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Combining life cycle analysis, human health and financial risk assessment for the evaluation of contaminated site remediation

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In the present study, the REC (Risk reduction, Environmental Merit and Costs), ReCiPe and PRINCETM methods for the estimation of the environmental, health and financial impacts of a soil remediation process have been evaluated. The evaluation was based on a case study in which a choice had to be made between soil excavation and steam extraction for the remediation of a former oil and fat processing plant. The example shows that it is complicated to come to one overall best remediation option, especially when different stakeholder preferences have to be taken into account. Results of the case study suggest that, besides environmental and human health and cost, the financial risk associated with the remediation project is also an important aspect to include in the evaluation.

Keywords: BTEX; contaminated site management; environmental impact; LCA; steam extraction

1. Introduction: selection of the best technology for contaminated site remediation

The selection of the best technology for contaminated site remediation has evolved from a rather simple and linear process into a complex procedure involving an increasing number of aspects that are all relevant for site remediation and management. While in the mid-1970s decision systems were mainly cost-based, the availability and feasibility of technologies was added as a criterion in decision making in the 1980s (Pollard *et al.* 2004). When soil remediation was initiated in Flanders (Belgium) in the mid-1990s, the assessment of soil contamination was risk based, while the BATNEEC principles (Best available technique not entailing excessive cost) were applied to the selection of soil remediation techniques and are still the main criteria upon which remediation experts rely.

Since the beginning of the twenty-first century, the importance of a more holistic approach to the management of contaminated land is recognised. This should ideally include an assessment of the environmental and health risk of contamination, an assessment of the environmental, social and health impact of the remediation process and a cost-benefit analysis of the remediation project (Pollard *et al.* 2004). As an answer to this growing complexity of relevant issues to take into account in soil remediation projects, several systems for decision making in contaminated site management have been developed over the last few years, taking into account multiple aspects such as the cost of remediation, the impact on human health and agricultural productivity, and the

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economic gain after remediation (Scholz and Schnabel 2006). For example, SuRF-UK developed a framework for balanced decision making in the selection of the remediation strategy to address land contamination as an integral part of sustainable development and defined 15 categories of environmental, social and economic indicators that can be used for sustainability assessment in support of remediation decision-making (Bardos *et al.* 2011).

Several examples and case studies that have been worked out during the last decade show that a life cycle framework can be helpful for the selection of site remediation options with minimum impact on the ecosystem and human health (Lemming, Hauschild, and Bjerg 2010). In the simplest models, only CO₂ emissions are used to calculate the 'carbon footprint' of a soil remediation process. The Soil Remediation Tool (SRT, AF Centre for Engineering and Environment 2010) and SiteWiseTM (US) (Naval Facilities Engineering Command 2011) have been developed to calculate the environmental impact of different phases of a site remediation project, expressed as a carbon footprint. A more detailed life cycle assessment (LCA) takes into account many more aspects such as emissions of contaminants into air, water and soil, energy use, generation of waste, etc.

The costs of soil remediation projects generally include project preparation and management, demolition work on the site, ground work and processing of soil, extraction and treatment of groundwater, monitoring system and environmental supervision, but the benefits for the environment and human health are usually not expressed in monetary terms, and a cost-benefit analysis of contaminated site remediation (e.g. Environment Agency 1999; van Wezel *et al.* 2007; Irvinne and Denne 2010) is not commonly performed. Moreover, certain soil remediation technologies, especially the more 'gentle' remediation technologies, are characterised by a lot of uncertainty with regard to the time frame within which the final remediation goals will be achieved. Unexpected situations can also result in an increase in the costs of the remediation project. This uncertainty associated with soil remediation projects makes it difficult to make a good estimation of the cost of the remediation. Contaminated sites carry great financial risk, and are potentially a great liability for their owners and investors.

