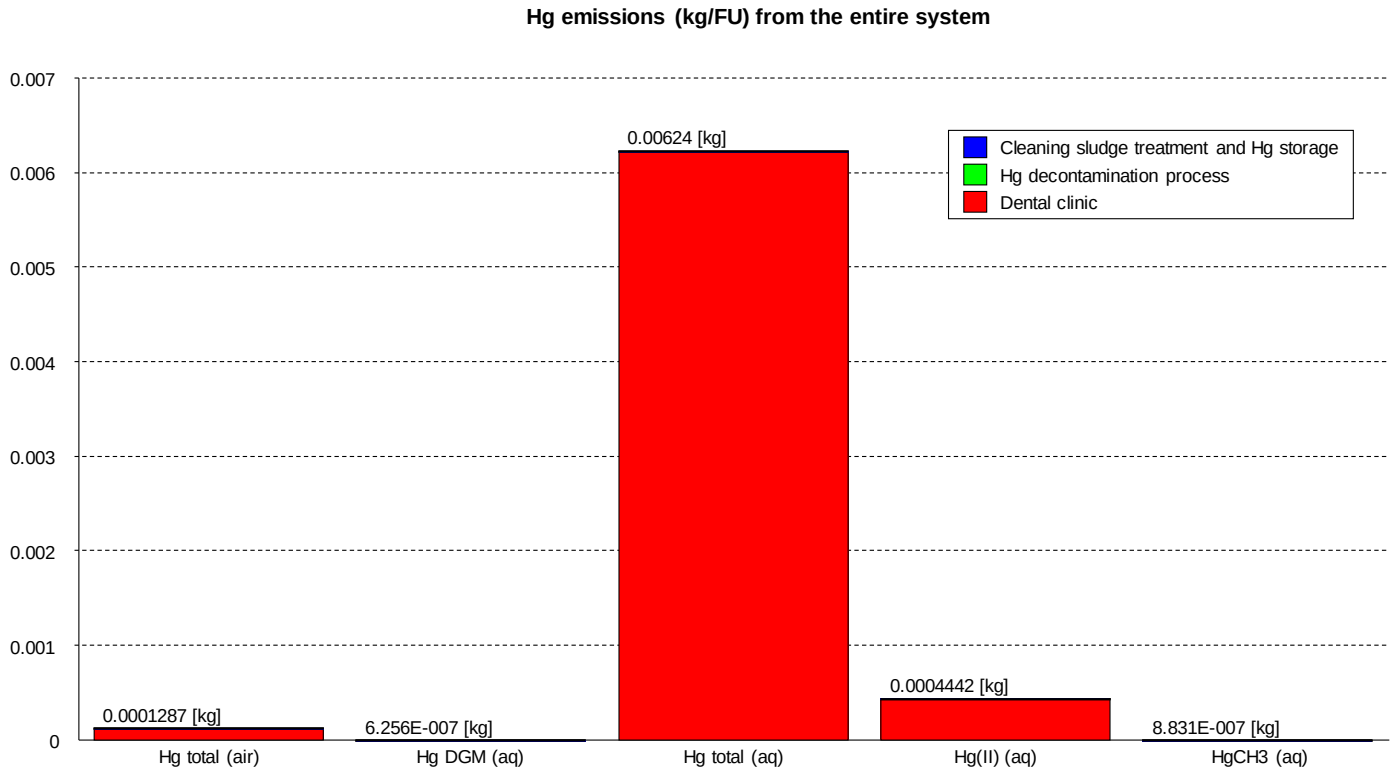

Figure 13 Total Hg emissions from the entire LCA system expressed in kg per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

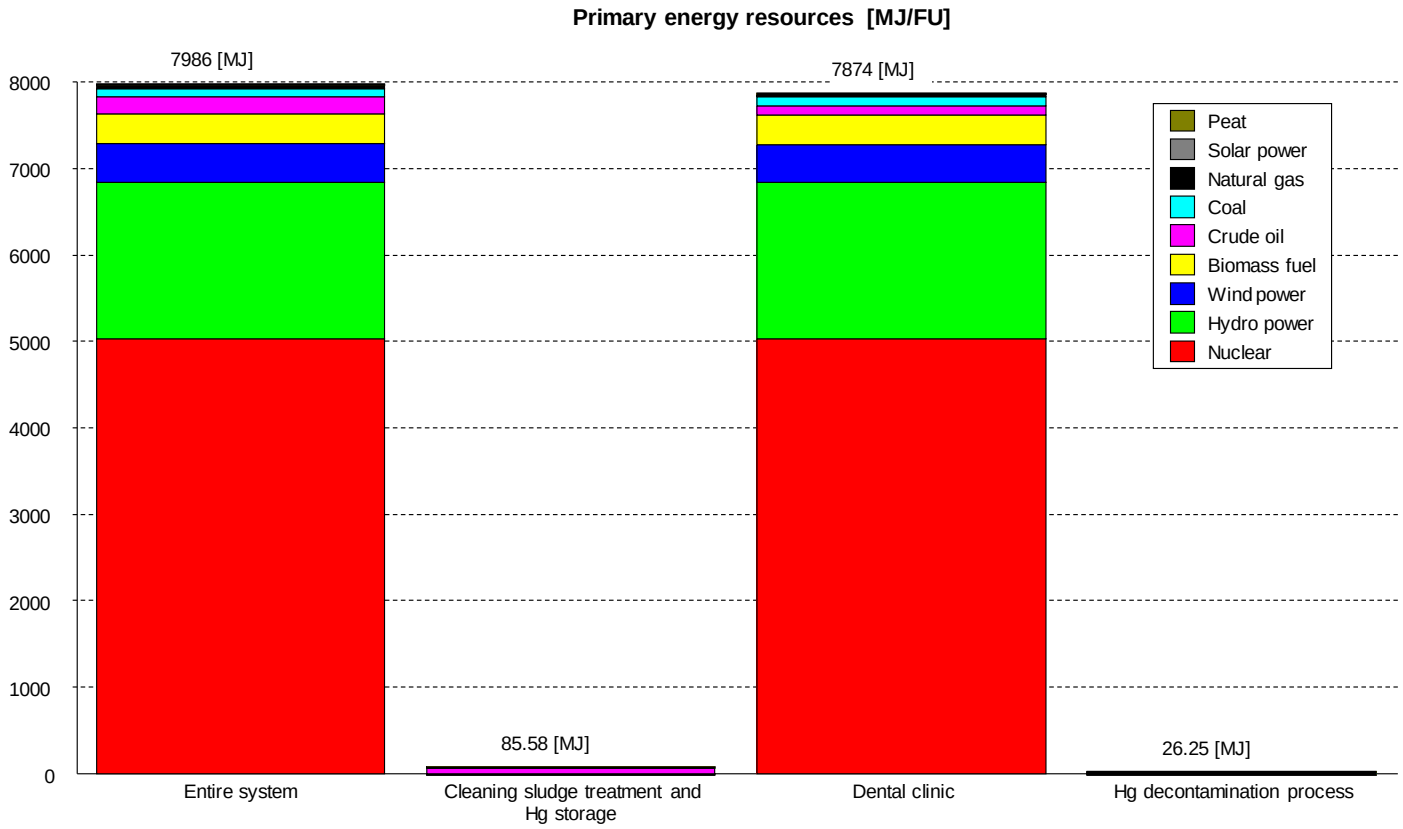

Figure 14 Use of primary energy resources from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in MJ per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

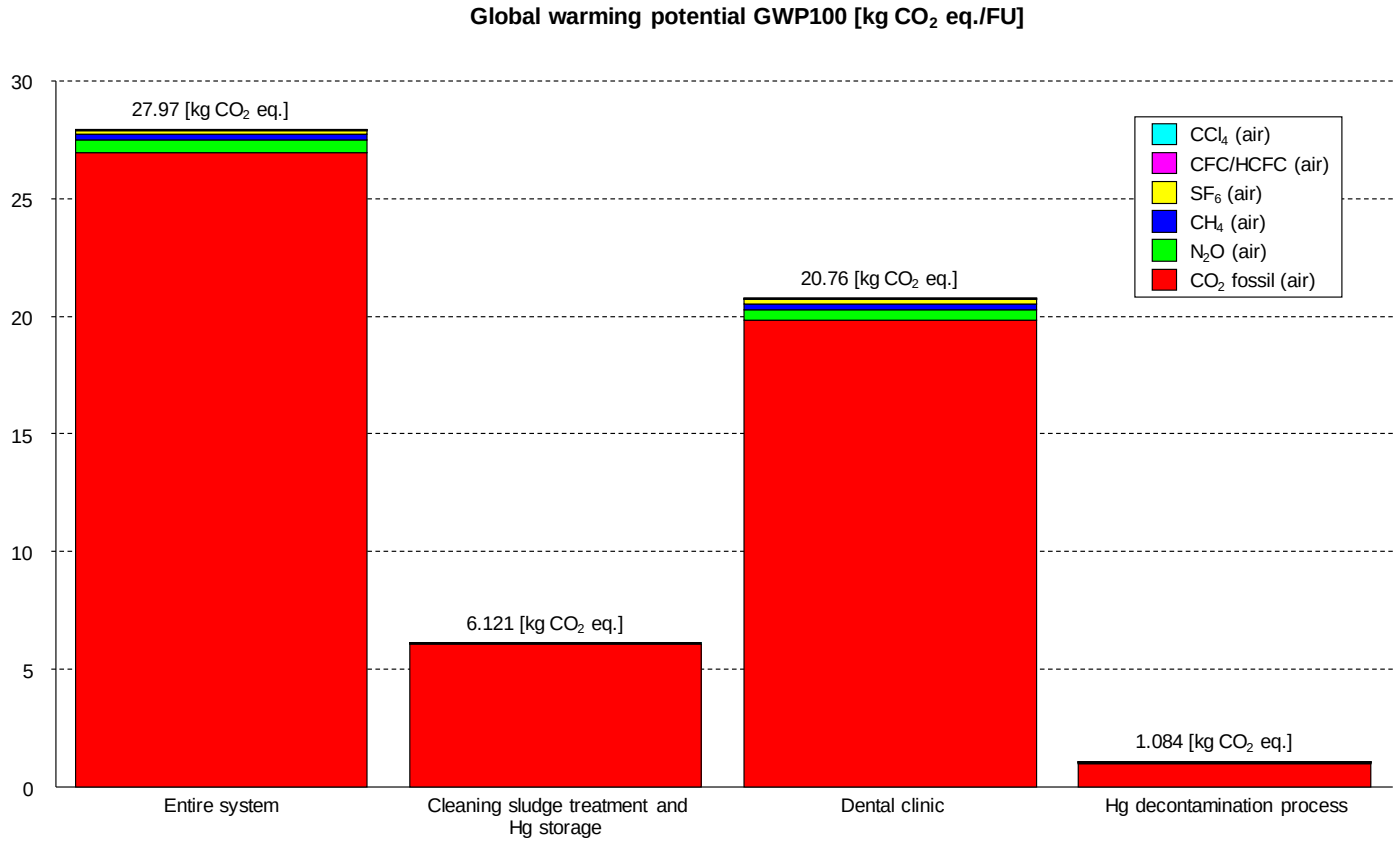

Figure 15 Global warming potential (GWP 100) from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in kg CO_2 equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

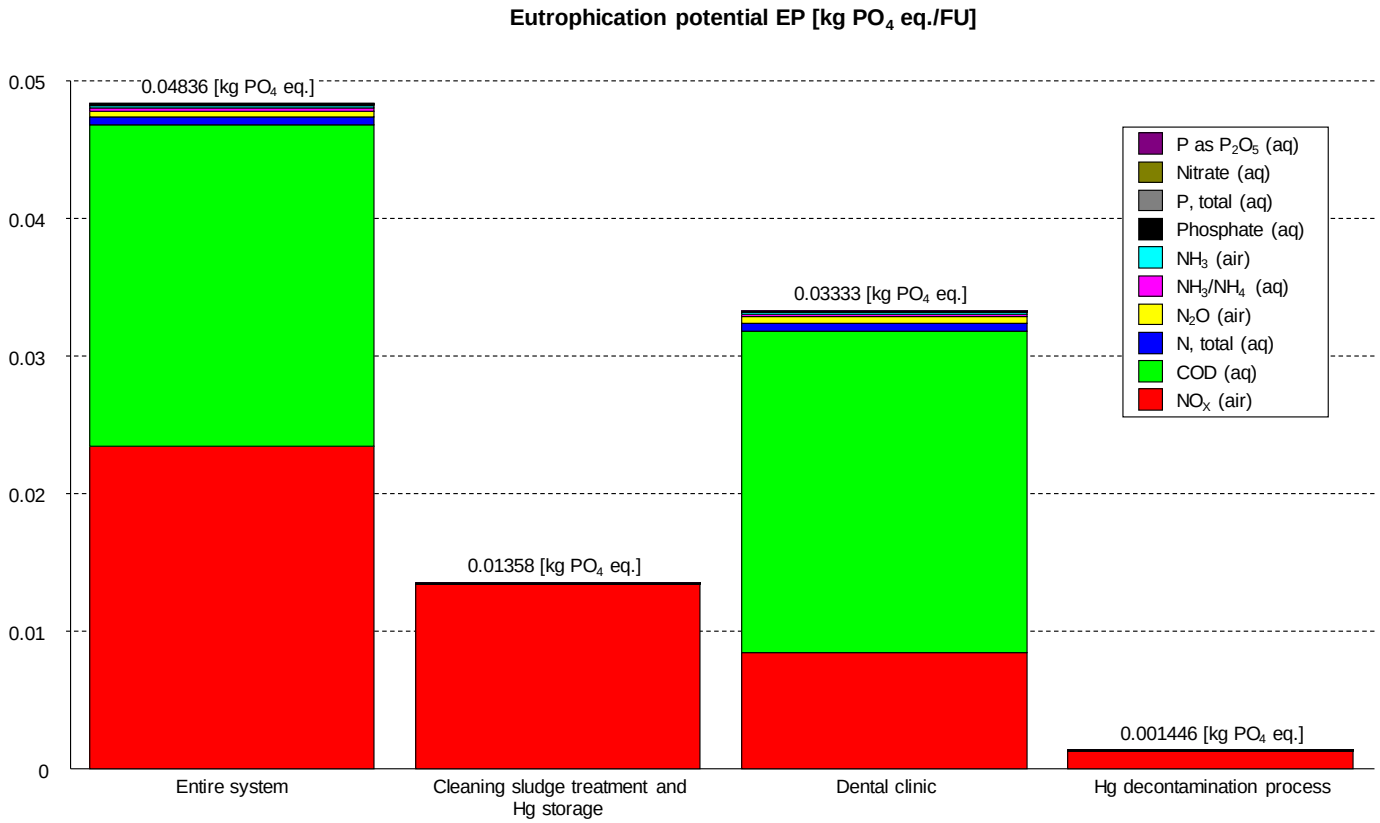

Figure 16 Eutrophication potential (EP) from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in kg PO_4^{3-} equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

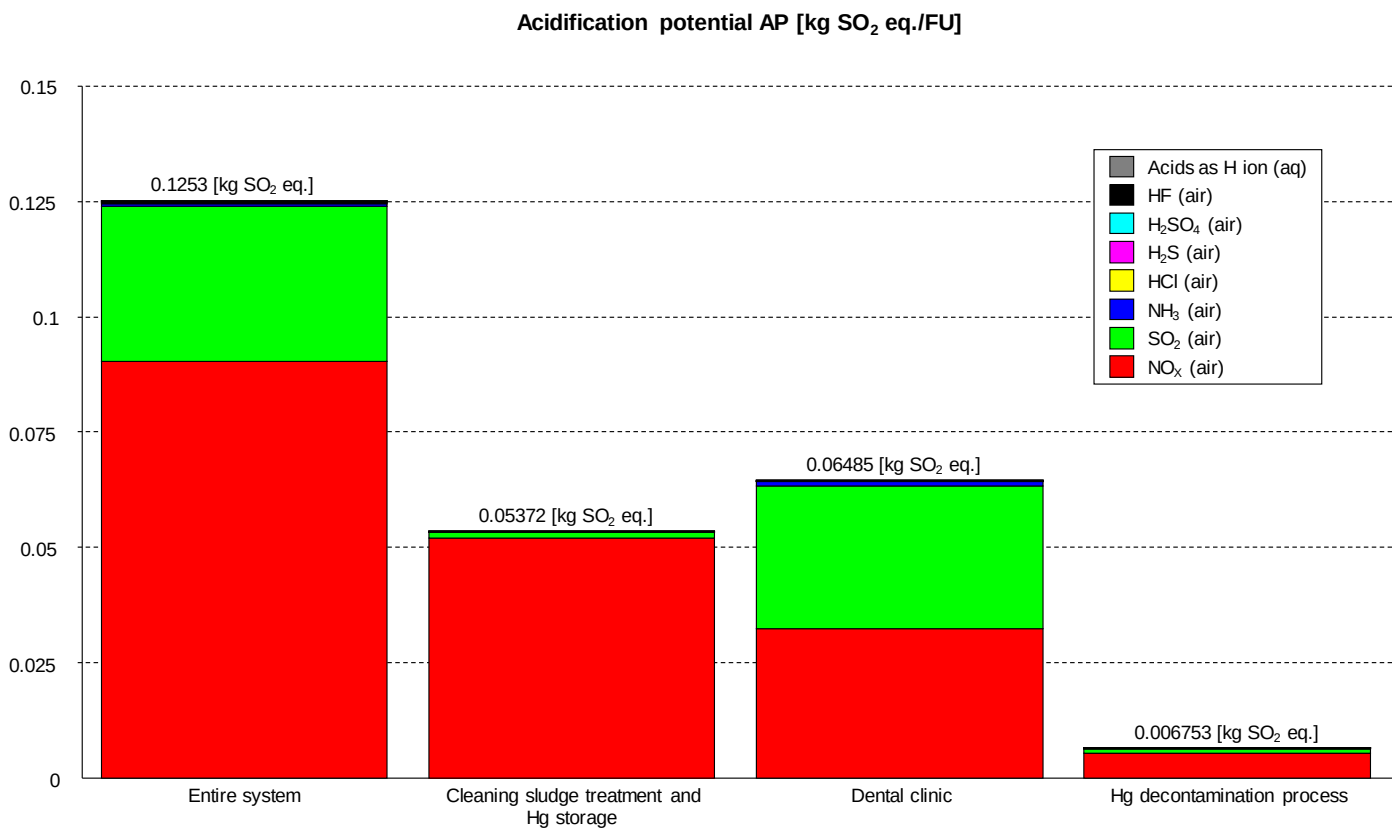

Figure 17 Acidification potential (AP) from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in kg SO_2 equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