In the present study, several tools that enable quantification of environmental and health impacts and financial risk of soil remediation projects were applied on a case study in which a selection had to be made between two soil remediation options. In particular, a choice had to be made between excavation of the contaminated soil, combined with groundwater remediation via pump and treatment, and an *in situ* technique such as a soil and groundwater remediation technique. The choice of the soil remediation options to be evaluated was based on a preliminary selection taking into account the type of soil contamination (with mineral oil and BTEX – benzene, toluene, ethylbenzene and xylene – as relevant contaminants), soil composition, extent (depth of contamination, area of contaminated site) of contamination, availability of technologies, etc. The two selected soil remediation options will be described in more detail in the Methodology section. Environmental and human health impacts of the two remediation options were assessed using a life-cycle framework, as is included in the REC (Beinat *et al.* 1997) decision support system and a life cycle assessment (LCA) with the ReCiPe impact assessment method (Goedkoop *et al.* 2012). Besides the cost of the remediation options, the financial risk of both remediation options was also estimated based on the PRINCETM method.

Other aspects, such as the involvement of different stakeholders in the decision-making process, the social acceptance of the soil remediation project, the value of remediated land, etc. were not taken into account in order to keep a clear focus in the paper. In view of the many aspects involved in contaminated land management and the different tools that are available and address one or more of these aspects, the implications of applying different

tools alongside each other deserve particular attention (Pollard *et al.* 2004). Therefore, the combination of the results in order to establish the best choice from an environmental, human-toxicological and financial point of view is also discussed.

2. Methodology

2.1. Description of the case study

In Flanders (Belgium), an obligation exists to carry out a preliminary soil investigation at every transfer of land on which a 'risk activity' is in operation or has been operated. The preliminary soil investigation consists of a historical investigation to check what type of risk activities have been carried out at the site and what was their exact location. The case studied in this paper concerns the remediation of a brownfield located in Flanders, with a surface of 1.6 ha where a former oil and fat processing plant was operating at the beginning of the twentieth century. For reasons of confidentiality, no map of the area can be provided. In the near future, the site will be redeveloped as a residential area with apartments. Based on the historical information, a limited number of soil and groundwater samples were taken and analysed. These results of this preliminary investigation indicated that the activities of this plant resulted in the contamination of soil and groundwater with oil and fat. In addition, the leakage of fuel tanks has contributed to the contamination of the site after closure of the oil and fat factory. Soil and groundwater are contaminated with mineral oil and BTEX (above threshold values) and also contain traces of polyaromatic hydrocarbons and heavy metals (below threshold values). Because the preliminary investigation proved that there may be a need to remediate, an 'exploratory' investigation (which is much more detailed than the preliminary investigation) was carried out in order to point the extent (area and depth) of the soil and groundwater contamination.

This exploratory soil investigation indicated that the soil on the site is a sandy soil, with a lot of debris in the upper two metres. Below this sandy soil layer the grain size of the soil becomes more silty, until a depth of 3.4 to 7 m is reached, depending on the exact location on the site. Finally, at a depth of 3.4 m to 7 m, a layer of clay is encountered. The soil is characterised by a severe contamination by mineral oil, moderate to high levels of contamination by BTEX and a low-level contamination by heavy metals and polyaromatic hydrocarbons. Only mineral oil and BTEX will be considered because the other contaminants occur in concentrations below soil remediation values. The maximum depth at which contamination occurs is 5 m. The depth of the groundwater table is between 0.5 and 1 m and groundwater is also contaminated by mineral oil and BTEX. At some locations, mineral oil occurs as a LNAPL (light non-aqueous phase liquid) layer with a thickness of approximately 10 cm on top of the groundwater table.

2.2. Selected remediation options and their environmental effects and costs

2.2.1. Soil excavation

Soil excavation and off-site cleaning is still the most frequently applied soil remediation technique in Flanders (Goovaerts *et al.* 2007). The contaminated site is characterised by good accessibility and 'hot spot' contamination occurring at a limited depth (not deeper than 5 m), which makes soil excavation a feasible remediation option. Moreover, no buildings are left on the site since the brownfield will be completely redeveloped into a residential area. During excavation, volatile emissions, odour nuisance and noise from