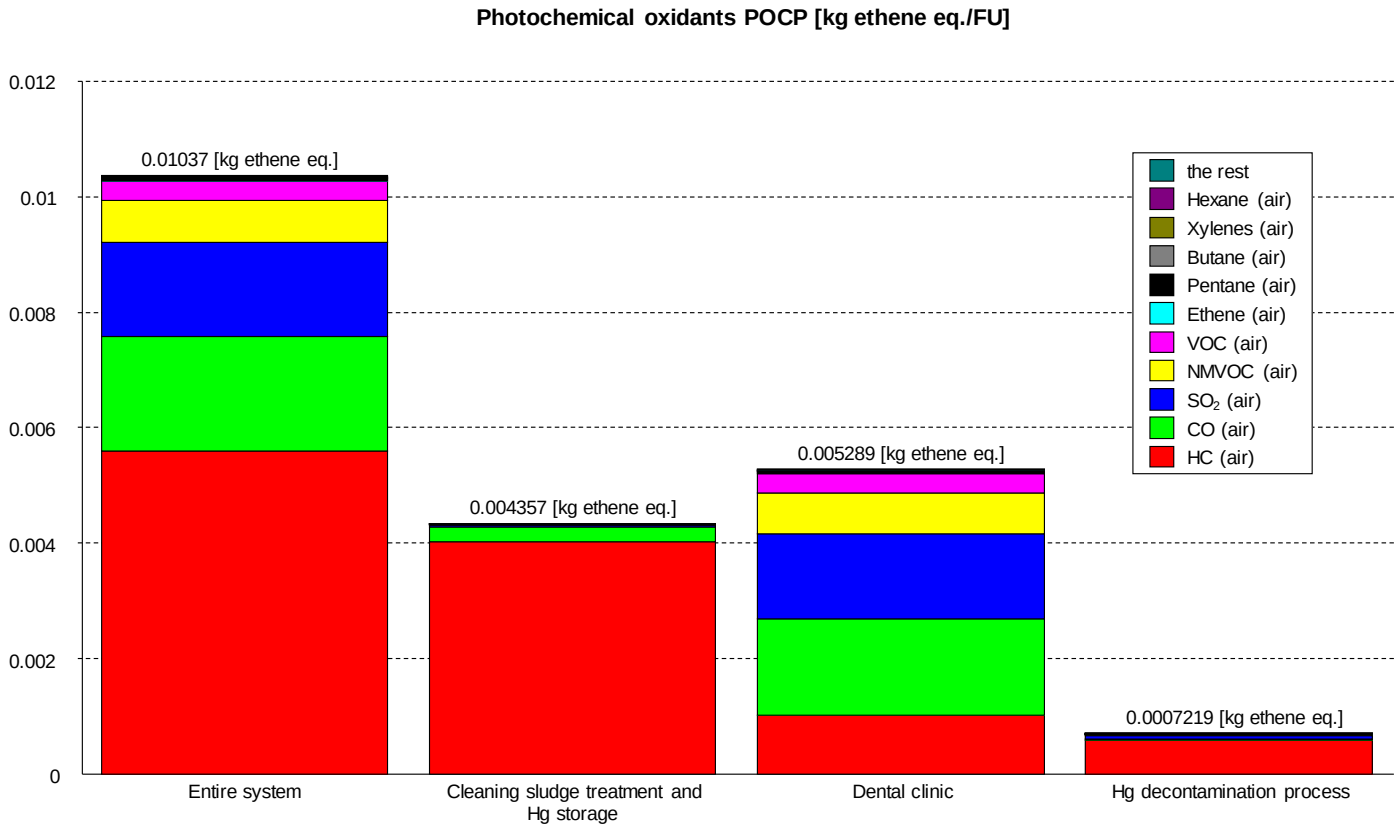

Figure 18 Photochemical ozone creation potentials (POCP) from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in kg ethene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

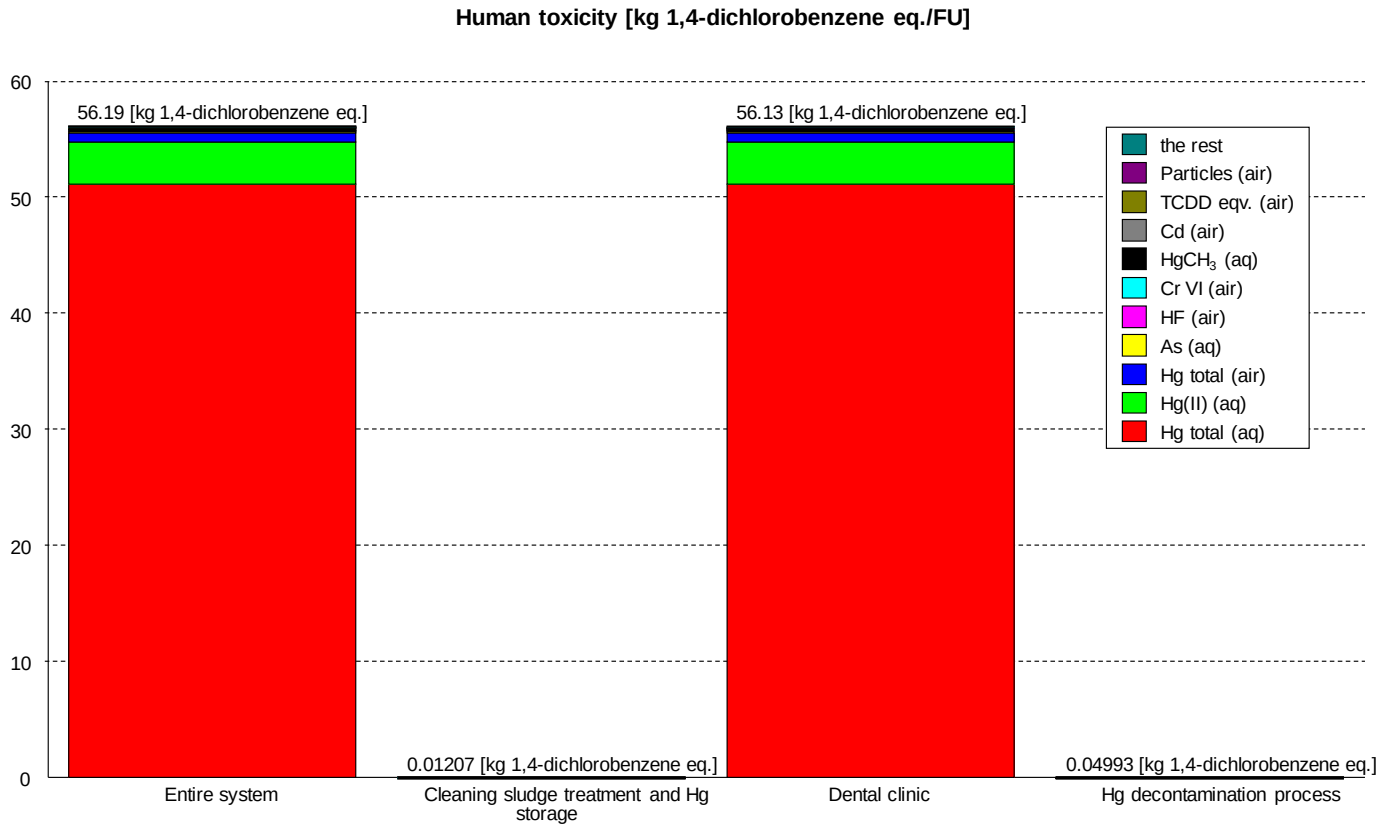

Figure 19 Human toxicity values from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

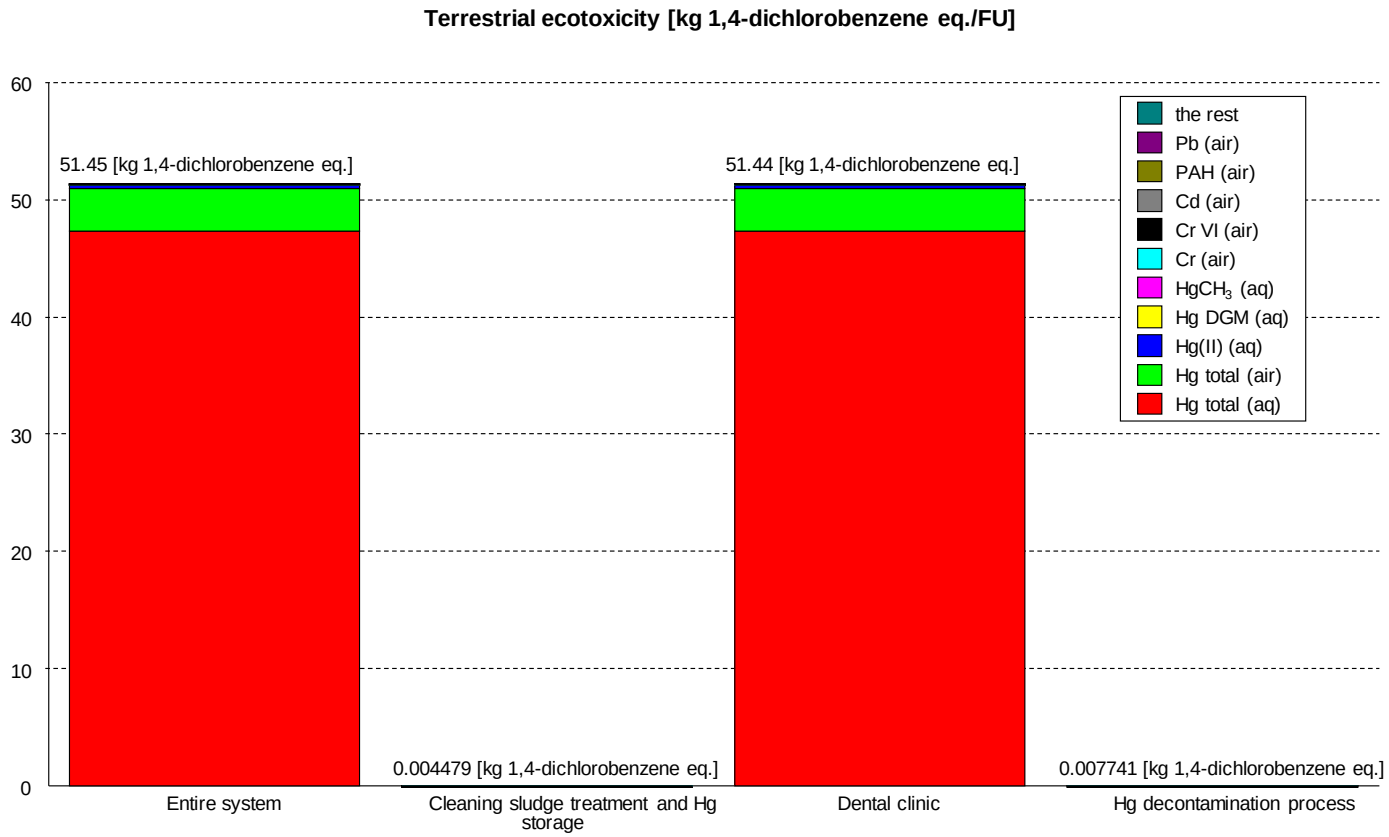

Figure 20 Terrestrial ecotoxicity values from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

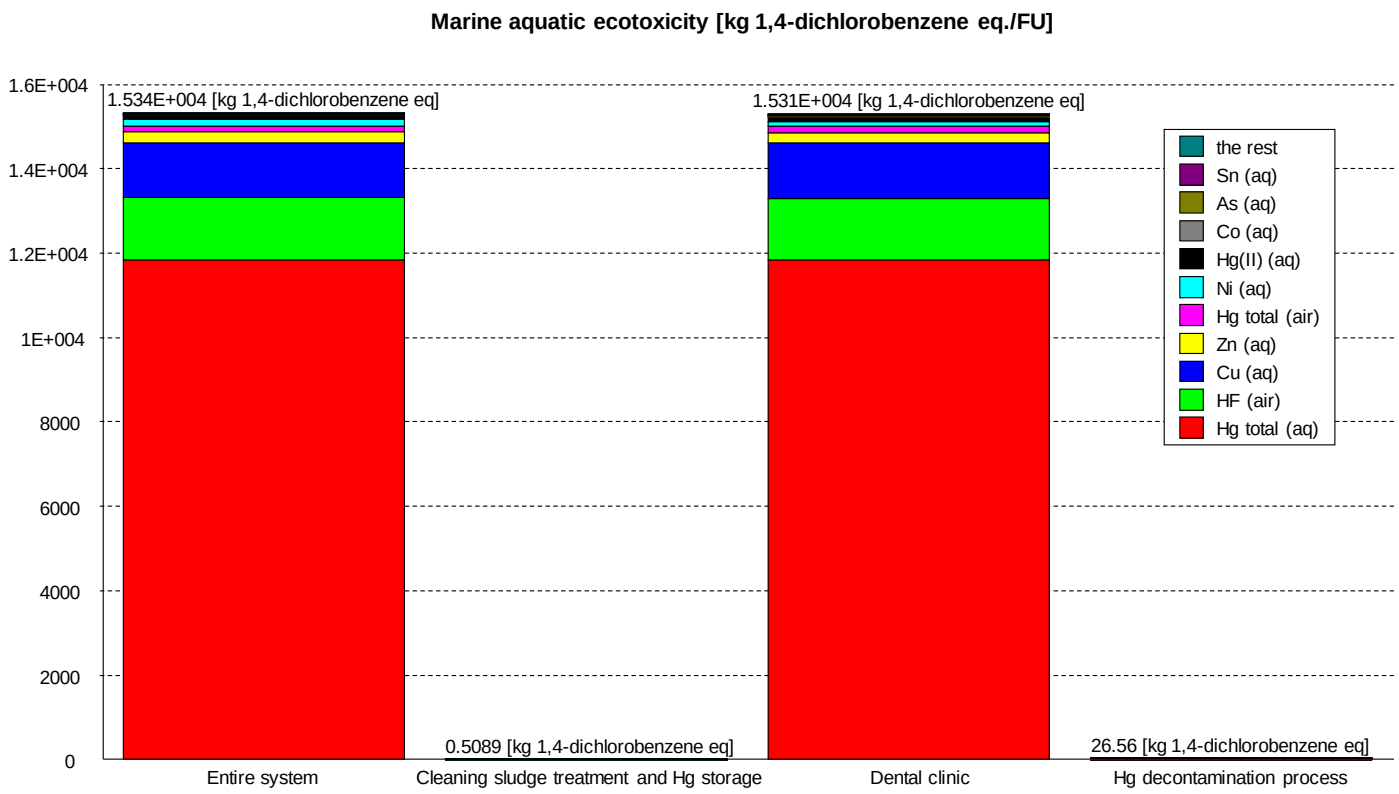

Figure 21 Marine aquatic ecotoxicity values from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

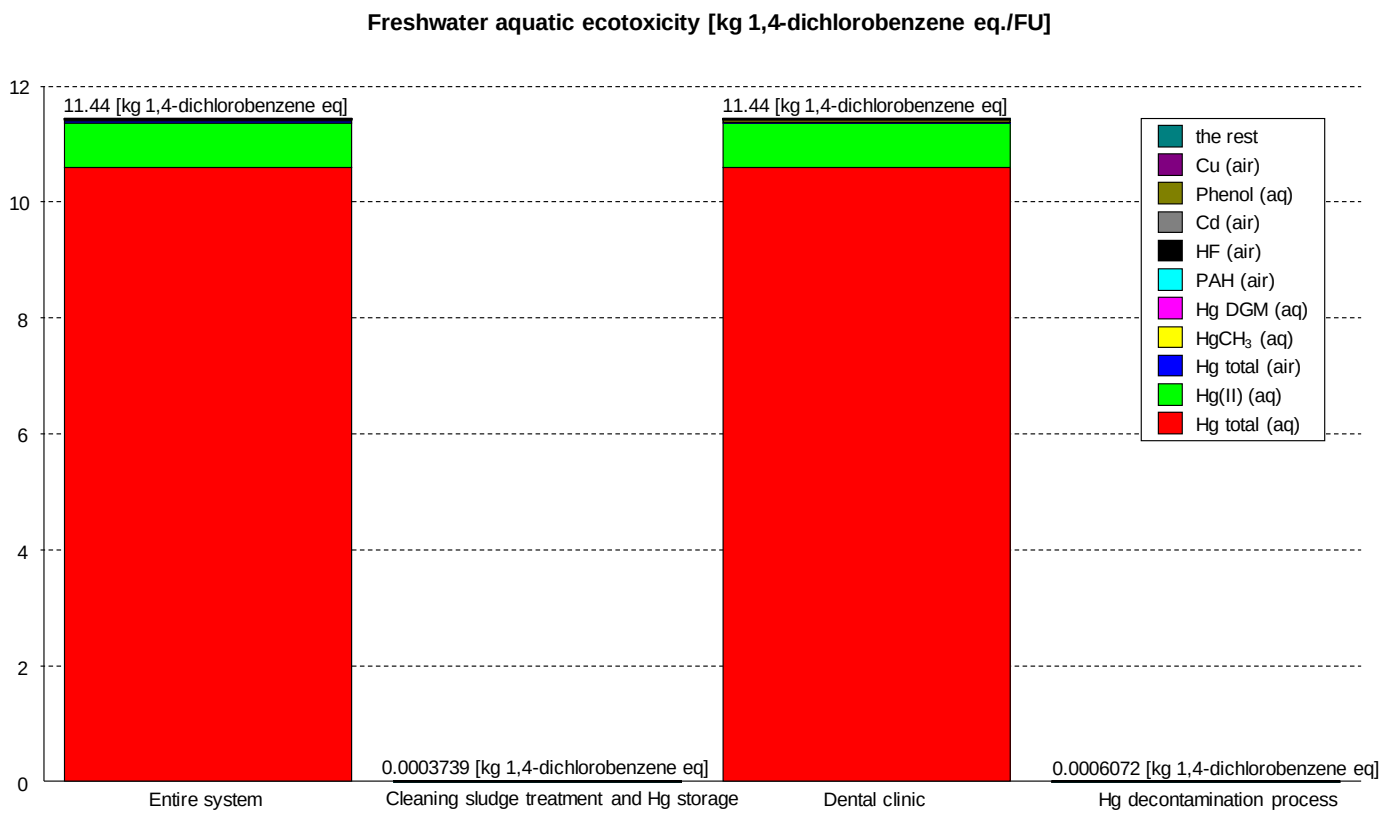

Figure 22 Freshwater aquatic ecotoxicity values from the entire LCA system and divided in Dental clinic, Cleaning sludge treatment and Hg storage, and Hg decontamination process and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

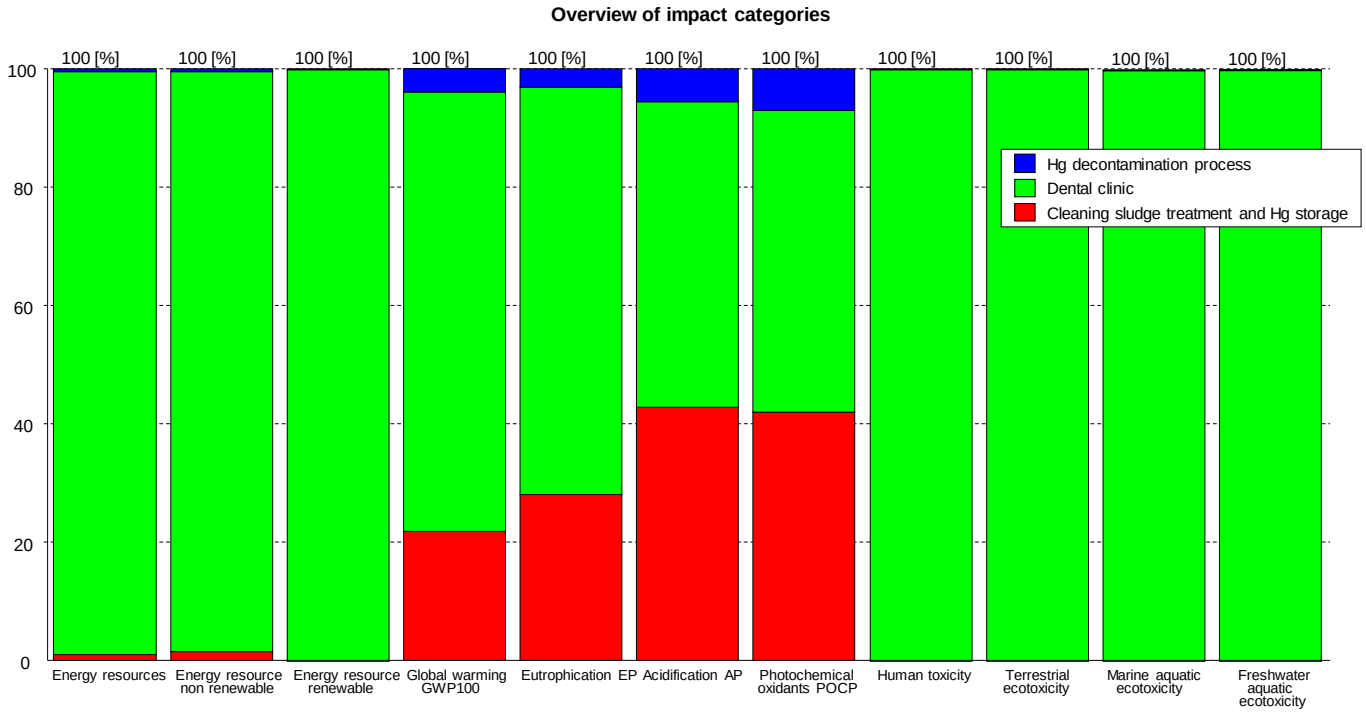

Figure 23 Overview of impact categories showing the relative contribution from the different parts of the LCA model. Scenario 1: with Hg decontamination, Hg processing, and final Hg storage.

8.3 Scenario 2: LCA results with only amalgam separation and final storage of amalgam

In this scenario, mercury is removed only by separating the amalgam in an amalgam separator. The amalgam is then sent to final storage in Sweden.

Figure 24 below shows that most of the various mercury forms come from the dental clinic and have slightly higher emissions than for scenario 1. The use of primary energy resources is also here dominated by the suction system for the amalgam separation at the dental clinic, see Figure 25. Global warming potential, Figure 26, also here shows that electricity consumption for the suction system is dominant for GWP. However, the enclosed activities have been significantly reduced as the sewage pipes are not cleaned and mercury is not recovered from the amalgam, but the amalgam is stored directly in Sweden. A similar relationship also applies to Eutrophication potential (Figure 27), Acidification potential (Figure 28) and Photochemical ozone creation potentials (Figure 29). For the toxicity and ecotoxicity values in Figure 30 to Figure 33, it is shown that these values are consistently slightly higher compared to scenario 1. This is due to the slightly higher emissions of Hg compared to scenario 1. Figure 34 shows an overview of the analyzed impact categories. Almost all environmental effects are related to the dental clinic itself.

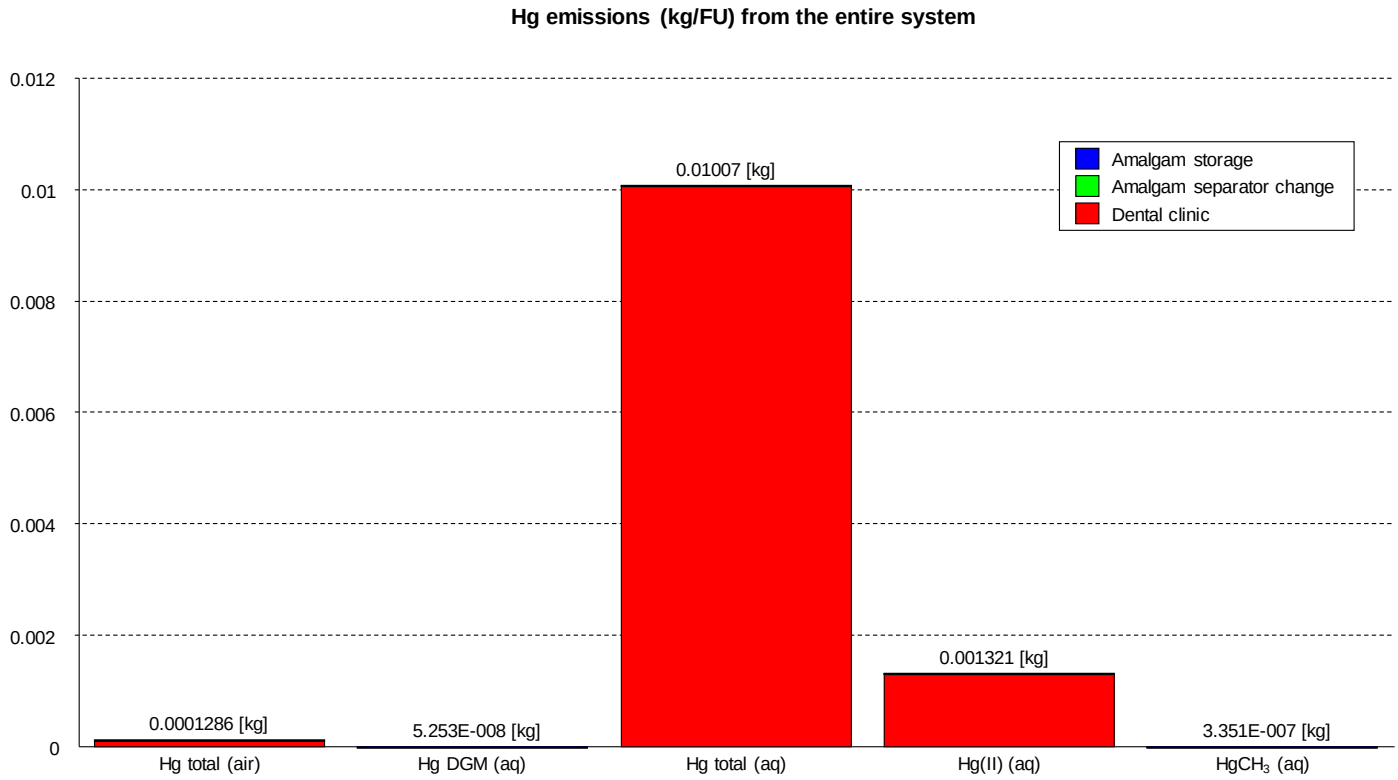

Figure 24 Total Hg emissions from the entire LCA system expressed in kg per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

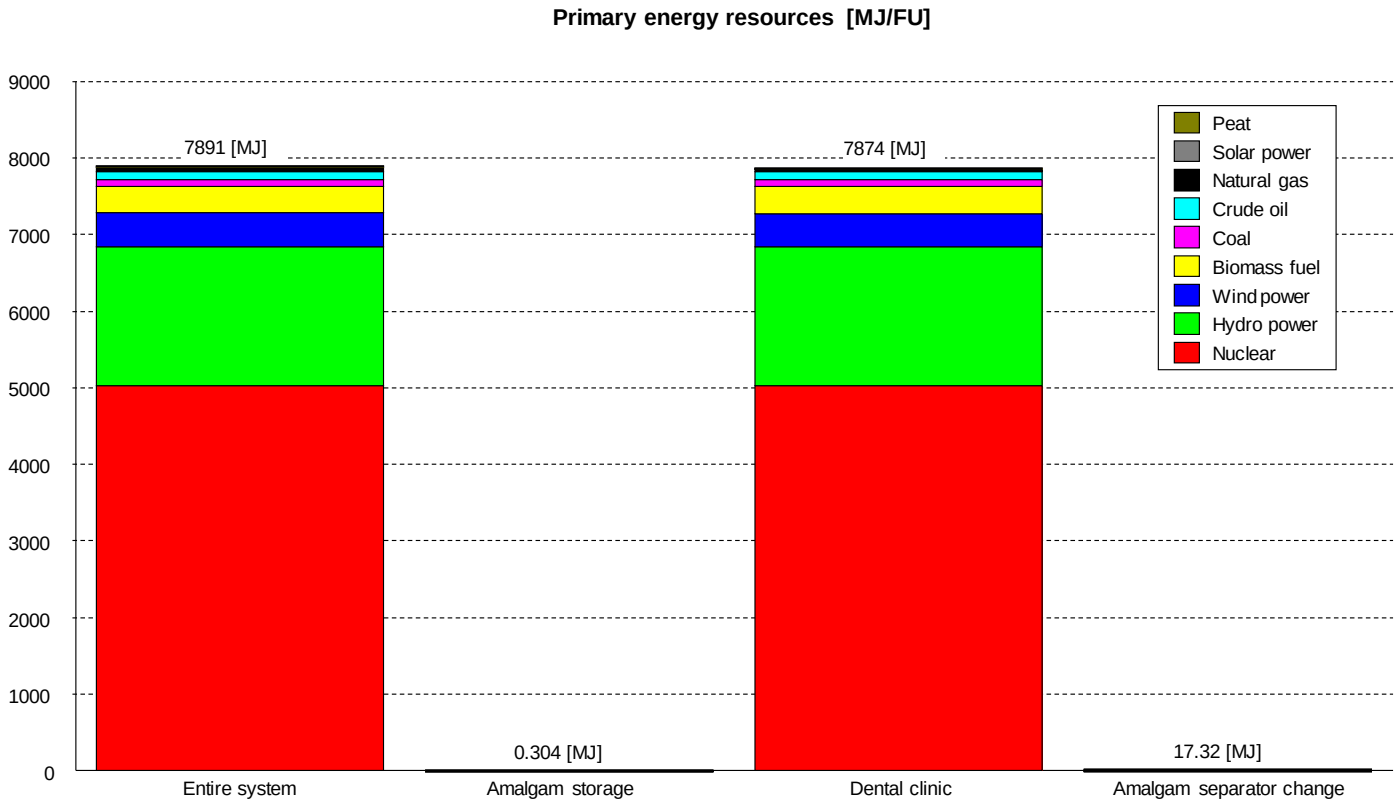

Figure 25 Use of primary energy resources from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in MJ per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

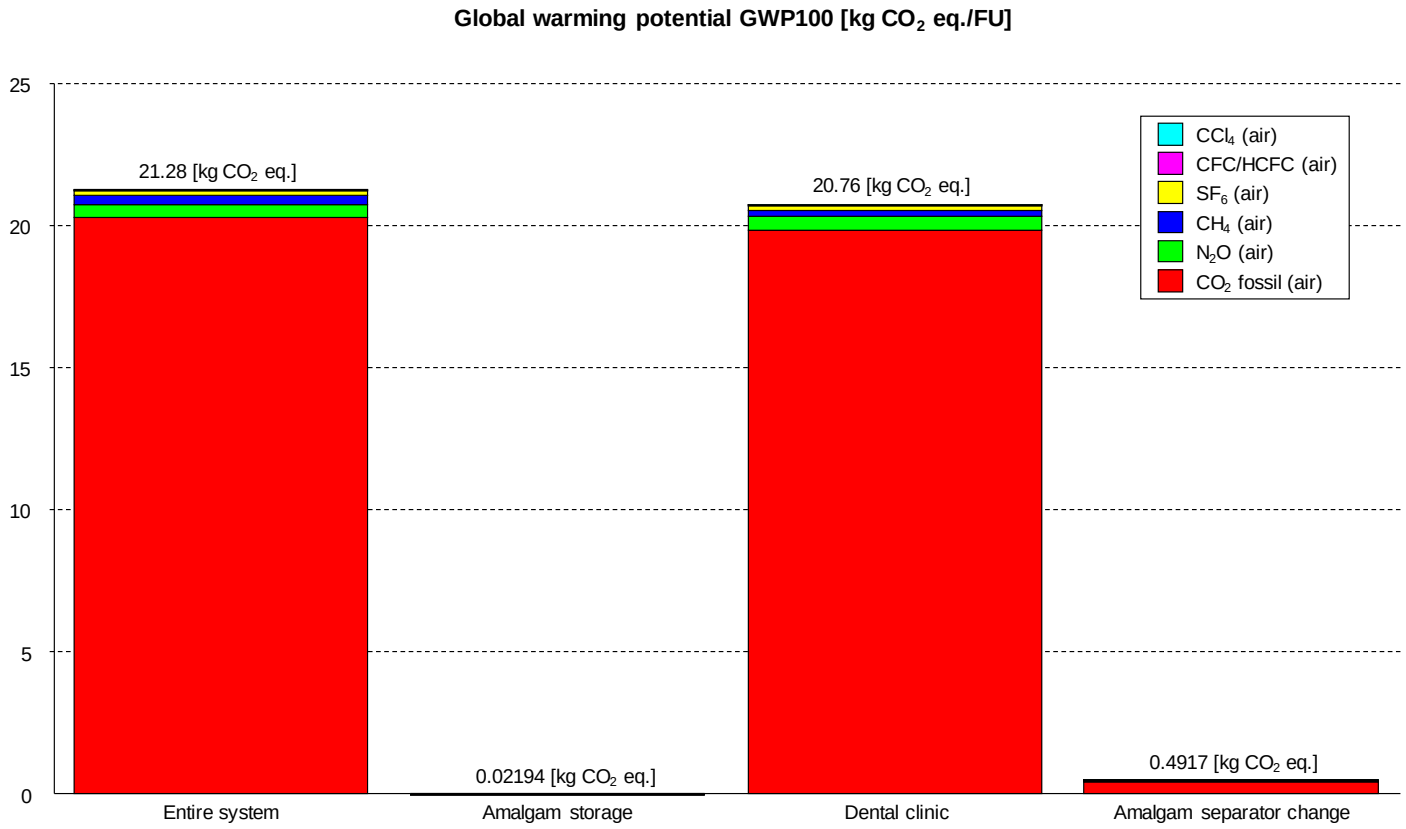

Figure 26 Global warming potential (GWP 100) from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in kg CO_2 equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

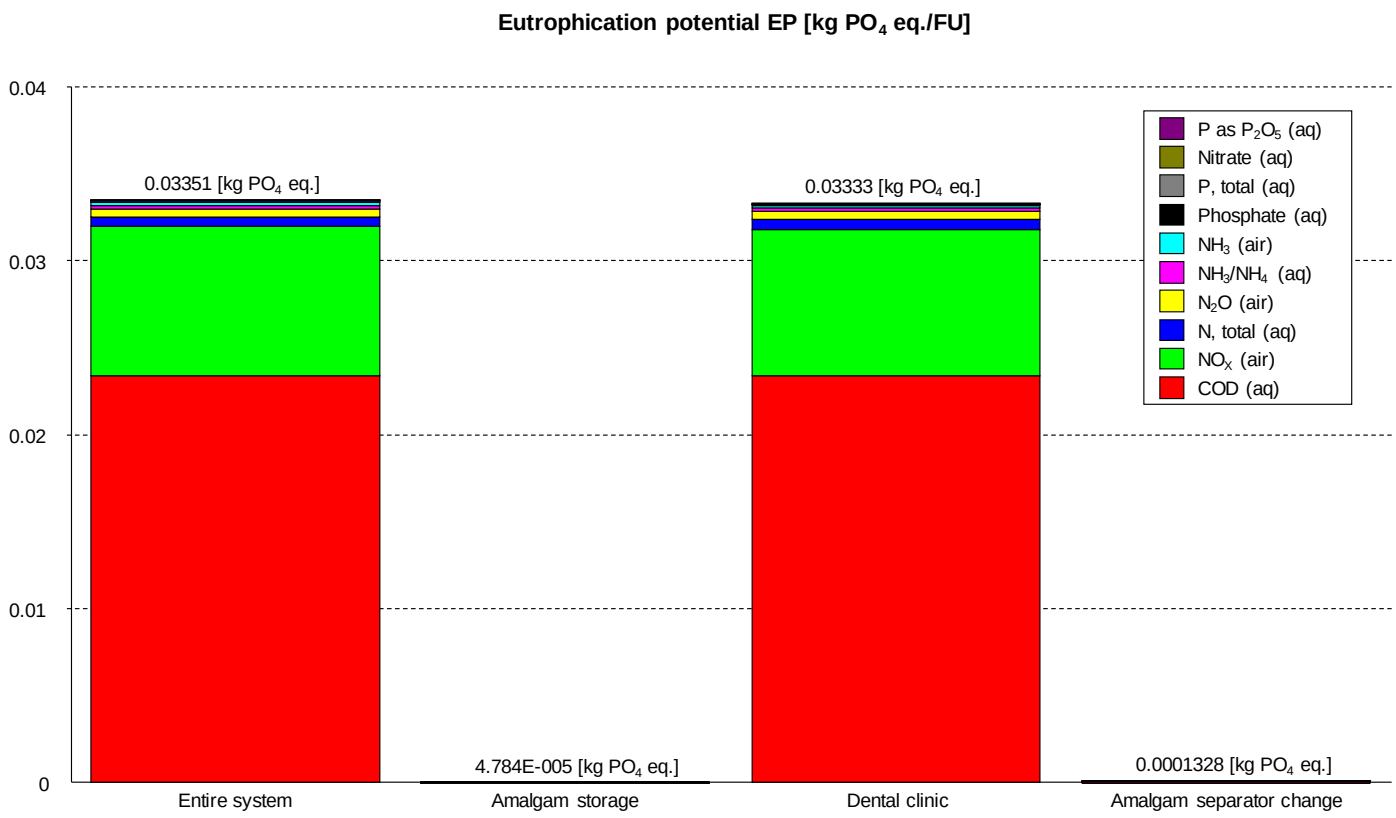

Figure 27 Eutrophication potential (EP) from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in kg PO_4^{3-} equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