excavators and transport equipment are possible adverse environmental effects. In addition, fuel is used to operate the diesel engines from the excavators, which is estimated to be approximately 0.1 litre of diesel per m³ of excavated soil (Goovaerts *et al.* 2007). If the contaminated soil is (periodically) stored on the site itself, precautions have to be taken to avoid secondary contamination of soil and groundwater through leaching from excavated soil. If soil is transported to a soil remediation facility (off site), the transport of soil also has to be taken into account. In the present study, treatment of the excavated soil was assumed in a treatment facility located 40 km from the contaminated site. However, only the transport of the contaminated soil and the refilling of the site with clean soil were taken into account, but not the treatment of the soil because no precise data could be obtained. The cost of treatment varies according to the type of plant, the source of energy/nutrients used, the type of soil being treated, the properties of the contaminants being treated and the soil treatment standard. The cost of soil excavation depends on the depth and amount of contaminated soil, the accessibility of the location and the capacity of the excavators used. For the groundwater remediation, a pump and treatment method was applied, using an active coal filter for groundwater treatment.

2.2.2. *In situ remediation: steam extraction*

During the preliminary investigation phase, phytoremediation with trees was considered as an *in situ* technique because it would take approximately four years before the redevelopment of the site will effectively start. Nevertheless, this option was not retained because four years is still a short time, especially for the mineral oil (C25-C40) contamination that is only degraded very slowly (Singh and Ward 2004). Moreover, mainly contaminants in the groundwater will be taken up by the trees (Schnoor *et al.*, 1995). Air sparging and soil vapour extraction is feasible to remove the BTEX contamination, but would still require excavation of a part of the site. Steam extraction has the ability to treat the mineral oil and BTEX contamination in soil and groundwater (Davis 1998). Moreover, the experience with steam extraction is limited in Flanders and the present case study could serve as an example to illustrate the possibilities of this technology.

Steam extraction is a remediation technology that was originally developed by the petroleum industry for the extraction of oil from oil reservoirs. At present, the technology has been further developed to be used in the removal of organic contaminants from soil (Davis 1998). Steam extraction is an *in situ* technique, allowing buildings to remain in place during remediation. Steam is injected into the contaminated soil, and both injection above or below the groundwater table is possible. In the centre of the remediation zone, composed of the different injection points, an extraction well is installed, through which the contaminated gas stream (steam) is collected by means of a vacuum pump. The gas is brought to a condenser, where contaminants and water can be separated. Contaminants mobilised by the steam injection process can be treated at the surface using conventional technologies such as thermal oxidation, catalytic oxidation or carbon adsorption (Davis 1998; Schmidt *et al.* 2002). In the present case study, uncondensed gases, water and condensed gases were cleaned over active coal filters. The equipment necessary to perform steam extraction mainly consists of a steam generator, a distribution system connected to the injection wells, an extraction system (pneumatic pumps and a vacuum pump), coolers and condensers and the purification equipment for gases and water. The energy demand, mainly necessary to generate steam, is the main contributor to the environmental burden caused by this technique. Another potential adverse effect of this

technique compared to soil excavation is the more uncertain result of the remediation. Residual contamination in a treated soil cannot be ruled out, while with soil excavation the contamination is removed together with the soil that is excavated.

2.3. Environmental impact assessment

The environmental impact assessment was carried out using two evaluation tools, namely the REC (Risk reduction, Environmental merit and Cost) method (Beinat *et al.* 1997) and the ReCiPe method (Goedkoop *et al.* 2012), which is incorporated in the SimaPro software program (Pré Consultants 2011). In the REC method, the environmental impact assessment part (Environmental merit, 'E' in REC) is based on the principles of LCA. Environmental merit in the REC model is designed to aggregate several types of environmental costs and benefits (e.g. waste production, clean soil and groundwater as a result of the remediation, etc.) into an index, which shows the overall environmental balance of soil remediation (Beinat *et al.* 1997). The aspects which are included in environmental merit are based on the indications of a life cycle assessment carried out for soil remediation and on interviews with soil experts (cf. Nijhof *et al.* 1996).