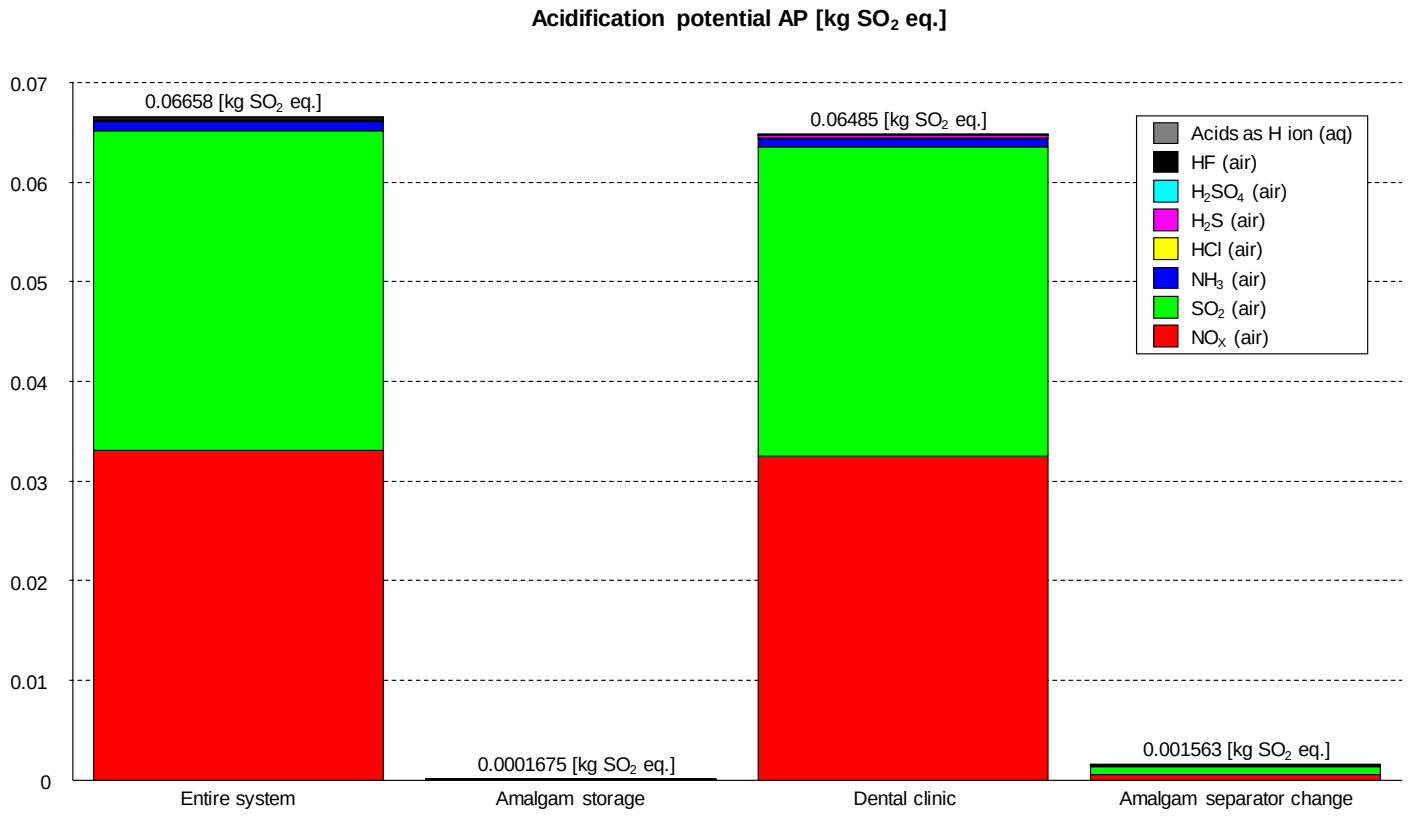

Figure 28 Acidification potential (AP) from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in kg SO_2 equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

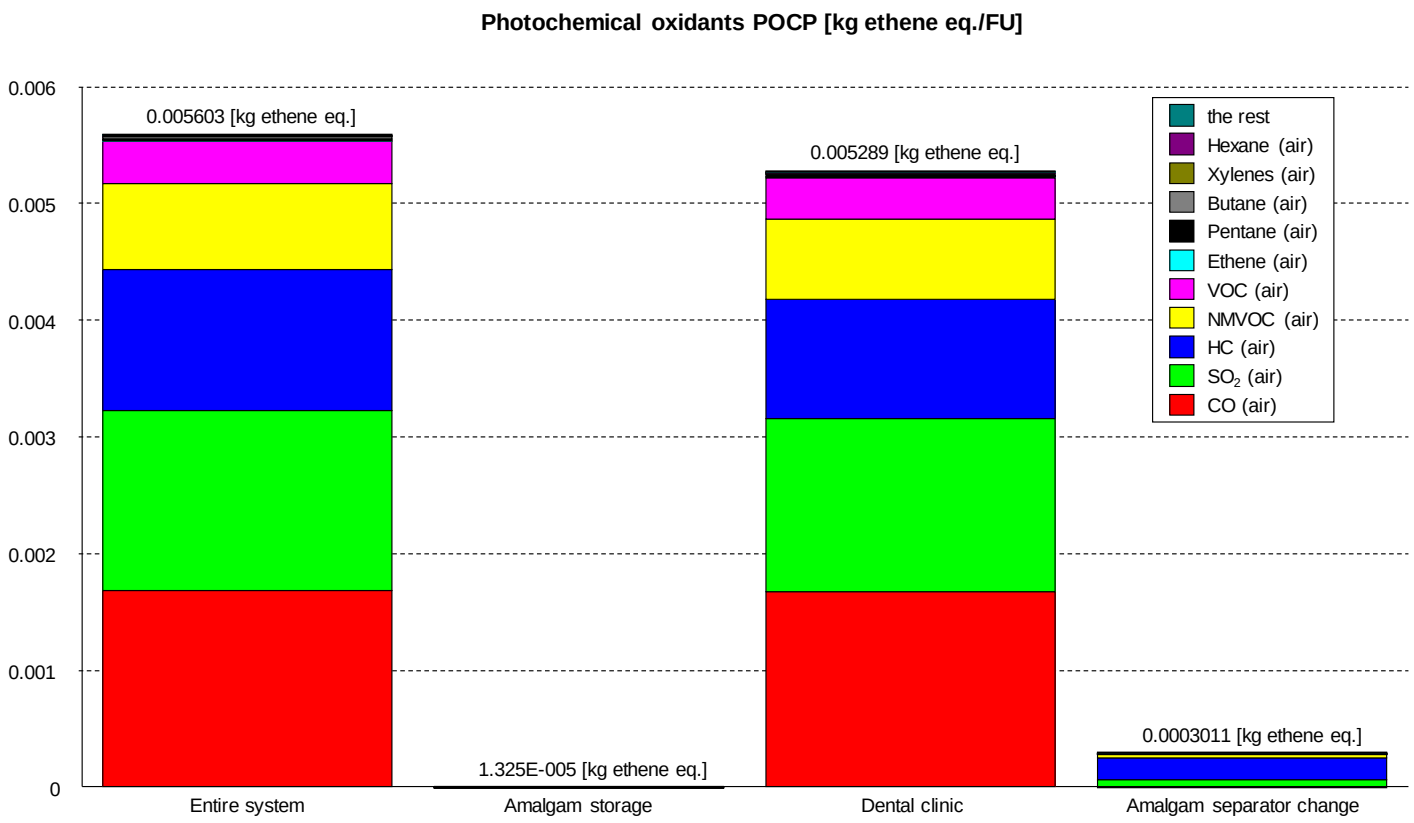

Figure 29 Photochemical ozone creation potentials (POCP) from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in kg ethene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

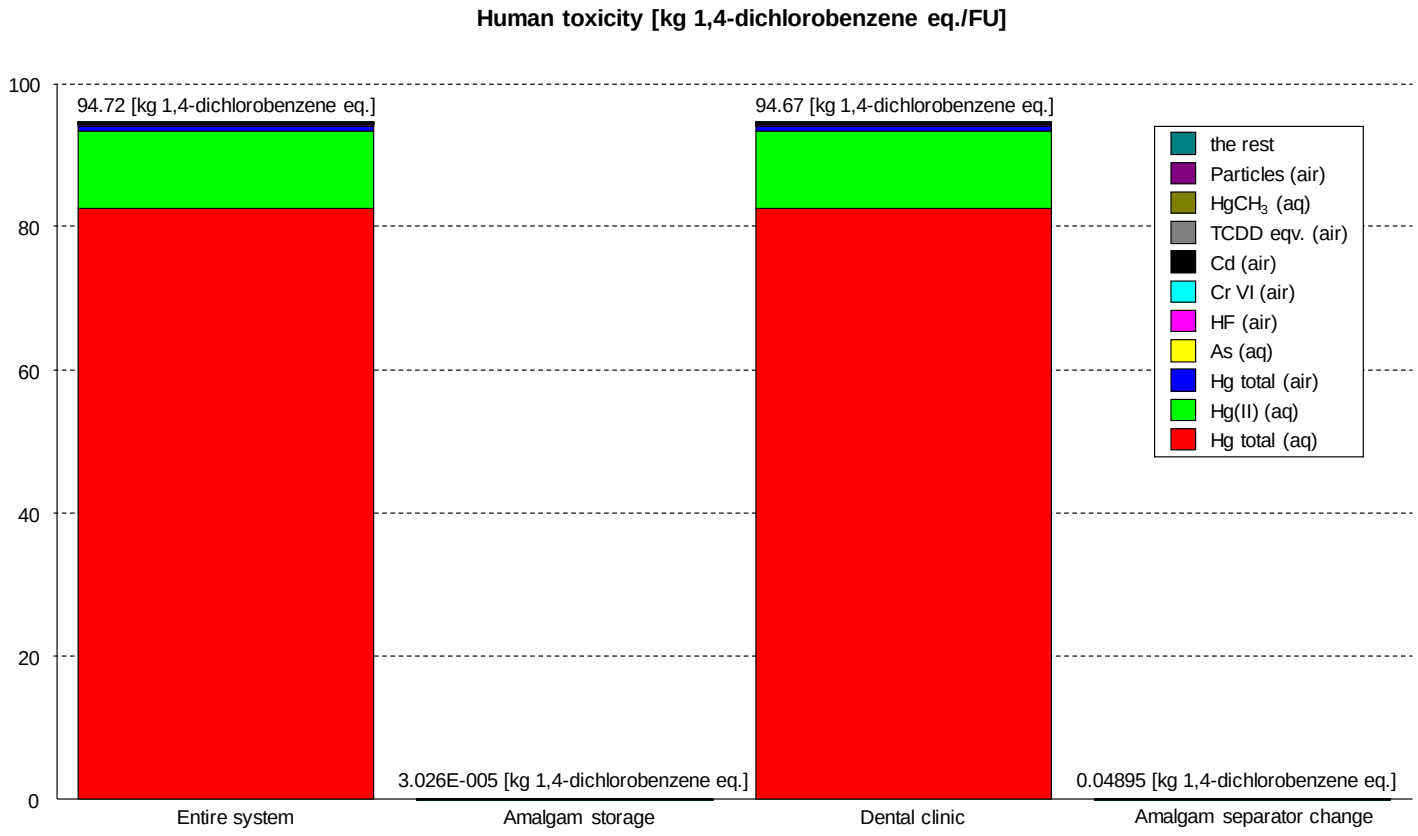

Figure 30 Human toxicity values from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

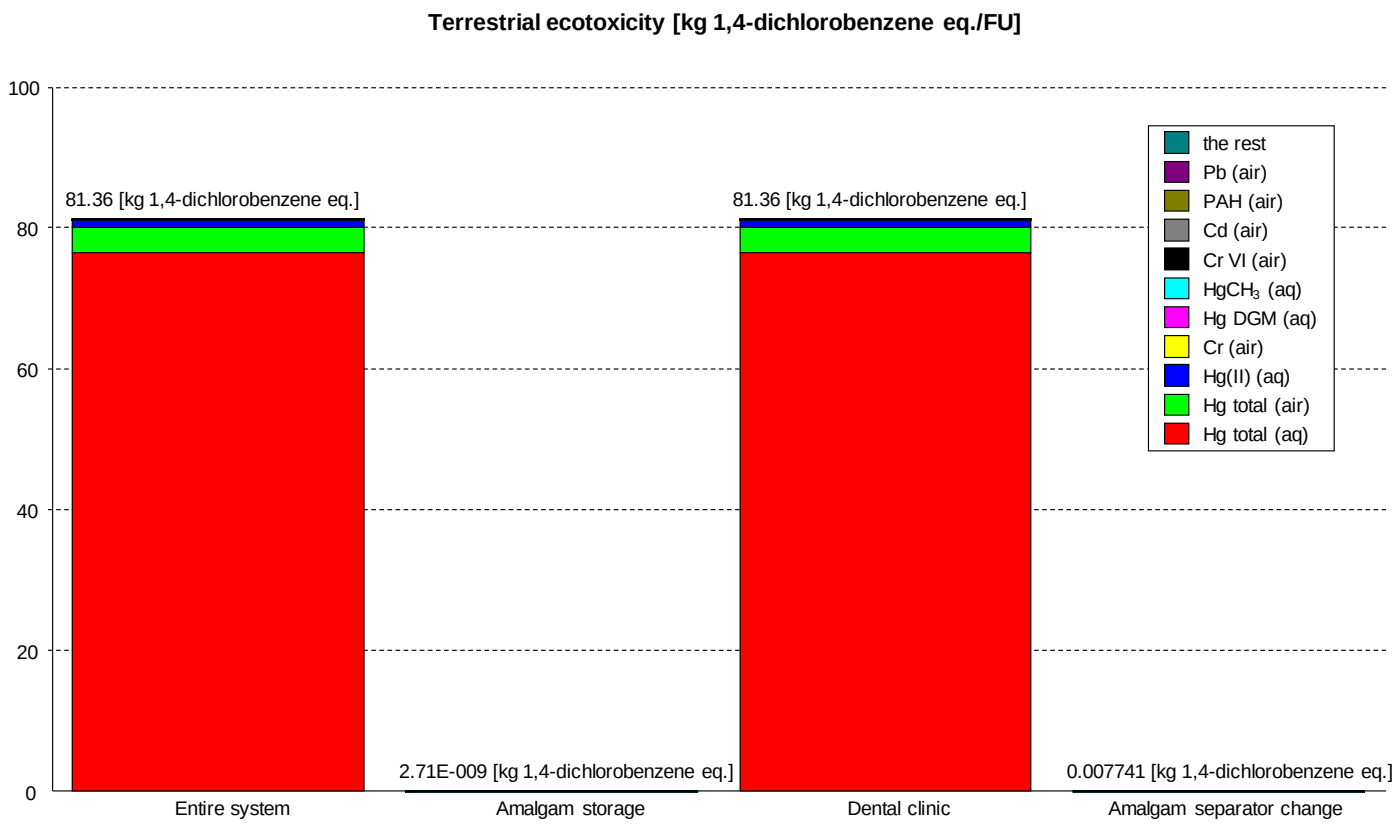

Figure 31 Terrestrial ecotoxicity values from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

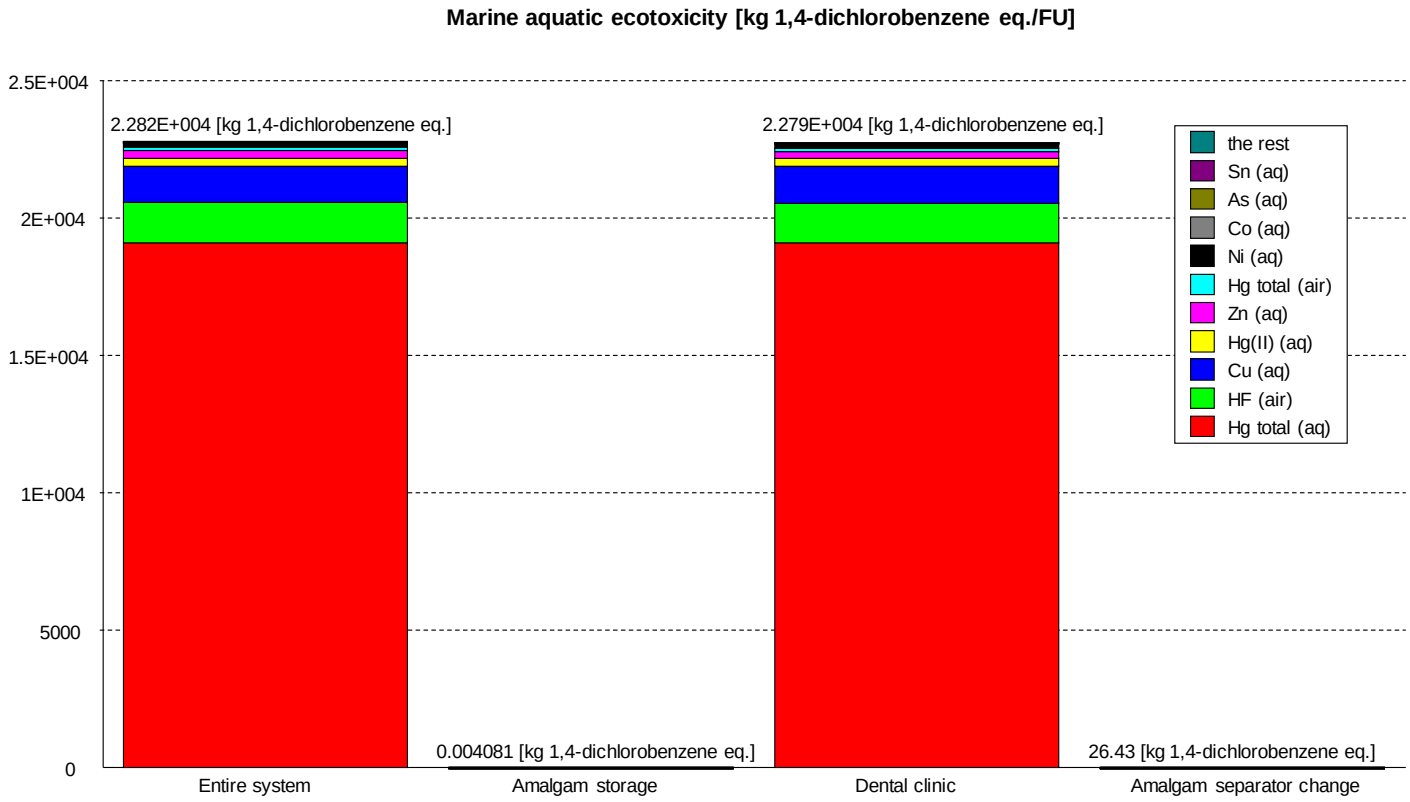

Figure 32 Marine aquatic ecotoxicity values from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

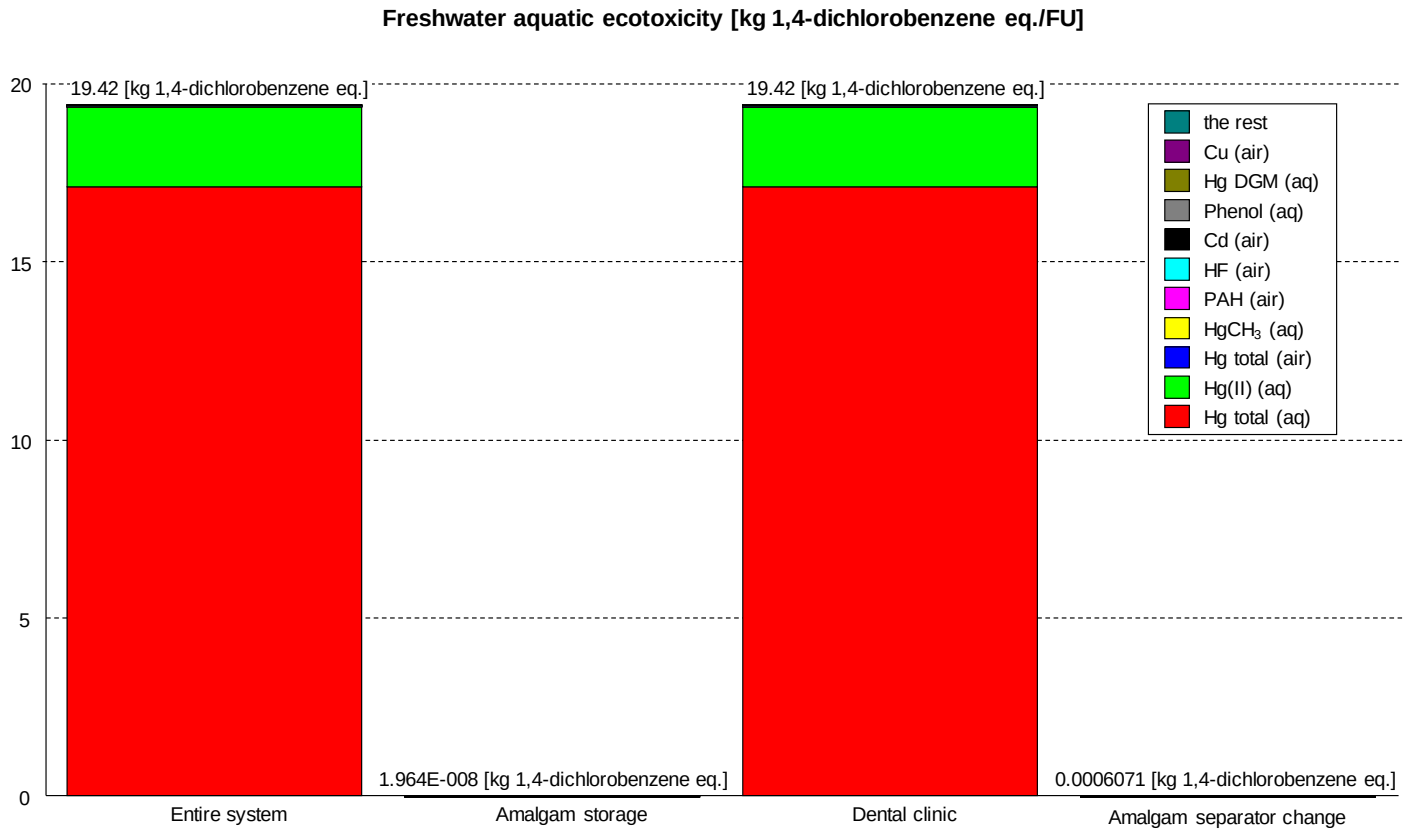

Figure 33 Freshwater aquatic ecotoxicity values from the entire LCA system and divided in Dental clinic, Amalgam storage, and Amalgam separator change and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 2: with only amalgam separation and final storage of amalgam.

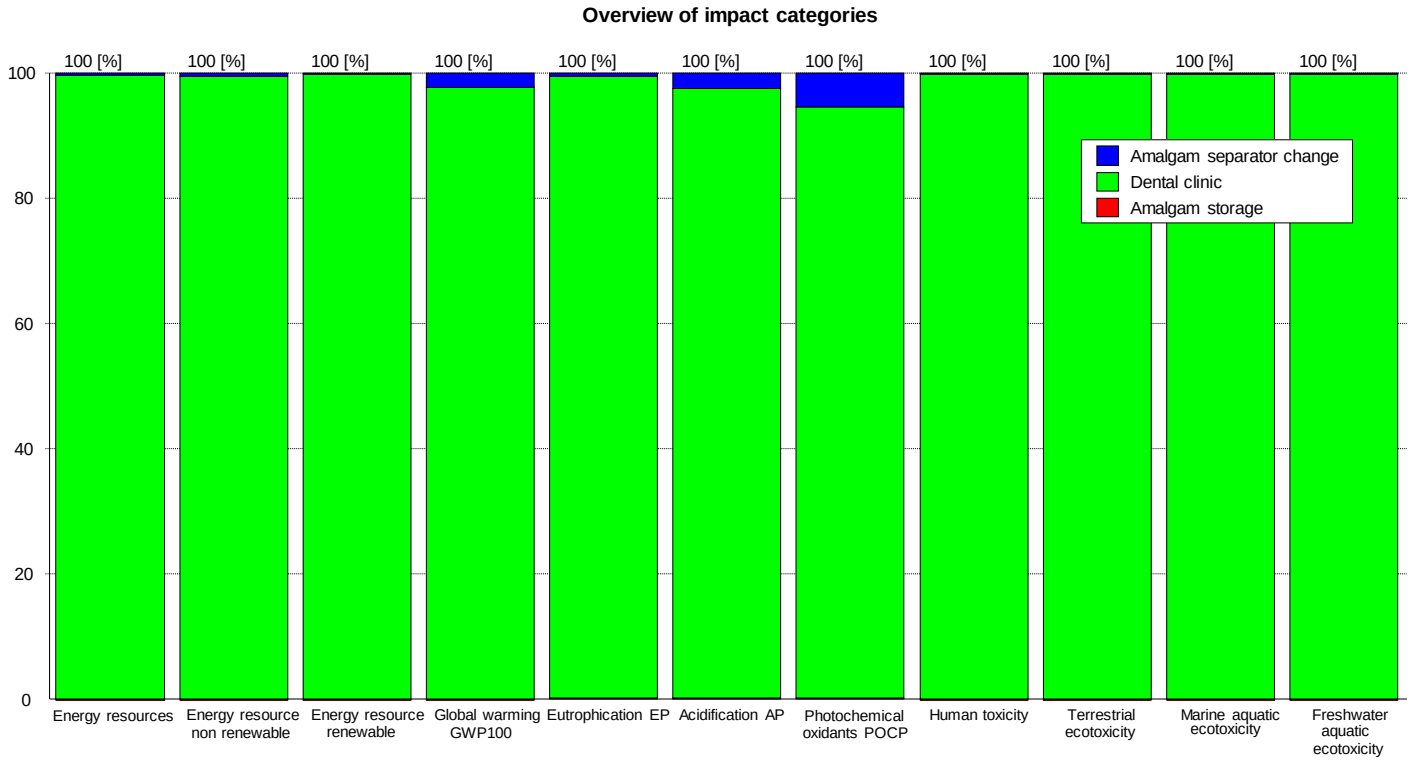

Figure 34 Overview of impact categories showing the relative contribution from the different parts of the LCA model. Scenario 2: with only amalgam separation and final storage of amalgam.

8.4 Scenario 3: LCA results without any amalgam separation – Hg direct to recipient

In this scenario, there is no cleaning of either amalgam or mercury. All amalgam from the clinic therefore goes directly to the recipient, often via a sewage treatment plant where the amalgam (Hg) can be emitted via the purified water or end up in the sludge from the treatment plant. This also means that there are no process parts other than the dental clinic itself in the LCA model.

The various emissions of Hg from the dental clinic are shown in Figure 35. Here, it is now shown that the total Hg emissions are significantly greater than for scenario 1. The use of primary energy resources is now less as no energy is needed for the cleaning process and the disposal of mercury, Figure 36. Global warming potential, GWP, is now lower for the same reason as for the energy use, Figure 37. Eutrophication potential (Figure 38), Acidification potential (Figure 39) and POCP (Figure 40) are also lower for the same reason. The toxicity and ecotoxicity values, shown in Figure 41 to Figure 44, are now significantly higher as Hg emissions have increased significantly. From the overview of the impact categories used, Figure 45, it is shown that all environmental impact comes from the uncleaned dental clinic.

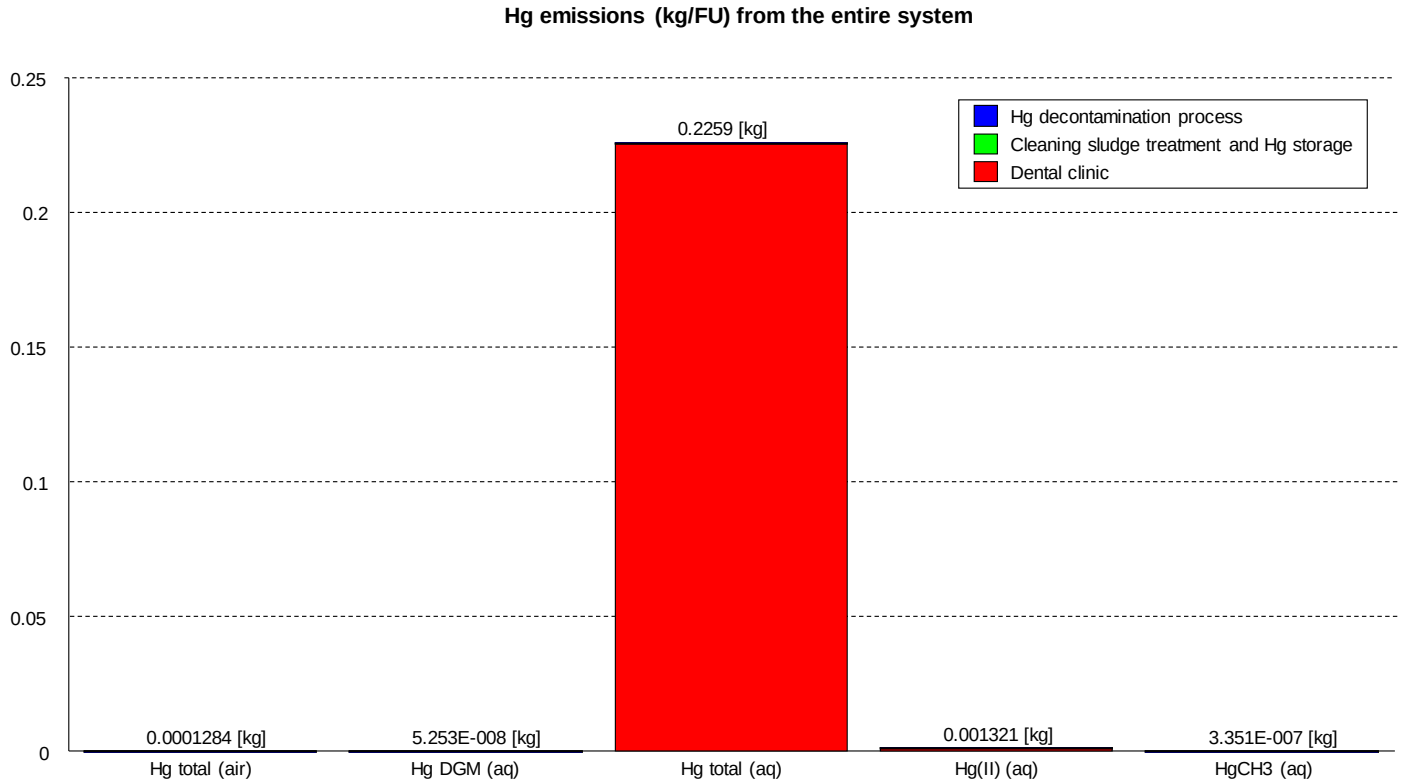

Figure 35 Total Hg emissions from the entire LCA system expressed in kg per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

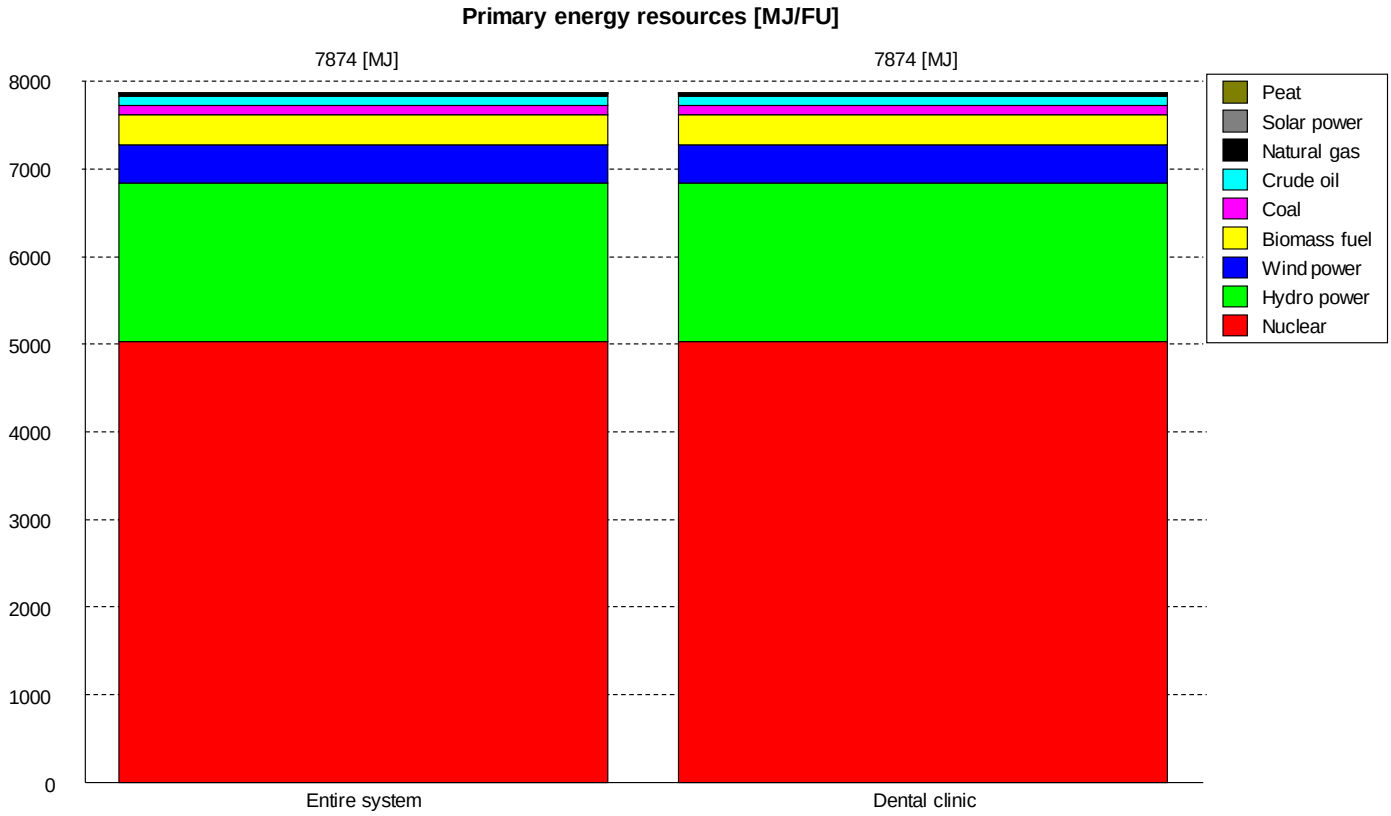

Figure 36 Use of primary energy resources from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in MJ per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

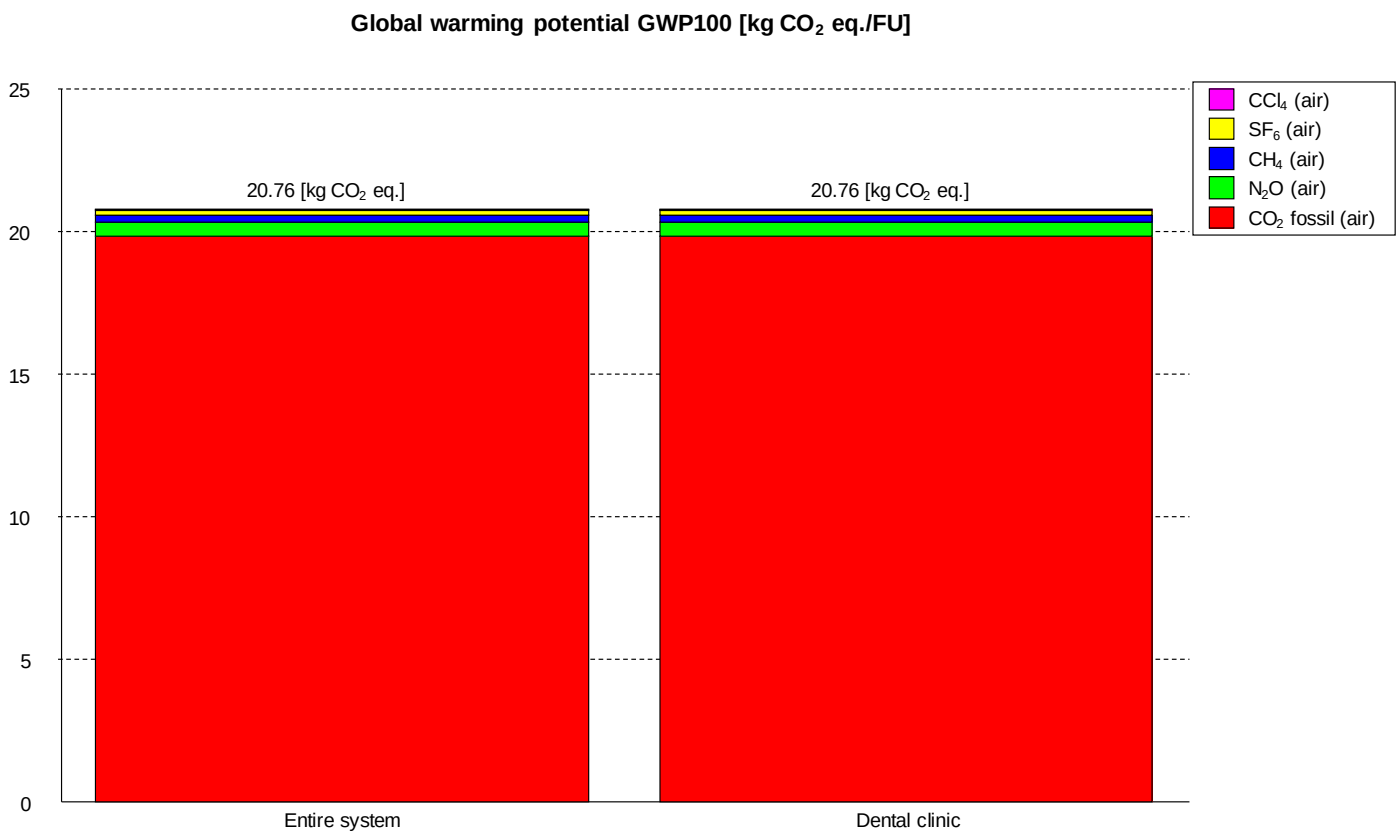

Figure 37 Global warming potential (GWP 100) from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in kg CO_2 equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