ReCiPe is life cycle impact assessment (LCIA) method developed by a number of Dutch research and consultancy organisations (RIVM, CML, Pré Consultants, and Radboud University Nijmegen). The ReCiPe 2008 method for life cycle impact assessment provides a method to calculate life cycle impact category indicators as it helps to transform the long list of life cycle inventory results into a limited number of indicator scores that are determined at two levels: 18 midpoint indicators and 3 endpoint indicators. The midpoint indicators (e.g. fossil fuel consumption, water depletion, urban land occupation, etc.) are relatively robust, but are not easy to interpret, whereas the endpoint indicators (damage to human health, damage to ecosystems, damage to resource availability) are easy to understand, but more uncertain (Goedkoop *et al.* 2012).

For both assessment tools (REC and ReCiPe), there are differences in the way inputs and outputs are taken into account. It is not the purpose of the present study to carry out a detailed analysis of the impact assessment methods included in the REC and ReCiPe methods, since a detailed comparison and evaluation of both impact assessment methods has been analysed elsewhere (Cappuyns and Kessen 2012). Nevertheless, the most pronounced differences between both methods are presented in the following section.

2.3.1. Comparison between the environmental impact assessment models

Before discussing the environmental impacts of the remediation options, some differences between the evaluation methods (REC and ReCiPe) should be addressed, since this affects the outcome of the evaluation tools. For the REC method, only the total amount of waste generated (waste soil, wastewater, other waste) is required as an input, while in the SimaPro tool, the type of waste is specified, which results in a different environmental impact of the disposal of activated carbon or mineral oil waste. With regard to the actual and future land use of the site, only the REC model takes into account the amount of space occupied during soil remediation. The destination of the site once it has been cleaned is accounted for in the ReCiPe model, since here the transformation of an industrial site into an urban site is part of land occupation, which contributes to the natural resources impact category (Cappuyns and Kessen 2012).

2.3.2. *Inputs for the environmental impact assessment models*

The functional unit was set to the remediation of a site with an area the same size as the site in the case study (namely 1.6 ha), within a time frame of 90 days.

Data on steam extraction used as input in the life cycle impact assessment were obtained from a pilot test performed by the soil remediation company and from the engineer in charge of the soil remediation project. The data concerning soil excavation were also obtained with the help of this engineer, based on his experience with previous excavation projects. The main input data used for the environmental impact assessment are provided as supplementary material (see Appendices A and B). The total amount of soil and groundwater that has to be extracted and/or cleaned, the installation of the equipment necessary to perform the remediation (for example, drilling of wells), the energy and fuel demand of the different engines used (excavators, pumps, trucks, etc.), the use of natural resources (water to produce steam, activated coal for the filter), the generated waste streams (water, mineral oil) and the personal transport of the operators and workers, were all taken into account. The production of the equipment necessary to carry out the remediation and the transport of equipment to and from the site were not included in the analysis. For the weighting of the different environmental effects, standard weighting factors that are available in the REC and ReCiPe models, respectively, were used. The environmental merit in the REC method is a combination of environmental costs and benefits of soil remediation. Each aspect in the list has been weighted by a panel of experts to quantify its importance in the environmental balance. If the resulting index is positive, then the operations have a positive environmental balance. For the weighting in the ReCiPe method, we used the ReCiPe midpoint method, in the individualistic perspective and on a European scale.

The software used to operate the impact assessment methods REC and ReCiPe was Excel 2007 and SimaPro 7.3 (Goedkoop *et al.* 2010), respectively.

2.4. *Human health risk assessment*

The concern over soil contamination is primarily based on health risks, from direct contact with the contaminated soil, vapour from volatile contaminants, and from secondary contamination of groundwater, surface water and vegetables. In most countries, soil remediation standards are based on health and ecosystems. Critical values for concentrations in the soil are calculated, either on the basis of human toxicology or of ecotoxicology, retaining the most critical value as soil remediation standard. In the present study, human health risk was quantified by applying the risk module ('R') incorporated in the REC method (Beinat *et al.* 1997).

2.4.1. *Risk reduction within REC*

The risk reduction module within the REC model is an Excel based program that can be used to calculate the risk of soil contamination for human health, ecosystems and 'other objects'. Because the site only covers a small area, ecological and other risks were considered not decisive and only human health risks will be assessed. The risks estimated in REC depend on the level of contamination, the exposure paths and on the presence of targets (Beinat *et al.* 1997).