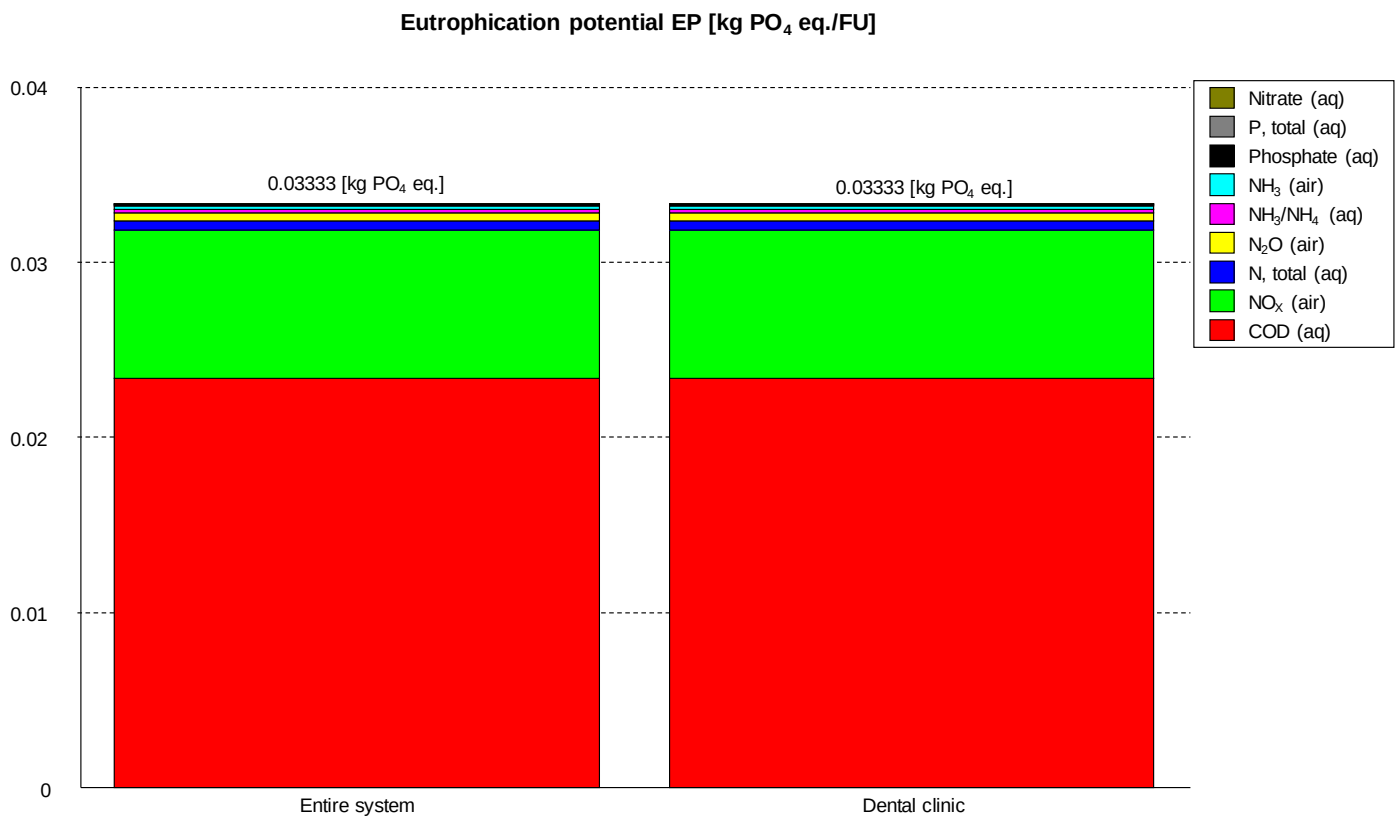

Figure 38 Eutrophication potential (EP) from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in kg PO_4^{3-} equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

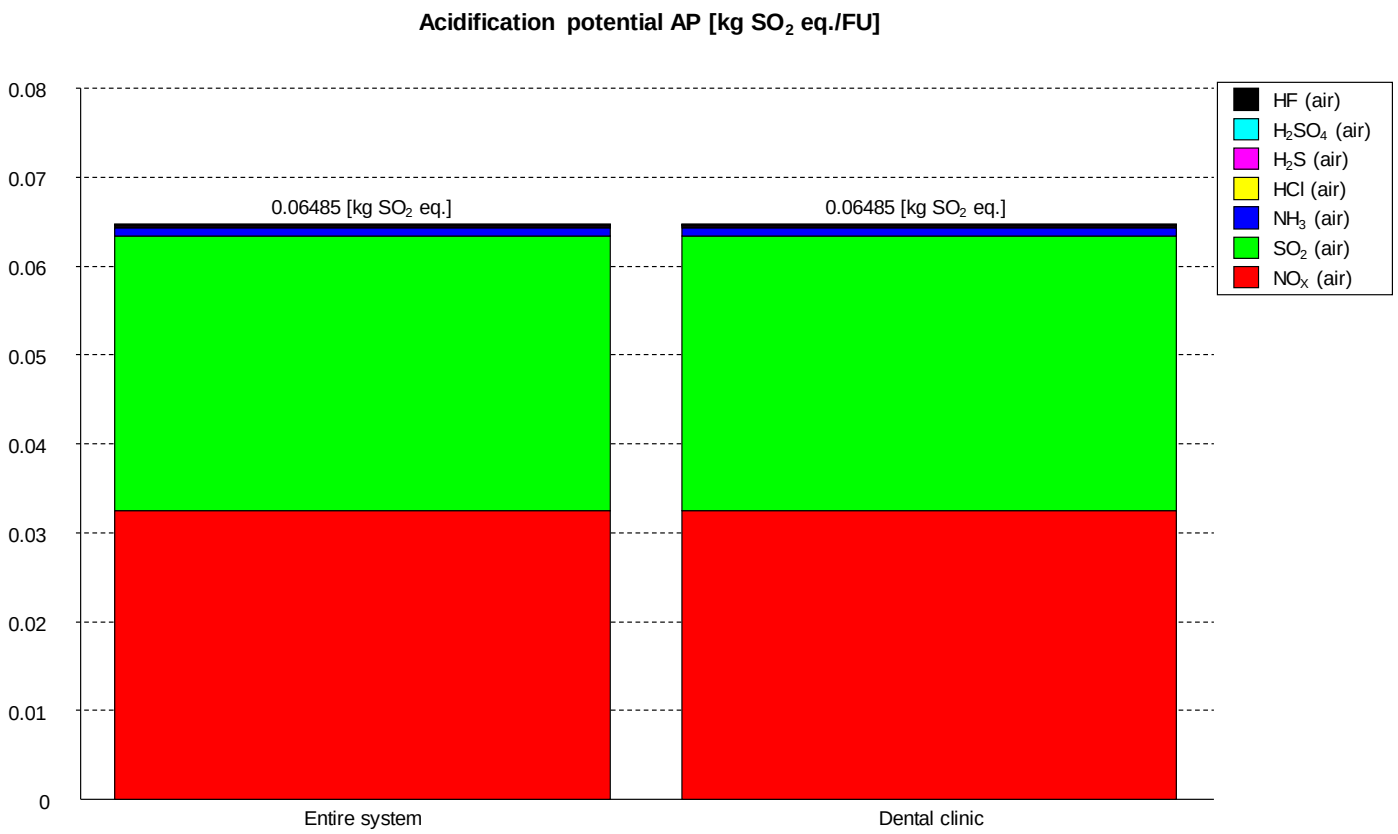

Figure 39 Acidification potential (AP) from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in kg SO_2 equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

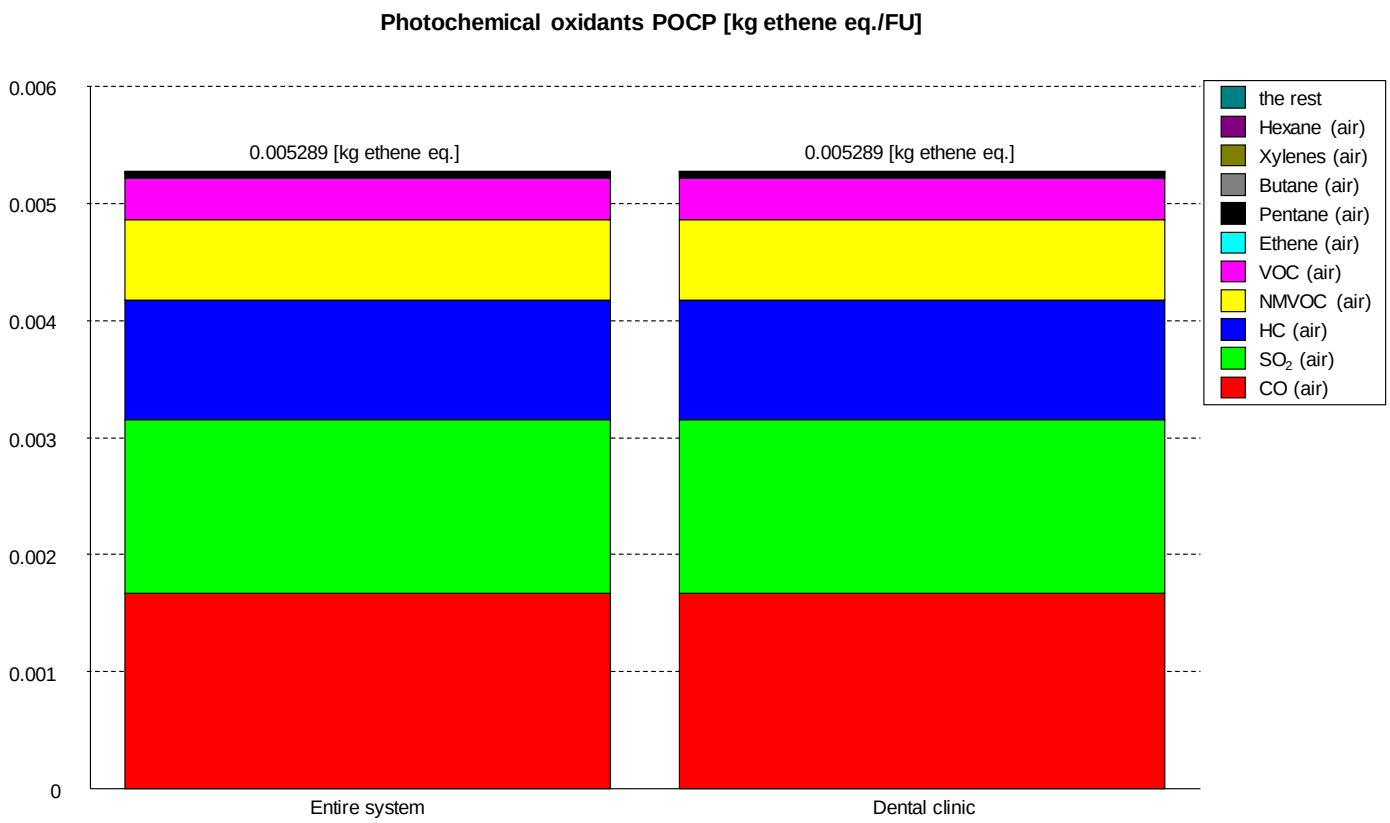

Figure 40 Photochemical ozone creation potentials (POCP) from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in kg ethene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

Figure 41 Human toxicity values from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

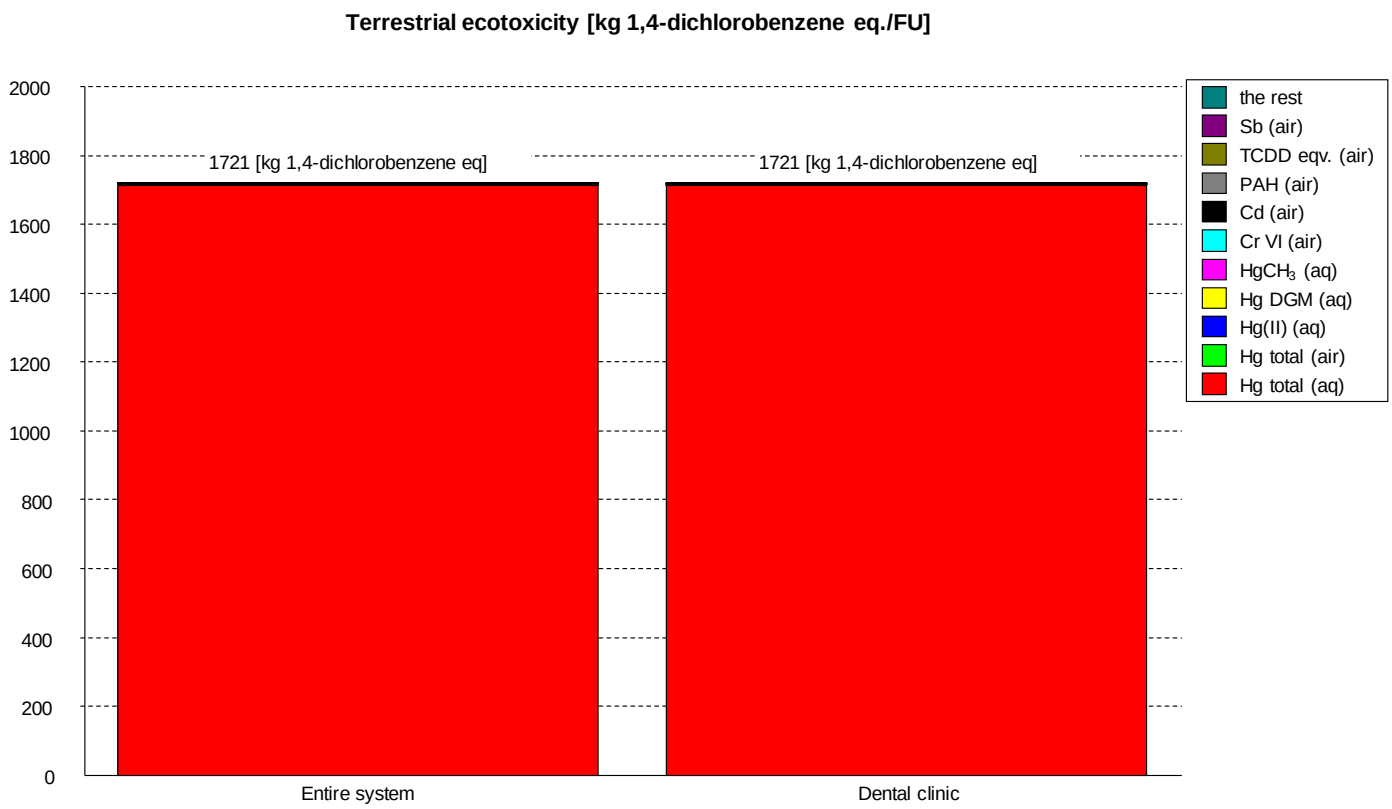

Figure 42 Terrestrial ecotoxicity values from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

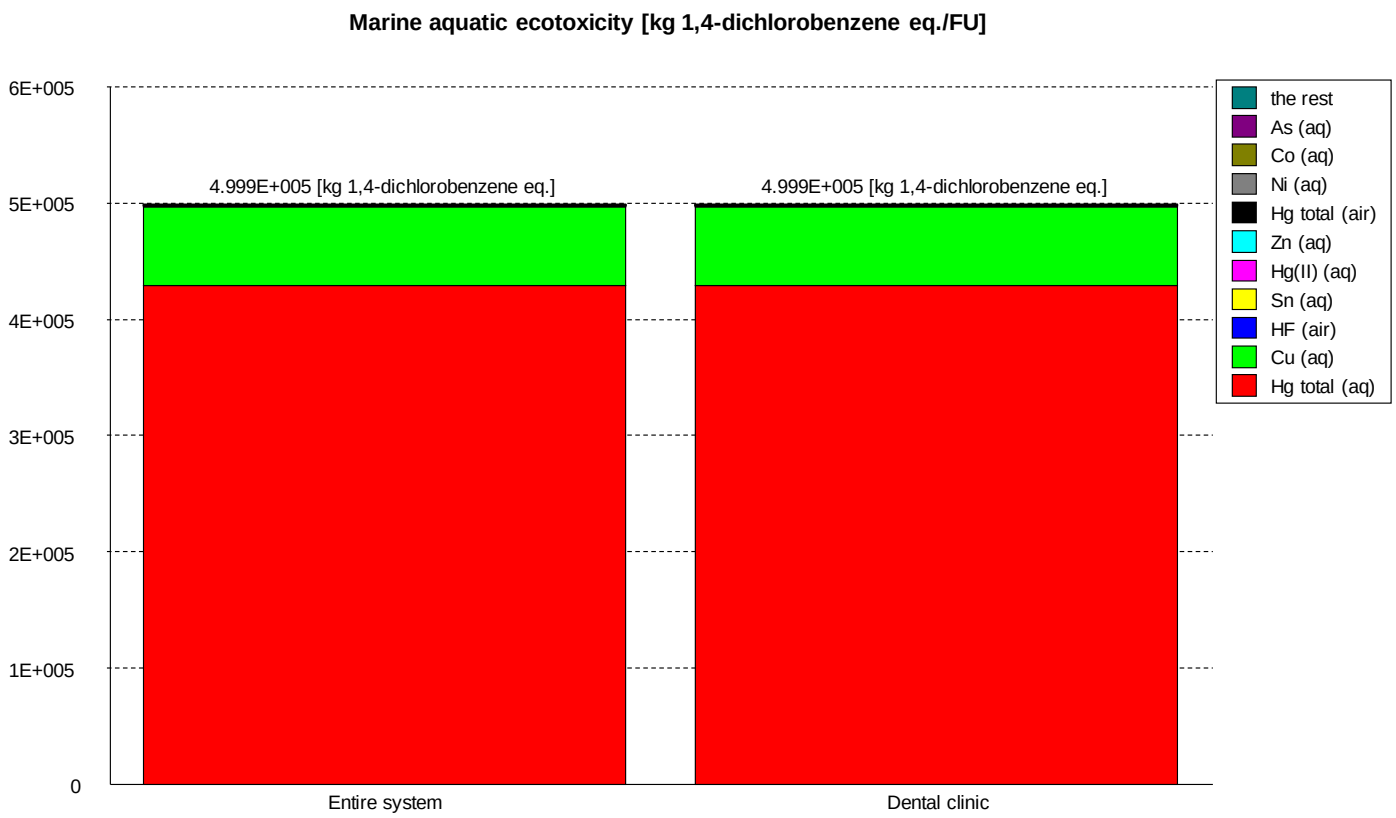

Figure 43 Marine aquatic ecotoxicity values from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