Risks of soil contamination are assessed based on possible exposure in relation to a human or ecotoxicological maximum tolerable risk level. This approach deviates from the general

concept of risks as it focuses on exposure instead of focusing on the chance of an adverse effect (which is the more traditional definition of risk). The term 'exposure reduction', therefore, would be preferable over the term 'risk reduction', which is however used in REC. (Beinat *et al.* 1997, 9)

A 30-year time frame (considered as the average time that people will live on the site) is automatically assumed in the REC model. The time profile of exposure (to contamination remaining after remediation) is compared to that in the absence of remediation (the do-nothing option). The difference provides the extent of risk reduction.

Exposure is based on the physicochemical exposure model CSOIL (Brand, Otte, and Lijzen 2000), considering different exposure scenarios, representing different situations on and around the contaminated site. Each exposure scenario is characterised by exposure pathways and a number of exposed objects. Within the case study discussed in this paper, the scenario of 'living without garden' was selected because this will be the prevailing scenario once the site has been redeveloped as a residential area. The exposure, calculated using the CSOIL model, is then compared with tolerable daily intake (TDI) values. The Risk Index (R) can be calculated based on little detailed information (mainly the area contaminated by different contaminants and contaminant concentrations) by using fixed exposure parameters and physicochemical models that predict the behaviour of substances in the environment. In this way, future situations can also be predicted (Beinat *et al.* 1997). "Although the calculated risk reduction in REC is based on a simple and straightforward model, it provides information to distinguish between alternatives based on their differences in terms of risk reduction" (Beinat *et al.* 1997, 10).

2.4.2. Assessment of human health within ReCiPe

Damage to human health is also addressed in life cycle assessment, but here different approaches also exist. In the ReCiPe method, damage categories concerned with human health and ecosystem health are defined, using the DALY (Disability Adjusted Life Years) concept for human health (Goedkoop *et al.* 2012). The characterisation factor of human toxicity accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical, and exposure factors can be calculated by means of 'evaluative' multimedia fate and exposure models, while effect factors can be derived from toxicity data on human beings and laboratory animals (Huijbregts *et al.* 2000). A commonly applied multimedia fate, exposure and effects model is USES-LCA (Uniform System for the Evaluation of Substances adapted for LCA purposes) (Huijbregts *et al.* 2000). An updated version of the fate, exposure, effect and damage parts of USES-LCA (referred to as USES-LCA 2.0) was used in the ReCiPe model (Huijbregts *et al.* 2005; van Zelm *et al.* 2008).

2.5. Cost and financial risk

2.5.1. Cost

Different aspects taken into account in the cost analysis within the REC tool include the cost of project preparation, preparatory work and demolition work on the site, land redevelopment, ground work, costs of processing, extraction of groundwater and eventually soil for *in situ* remediation, treatment installation, screening constructions, monitoring system, management and environmental supervision and secondary costs (Beinat *et al.* 1997). Because insufficient information concerning these different cost

categories could be made available (partly for reasons of confidentiality concerning subcontractors), the estimation of the costs was based on information on the cost of different best available soil remediation techniques in Flanders, as described in the report of Goovaerts *et al.* (2007).

2.5.2. Financial risk

In order to have a more structured overview of the financial risks associated with the different soil remediation options, a risk register and risk matrix were constructed.

Based on the work of Hetterschijt *et al.* (2000), a literature search and conversations with soil remediation experts, the potential financial risks of soils excavation and steam extraction as remediation techniques were listed. A simplified risk register, constructed in accordance to the PRINCE2TM (PROjects IN Controlled Environments) method (APM Group 2011), was set up for each soil remediation option. In this register, the probability of a risk turning into a reality is given by a percentage based on interval ranges of 20%. The effect, namely the additional cost of the remediation, is given in euros. The reason for this approach is that this enables us to make a clear distinction between small and significant risks, which will be important for costly remediation operations. As a second step, a risk matrix was constructed representing the severity (X-axis) and probability of occurrence (Y-axis) of the different financial risks that had been identified. The risk matrix is based on the data collected in the risk register and the different risks are indicated with their E (stands for excavation) and S (stands for steam extraction)-codes, which are explained in the risk register. By doing so, the combined effect of probability and severity can be evaluated.