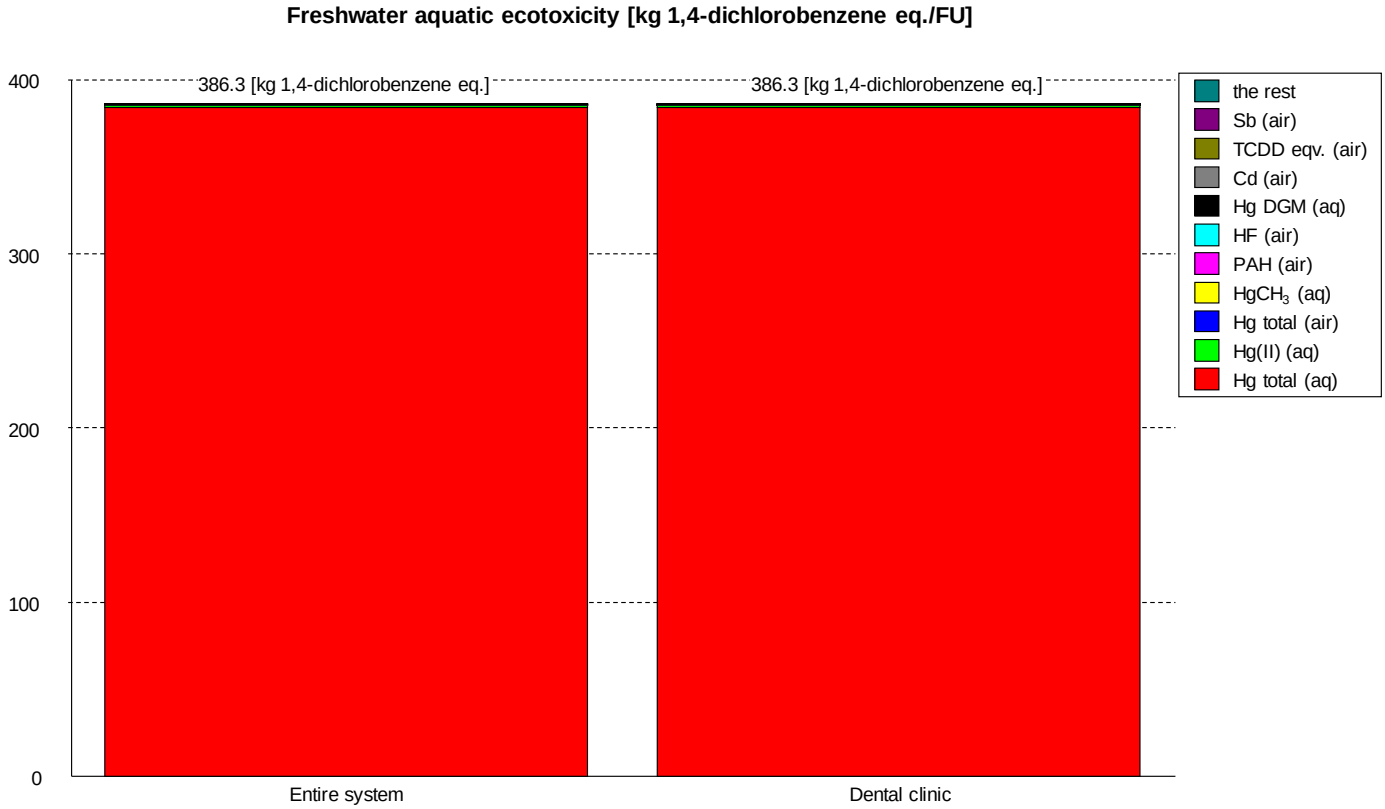

Figure 44 Freshwater aquatic ecotoxicity values from the entire LCA system including only the Dental clinic without Hg/amalgam separation and expressed in kg 1,4-dichlorobenzene equivalents per functional unit. The functional unit is one dentist's chair for one year of operation (226 working days). Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

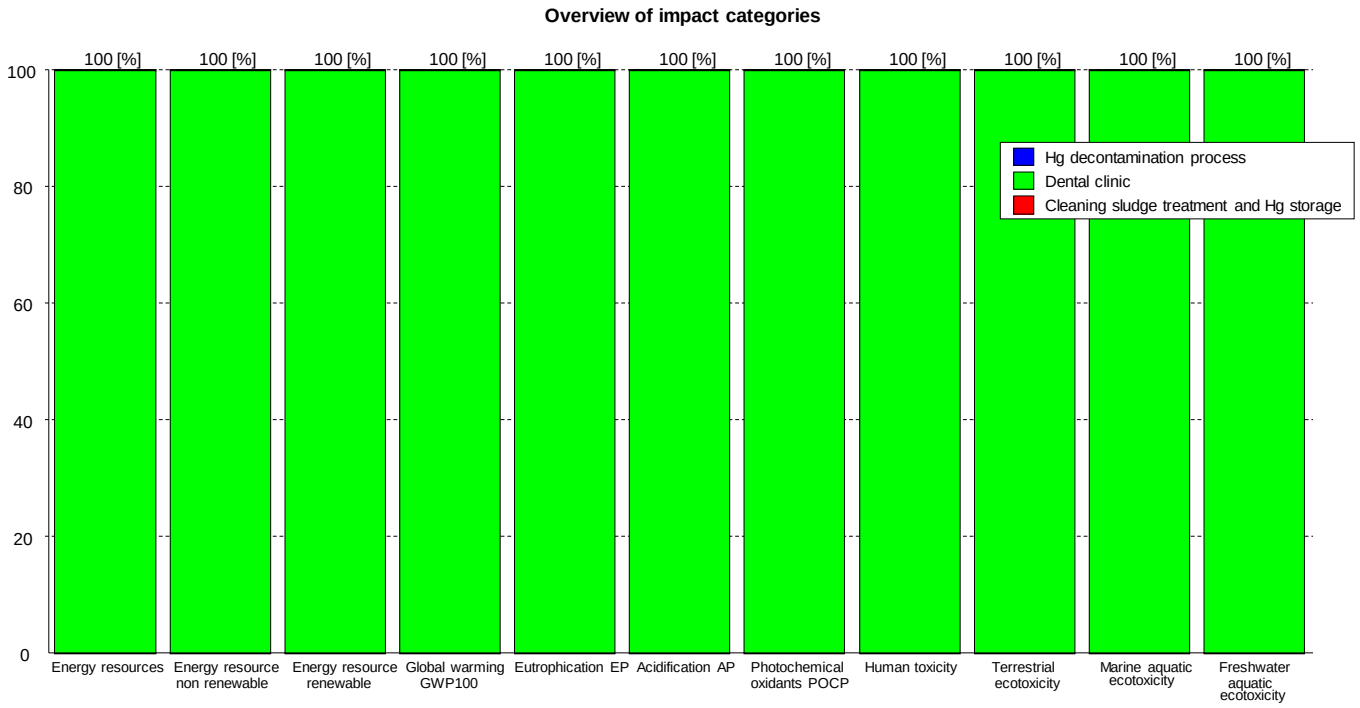

Figure 45 Overview of impact categories showing the relative contribution from the different parts of the LCA model. Scenario 3: with no mercury or amalgam separation or handling, all to recipient.

9 Discussion, conclusions and recommendations

9.1 Discussion

As previously shown in this study, most of the amalgam is separated by the amalgam separator, which is placed either directly in the dentist's chair (dry system) or at the end of the sewage-pipe system in the building, usually in the basement (wet system). However, the separation of amalgam in the separator is not complete since very fine-grained amalgam from e.g. drilling and grinding as well as dissolved mercury in the aqueous phase follow the wastewater into the main sewage system, as the separator is based on sedimentation and lacks e.g. an absolute filter for removal of particles and carbon filters to separate dissolved Hg in the aqueous phase. In the LCA models, a purification rate of 98.6 % has been assumed for the separator. This condition and the fact that there is also an emission of Hg to air via the suction system's ventilation, means that the dental clinic itself contributes with the largest emission amounts of Hg to the recipient from the entire system. The Hg decontamination process itself or the disposal and final storage of Hg only contributes to a minor part of the total emissions of Hg. However, it should be noted that the project did not have access to direct emission data from the Hg sludge and separator processing but were estimated based on Hg concentrations in outgoing air and water.

From the above conditions, one can conclude that the total Hg emissions could be reduced by an improved filtering technique on outgoing water and air from the dental clinics. The discharge of Hg otherwise passes through the sewage system to the sewage treatment plant where it can be discharged with outgoing water or end up in the sewage sludge.

The amount of amalgam that accumulates in the dental clinic's sewage pipe system depends on several different factors and can therefore vary greatly between different clinics. Aspects affecting the accumulation of amalgam in the pipelines can e.g. be; the slope of the pipe system, the water flow in the pipes, the material and surface structure of the conduits, biogenic growth in the conduits etc. This condition is also shown by the varying amounts of amalgam obtained from the various Hg decontaminations. The design of the clinics' sewage pipe systems is therefore an important aspect for the remediation, and in the long term it might be conceivable to design the pipe systems in such a way that recurring Hg remedies can be minimized and most of the amalgam can be captured in the separator.

In systems with anaerobic environments and microbial growth, together with inorganic mercury, there may be a risk that methyl mercury ($HgCH_3^+$) can be formed. In the chemical analyzes of outgoing water, methyl mercury has also been found. This should be analyzed further to gain an understanding of the circumstances under which methylmercury can be formed and how Hg remediation is affected by this.

The sludge from the decontamination and the amalgam separators goes to a process where the sludge is dewatered and distilled at high temperatures to separate Hg and finally deposit it for all time. The amalgam separators are emptied of amalgam and cleaned and then reused at the dental clinics. The residue from the high-temperature distillation is then taken care of by external companies to extract the remaining metals (Ag, Cu, Sn). These recycling processes are slightly outside this project and in addition, it has not been possible to access technical data from these processes. In general, however, it can be said that recycling these metals can be a positive side effect of the process of extracting and final storage of Hg from amalgam. This metal recycling should then be compared with other metal recycling of these metals as well as new recovery of the metals from ore. The total resource utilization of these metals must also be considered. This means that the recycling process should be energy wise and environmentally in parity or better than these processes.

In this study, we also compared today's Hg management system for dental clinics with some alternative methods. These are reference scenarios entirely without purification of amalgam (scenario 3) where this goes straight into the recipient and a scenario with only amalgam separation and subsequent storage of amalgam (scenario 2). The amalgam separators are emptied of amalgam and are locally cleaned and reused in the same way as in today's system. Figure 46 to Figure 55 shows a comparison of these scenarios for all environmental impact categories included in the study.

Figure 46 shows the metal balances for the metals included in the amalgam, for the different scenarios. As can be seen, most of the metals (Ag, Cu, Sn) are recovered except for mercury that is finally stored in today's Hg management system (scenario 1). In the management system with only amalgam separation, all metals in the amalgam are finally deposited, which is then lost and then entails a permanent resource use of these metals but remain in available form. In scenario 3, however, all metals disappear as emissions to the surrounding recipient.

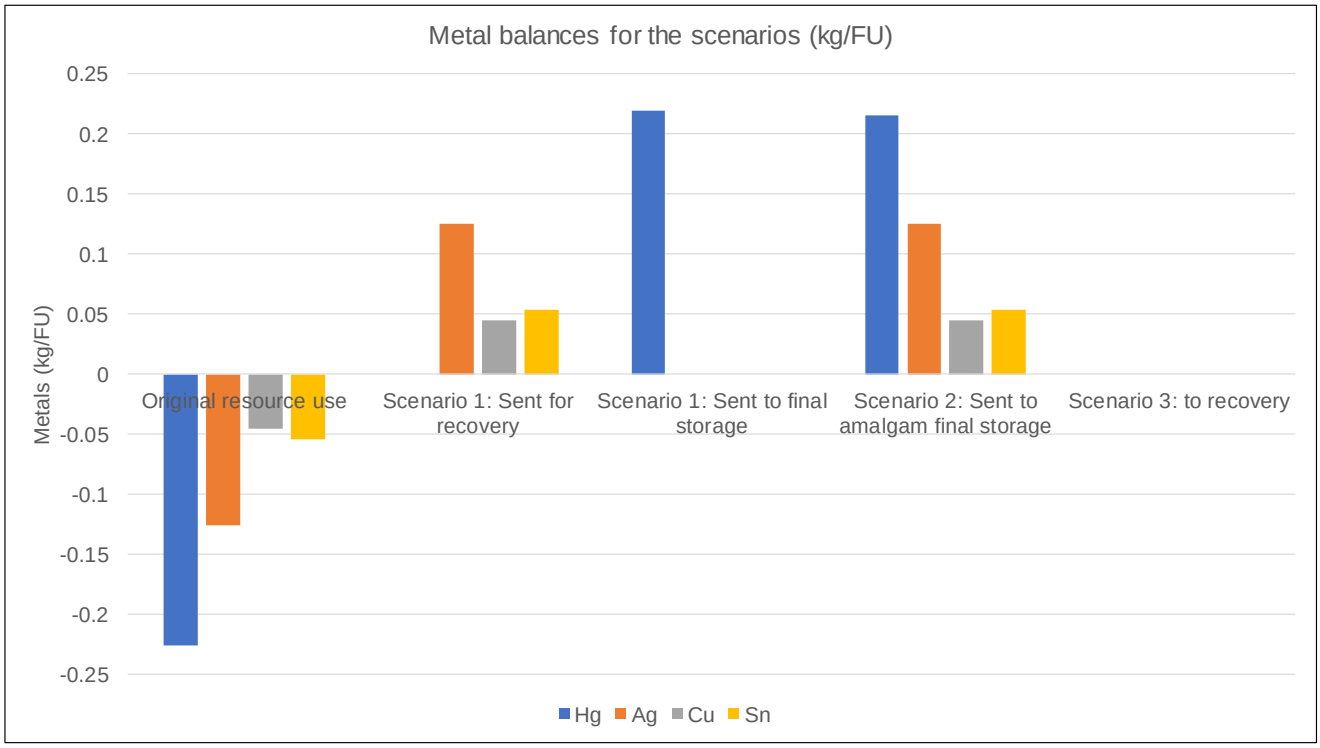

Figure 46 Scenario comparison of the metal balances showing also the resource use of the metals.

The total emissions of mercury from the different scenarios are shown in Figure 47. The figure clearly shows that the cleaning measures for Hg found in scenario 1 and scenario 2 have a good reducing effect compared to scenario 3 without separation and cleaning. The system with only Hg separator (scenario 2) also has a good reducing effect of emissions.

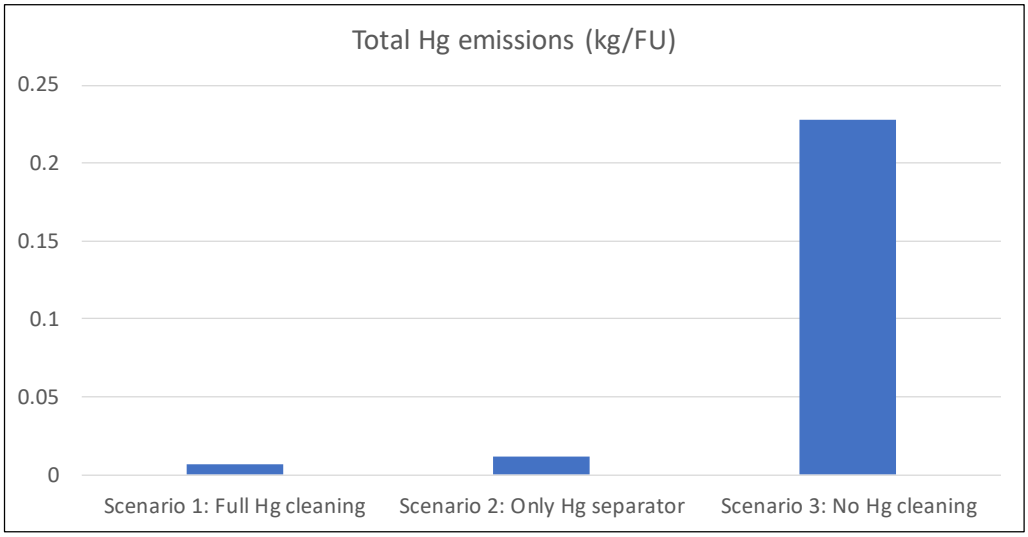

Figure 47 Scenario comparison of the total Hg emissions from the entire LCA model systems.

The use of energy resources is of course also higher when using a more complex cleaning method as shown in Figure 48. The fact that the system without purification has such high energy resource use is due to the fact that the suction system at the dental clinic is included as part of the cleaning technique.

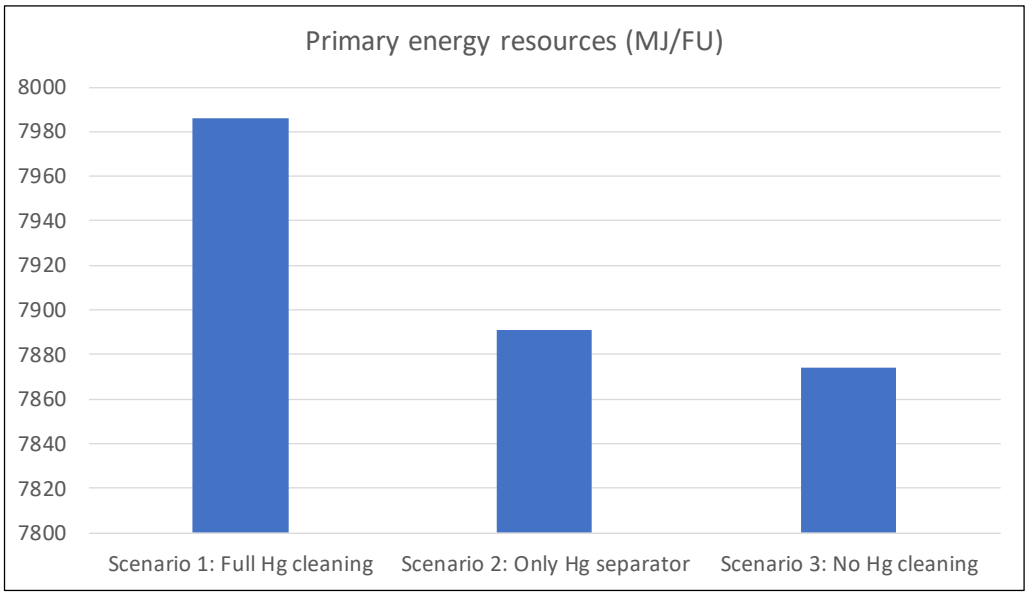

Figure 48 Scenario comparison of the use of primary energy resources for the entire LCA model systems.

The emissions of greenhouse gases that give rise to global warming will then also be lower for a purification system that uses less energy and is less complex or for a case without purification, as shown in Figure 49.

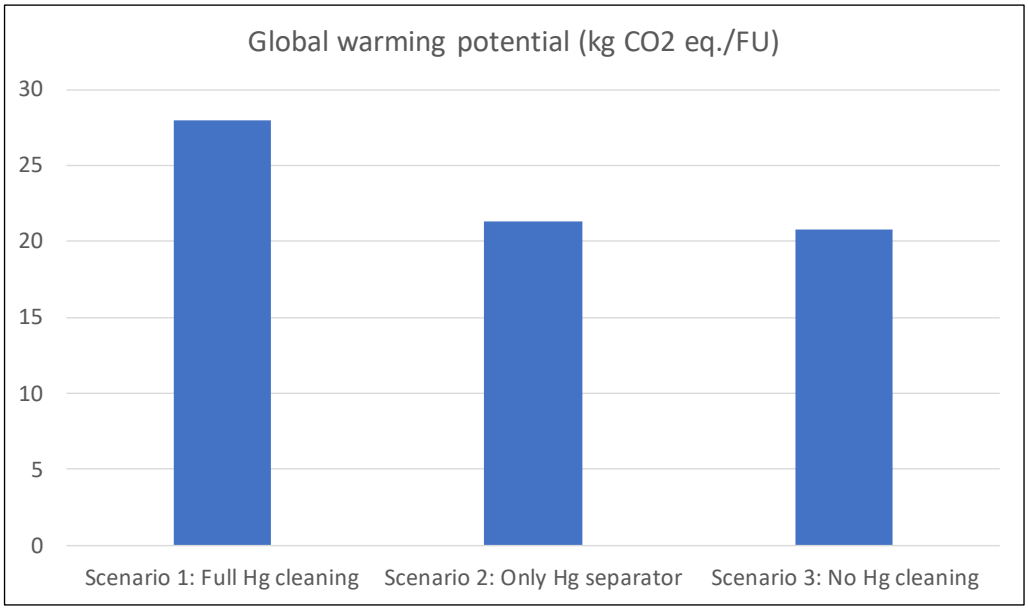

Figure 49 Scenario comparison of the Global warming potential (GWP100) for the entire LCA model systems.