2.6. The Triangle Tool

The Triangle Tool is a simple decision support tool for evaluating weighting sets and helps decision makers evaluate to what extent results depend on the chosen weighting set. The Triangle Tool shows which combination of weighting factors makes option A preferable to option B, and vice versa (Hofstetter *et al.* 2000).

In principle, LCIA methods such as ReCiPe (Goedkoop *et al.* 2012), but also other methods resulting in multiple indices, need a weighting of the damage indicators. However, in practice, a ranking of the alternatives seems to be possible in many cases, based on the line of indifference and the areas of relevant superiority within the weighting triangle without actually choosing one specific weighting set (Hofstetter *et al.* 2000).

3. Results and discussion

The environmental impact of the two remediation options, calculated using the REC and ReCiPe methods, is presented in Figures 1 and 2 respectively.

3.1. Environmental impact assessment

The environmental impact in REC is quantified by an 'E-index', which has no unit. A negative E-value indicates a negative environmental impact, whereas a positive value denotes a positive environmental impact. In Figure 1, only the negative contribution to the environment of the different remediation options is presented because the positive environmental impact, consisting of clean soil and groundwater, is characterised by a

Figure 1. Weighting of the impact categories with a negative contribution to environmental quality using the environmental merit (REC method) for both remediation options (modified after Cappuyns and Kessen 2012).

value around 1.5 for both remediation options; presentation of this positive environmental merit in Figure 1 would make the figure unclear. The adverse environmental impact of excavation is characterised by an E-value that is slightly more negative than in the case of steam extraction (Figure 1). Soil excavation performs better with regard to loss of groundwater and generates less waste, while steam extraction performs significantly better with regard to the energy used and the space used.

Figure 2. Weighting of impact categories and comparison of soil excavation and steam extraction using the ReCiPe method (modified after Cappuyns and Kessen 2012).

In Figure 2, the environmental impact of both remediation technologies assessed with the ReCiPe method is established for purposes of comparison, detailing the different impact categories that contribute to the overall environmental impact. The higher global environmental impact of soil excavation is caused by its higher energy demand, expressed as a depletion of fossil fuel. In turn, the burning of fossil fuels contributes to climate change, which affects both ecosystems and human health. Human toxicity is the second most important impact category, mainly because the residual BTEX concentrations in the groundwater are higher than in the case of steam extraction (because BTEX degradation is enhanced by the higher temperatures as a consequence of steam injection).

In the case study analysed in this paper, both impact assessment methods selected the same (*in situ*) soil remediation option as having the lowest environmental impact. However, in other cases where, for example, a certain type of waste has a major environmental impact, different conclusions (i.e. the selection of different soil remediation options with the best environmental performance) are likely to be obtained from both methods. Therefore, the boundary conditions and the assumptions behind each LCA based evaluation tool should be well known, in order make a correct interpretation of calculated environmental impacts.

3.2. Human health risk assessment

The risk index calculated in the REC model uses the Tolerable Daily Intake (TDI) as a toxicological limit. Compared to the CSOIL model, on which the REC model is based, the excess carcinogenic risk via inhalation is not taken into account in the risk index (R) calculated in REC. The risk reduction model only provides information to distinguish between alternatives and highlights their differences in terms of risk reduction. Soil excavation is characterised by a slightly lower risk compared to steam extraction (Figure 3; mineral oil is not presented because the calculated risk index was close to 0), but the difference is minimal. Ethylbenzene is the contaminant which causes the most concern for human health.