The eutrophication and acidification potential also become lower for a less complex system or a system without Hg purification, as shown in Figure 50.

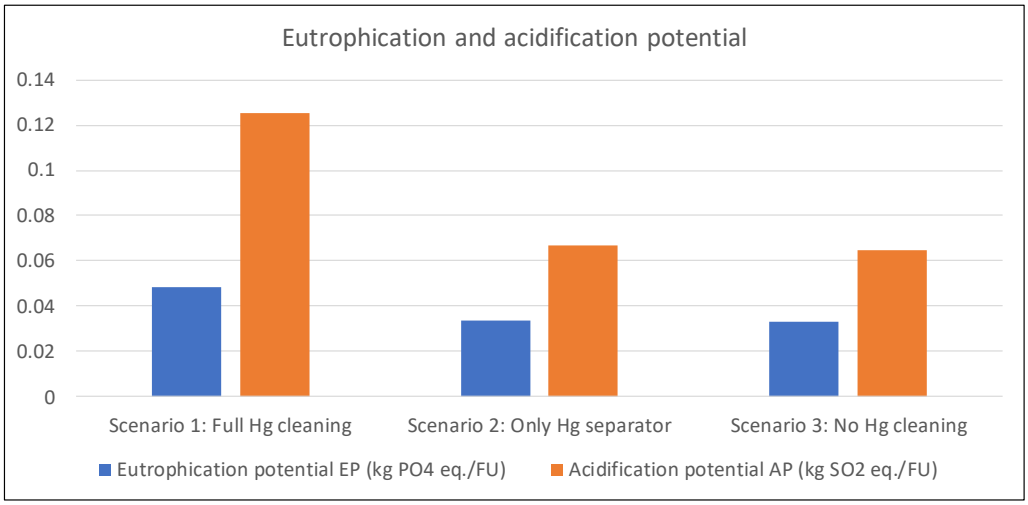

Figure 50 Scenario comparison of the eutrophication and acidification potential for the entire LCA model systems.

The formation of ground-level ozone is mainly due to the availability of hydrocarbons and the NO_X environment where the emission occurs, as well as the availability of sunlight. The formation of POCP is thus calculated based on an assumed situation for the method and is assumed to be the same in the three scenarios. The values shown in Figure 51 are thus formation potentials that are best used as a comparison between the different scenarios. As shown in the figure, this also shows an increased emission level for a more complex cleaning method.

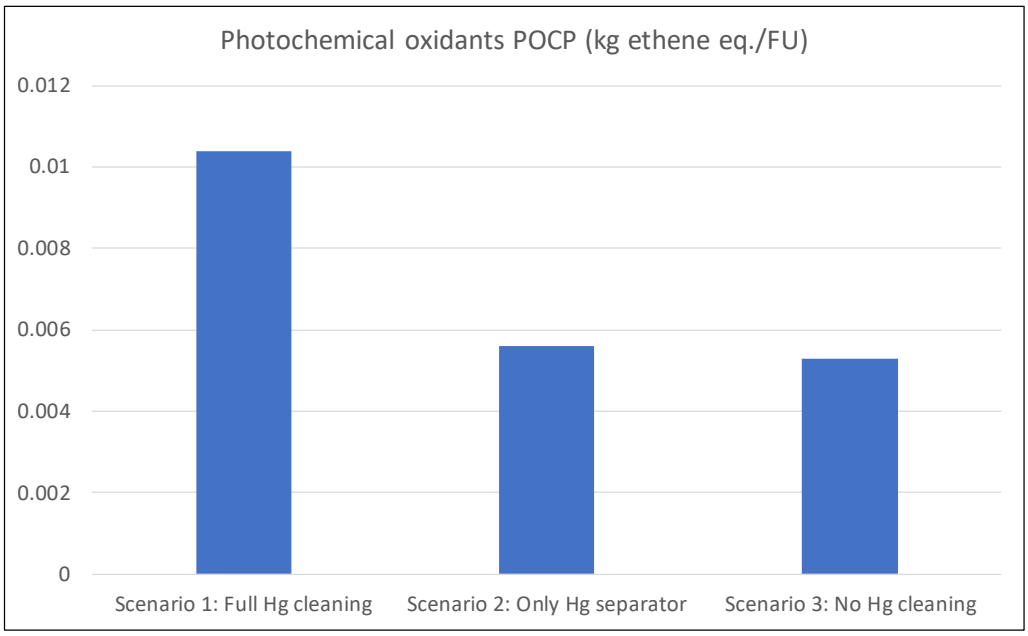

Figure 51 Scenario comparison of the photochemical ozone creation potential (POCP) for the entire LCA model systems.

Figure 52 to Figure 55 shows a comparison of four different toxicity values for the three different scenarios. The values are shown in kg 1,4-dichlorobenzene equivalents per functional unit. The results show Human toxicity, Terrestrial ecotoxicity, Marine aquatic ecotoxicity and Freshwater aquatic ecotoxicity. As clearly shown in the figures, all toxicity values indicate major improvements when mercury cleaning methods are used. Even the use of only an amalgam separator provides major improvements. We have also noted that high values are obtained for Marine aquatic ecotoxicity where the toxicity factors for this method are also high. However, we have not really been able to find a good explanation for these high values compared to the other toxicity values.

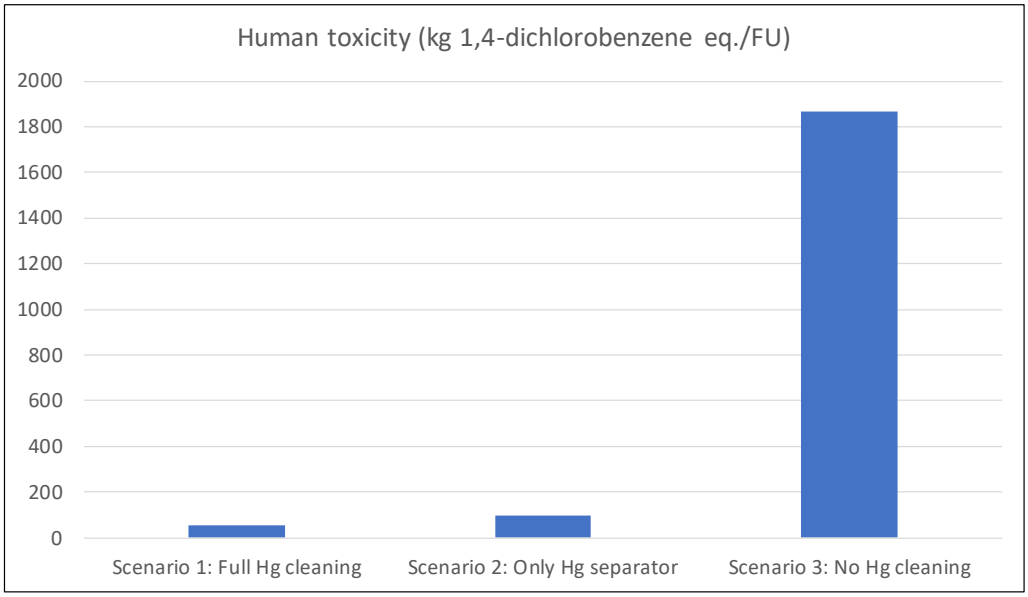

Figure 52 Scenario comparison of the Human toxicity for the entire LCA model systems.

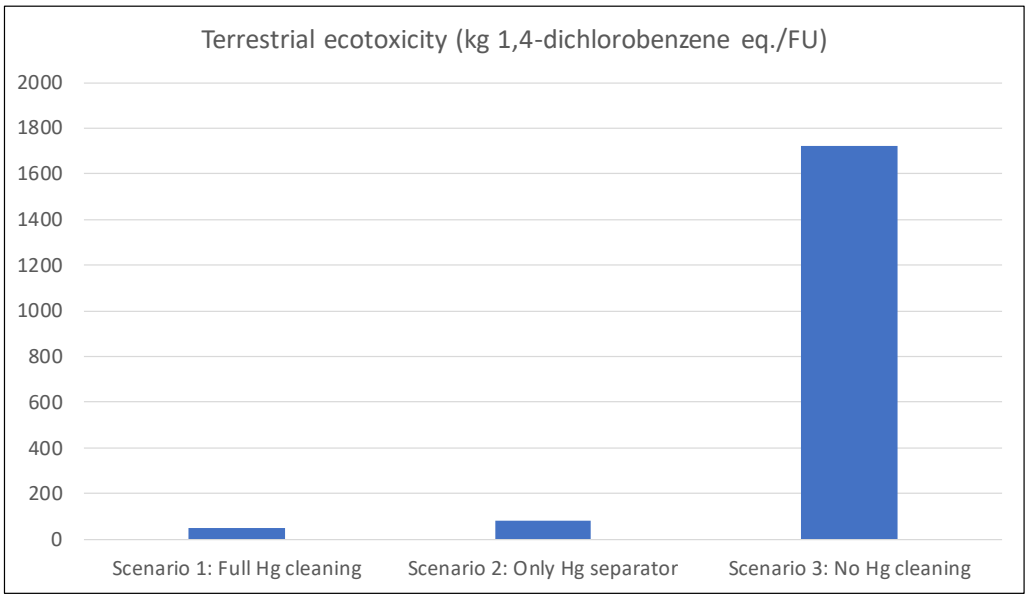

Figure 53 Scenario comparison of the Terrestrial ecotoxicity for the entire LCA model systems.

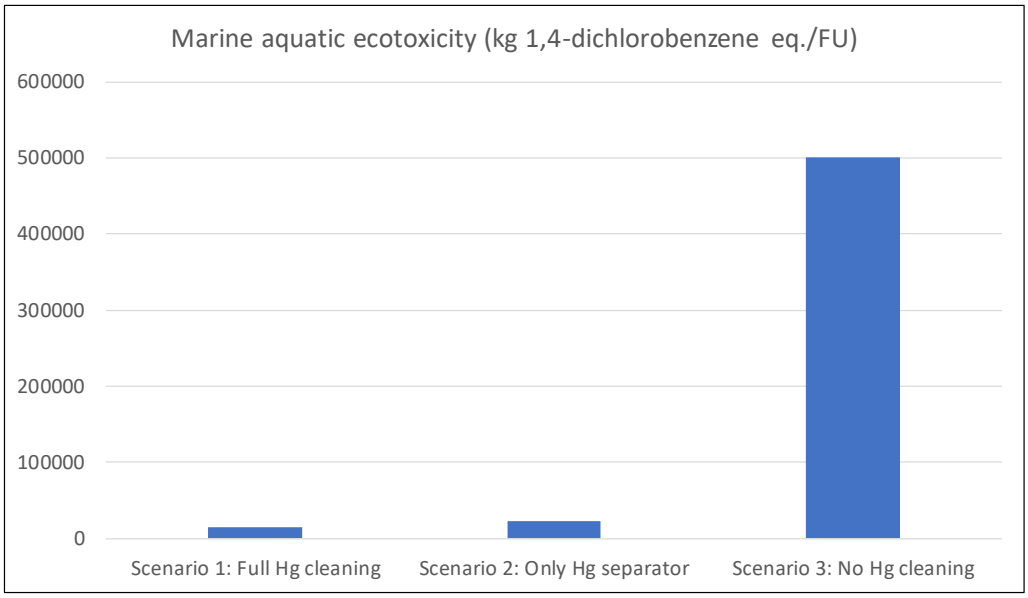

Figure 54 Scenario comparison of the Marine aquatic ecotoxicity for the entire LCA model systems.

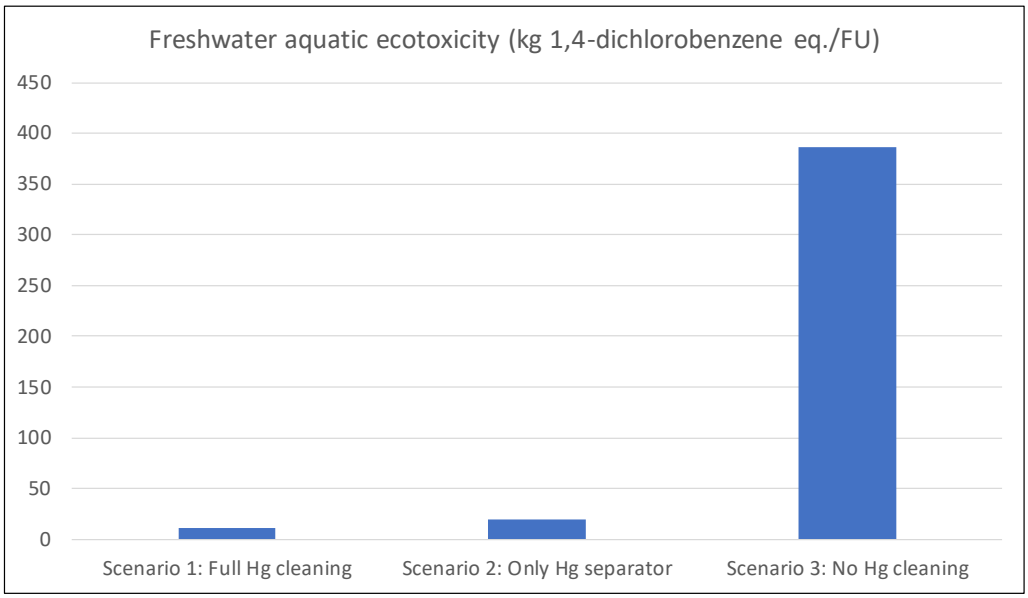

Figure 55 Scenario comparison of the Freshwater aquatic ecotoxicity for the entire LCA model systems.

9.2 Conclusions

Air measurements showed diverse air Hg concentrations in different dental facilities. IVL conclude that the Hg concentration depends on too many factors (such as; type of facility, age of facility, number of chairs, type of ventilation system etc.) to be able to generalize how much handling of dental amalgam contributes to the indoor Hg concentrations at dental clinics. At no clinic has harmful Hg levels been observed, even during DC activities when the levels increased significantly. Air concentrations dropped quickly after the DC, which shows a quick recovery back to background indoor levels, possibly thanks to good ventilation.

IVL water sampling and analysis are not comparable with SRAB's and Medentex techniques, which makes direct comparison unsuitable. Although, results from this study showed that small amalgam particles and dissolved Hg species pass the AS filters and are discharged to wastewater. All visited clinics were different and had different set-up of the vacuum system. Water was sampled at different clinics, at different times of the day as random samples. This is not the best way to achieve representative samples. Therefore, no conclusions regarding the total amount of emitted Hg into water should be drawn from results of this study.

IVL was able to measure different mercury species in the water, which added more information about the behavior of Hg in dental systems than before studied. Of total Hg measured in water samples, 4 % was in its oxidized form as Hg(II), which probably originates from the oxidation of amalgam particles in the water, 0.5% as dissolved gaseous mercury (DGM) and 0.05 % was as the bio accumulative form methylmercury (MeHg). DGM and MeHg is generally formed by certain bacteria.

Although MeHg and DGM concentrations were low, the finding of MeHg and DGM in the samples indicates a potential in-situ formation in the enclosed pipe systems of dental clinics. Further studies must confirm that these systems pose a suitable place for MeHg formation, which needs an oxygen poor environment and the presence of certain mercury resistant bacteria (Hu et al., 2013).

Built-up dental amalgam stuck in the pipe system of a dental clinic, as well as amalgam in the amalgam separator, can dissolve and release small amounts of Hg into the passing water. Dissolved Hg species can pass the AS and are therefore leaking into the environment. The removal and cleaning of the pipes by DC could lower the risk of the formation of dissolved Hg species, and thus lower the environmental burden of Hg.

9.3 Recommendations

Based on experiences gained during this study, IVL here present some recommendations for improving the handling and collection of Hg from dental clinics.

It has been shown that small amalgam particles can pass the AS and be discharged to the waste water. Therefore, a development of more efficient AS filters is recommended. Also, dissolved mercury species in water can pass the AS filter. A development of a technique to capture dissolved mercury species in water is needed to supplement the AS, which with present technique mainly captures bigger particles.

The emissions of Hg to air, through the vacuum system, can easily be reduced by using an active coal filter. Active coal absorbs and collects gaseous mercury and is thus cleaning the exhaust gases from Hg. The technique is cheap and reliable and is easy to install.

A well-functioning ventilation system is important to ensure good air quality and low indoor Hg levels for staff and patients at dental clinics.

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11 Annex 1 - Data collected during dental clinic visits

Table 7 Measured average GEM concentrations in premises of dental clinics A-J before decontamination (DC), during DC and measured directly after DC was finished.

Before DC ——— Clinic	Entrance/Reception/Waiting room/Guest toilet GEM [ng/m^3]	Staff premises GEM [ng/m^3]	Treatment room(s) GEM [ng/m^3]	Cellar/ room with AS GEM [ng/m^3]	Outlet air vacuum system GEM [ng/m^3]
A	230	330	540	2 850	6 300
B					4 900
C	22	34	21	144	9 600
D	17	8	12		1 900
E	230	530	550		
F	360		520	123	830
G	35	110	72		
H	33				
I	180		850	3 600	510
J	450	400	1 300		

During DC _____ Clinic	Entrance/Reception/Waiting room/Guest toilet GEM [ng/m^3]	Staff premises GEM [ng/m^3]	Treatment room(s) GEM [ng/m^3]	Cellar/room with AS GEM [ng/m^3]	Outlet air vacuum system GEM [ng/m^3]
A					
B					
C	150				
D					
E	292		290		
F			1 350		
G	460		1 350		2 900
H	1 020	24	820		2 700
I			1 070		
J		1 800	3 600		

After DC _____ Clinic	Entrance/Reception/Waiting room/Guest toilet GEM [ng/m^3]	Staff premises GEM [ng/m^3]	Treatment room(s) GEM [ng/m^3]	Cellar/room with AS GEM [ng/m^3]	Outlet air vacuum system GEM [ng/m^3]
A					
B	650	190	360		7 200
C	23		18		
D					
E					
F					
G					
H	600		340		
I			1 015		
J		3 400	3 000		

Table 8 Mercury concentrations of samples collected and analysed by IVL.

Sample ID.	DGM [µg/L]	Hg(II) [µg/L]	HgTot [µg/L]	MeHg [µg/L]
A1	-	7	2200	-
A2	-	6	1300	0.1
A3	15	5	570	0.02
A4	2	-	670	-
B1	-	0.7	1040	0.1
B2	-	1320	110000	2
B3	-	6	1010	0.04
C1	-	331	1200	0.005
C2	0.006	250	1500	-
C3	3	180	600	0.02
C4	0.2	123	280	0.2
C5	-	110	24	-
D1	0.008	0.10	165	0.005
D2	-	0.03	130	0.03
D3	0.010	0.2	49	0.0009
D4	0.006	0.05	84	0.02
E1	-	2.8	35	0.006
E2	-	0.4	24	-
E3	0.1	0.4	2200	-
E4	-	333	48000	1023
E5	-	11	760	-
F1	-	1	1700	-
F2	0.4	5.0	6200	-
F3	0.02	0.02	11	-
F4	-	0.09	77630	791
G1	-	-	100	-
G2	0.0007	0.7	100	-
G3	-	2.2	52	-
H1	0.05	0.3	2000	0.006
H2	0.12	44	16087	-