A much higher human toxicity level is attributed to soil excavation by the ReCiPe method compared to steam extraction (Figure 2), due to the higher residual BTEX

Figure 3. Risk index calculated using the REC methodology for benzene, toluene, ethylbenzene and xylene for Excavation and Steam extraction as remediation options.

concentrations in the groundwater after soil excavation. Human toxicity is also the second most important impact category calculated using the ReCiPe method, after fossil fuel consumption. The human toxicity of BTEX was assessed by using the generalised impact assessment in ReCiPe, based on the concept of DALY (disability adjusted life years) as a concept to address human health damages in LCA (Hofstetter 1998). For organic contaminants (as is the case in the present study), all exposure routes are considered (air, drinking water, food), which is a plausible assumption. Concerning the carcinogenicity of a substance, the individualistic scenario in ReCiPe includes the substances with strong evidence of carcinogenicity (mineral oil and benzene) only, not the substances within sufficient evidence of carcinogenicity (toluene, ethylbenzene and xylene) (IARC 1999, 1984; Goedkoop *et al.* 2012).

Although the 'risk reduction' module in REC and the 'damage to human health' in the ReCiPe methodology rely on different concepts (TDI versus DALY respectively), the relative human risk classification of both remediation options is the same: the site remediated by soil excavation is characterised by a more important risk for human health than steam extraction. However, a closer examination of the results shows that, for example, a very low risk is attributed to mineral oil in the REC method, while in the ReCiPe method mineral oil contributes to the damage to human health because of its carcinogenic properties. It should be clear that both models have not actually been compared and that the outcome of both models may greatly differ, especially when carcinogenic components are of concern.

3.3. Costs and financial risk

3.3.1. Cost of soil remediation

The average price for the excavations is estimated to be in the range 4–16 €/ton (Goovaerts *et al.* 2007). This does not include the off-site treatment of the soil, for which different options can be considered. For soil washing, the price (30–70 €/ton, including transport of soil) is mainly determined by the type and energy demand of the washing installation and the additives used in the washing solution. For *ex situ* bioremediation, the cost of off-site treatment depends on the soil type and the degree and type of contamination. A sandy soil with a moderate level of contamination by low molecular weight mineral oil components is much easier to treat than a clay soil contaminated by 'heavy components' (C30). Market prices are in the range of 20–50 €/ton (Goovaerts *et al.* 2007). Finally, the cost for of thermal treatment of contaminated soil (65–80 €/ton) depends on the soil composition, moisture content and contamination type. It is clear that the off-site remediation of the contaminated soil determines the total cost of soil excavation and cleaning as a remediation option (Goovaerts *et al.* 2007).

Because experience of full-scale remediations with steam extraction is still scarce, an estimation of the costs associated with steam extraction remains difficult. Compared to other, more conventional techniques such as air sparging and biosparging, more energy and other (more costly) materials (e.g. stainless steel for the conducts) are necessary. The cost of soil remediation by means of steam extraction is estimated to be in the range 31–280 €/ton, with an average cost of 40–120 €/ton (Goovaerts *et al.* 2007).

For the present case study, the cost of soil excavation and cleaning was estimated to be approximately 45 €/ton, while for steam extraction a price of 80 €/ton was assumed.

Besides the cost of the soil remediation itself, costs of preliminary soil investigations and risk assessment (mainly the costs of model implementation and information

collection) are also important to take into account. Particularly when the level of uncertainty is too great to make a decision, it needs to be reduced by obtaining additional information, which involves the additional expense of committing more resources (Chen and Ma 2007).

3.3.2. Financial risk of soil excavation and steam extraction

The different financial risks associated with the two soil remediation methods are put into three different categories: organisational, financial and soil-technical risks (Tables 1 and 2). The most important cost associated with soil excavation is the incomplete removal of contaminated soil, but the probability of this is rather low, especially when the extent of the soil contamination has been properly mapped. Considering steam extraction, many more potential risks can be identified (Table 2). Under-estimation of the treatment cost per unit of soil volume, because neither the hydraulic permeability nor the ratio between horizontal and vertical permeability are correctly estimated, would incur the highest cost.

For the case study where steam extraction was compared with soil excavation, steam extraction was the preferred technique based on the environmental and human health

Table 1. Risk register for excavation as a remediation option.

Description of risk	Category	Probability	Cost	Measure to be taken
Because of insufficient knowledge about the extent of the contamination, not enough soil is withdrawn, and target values are not reached (remark: during soil excavation usually too much soil is removed, so this risk is actually very small). (E1)	Organisational	0–20%	€374,400	Invest more in soil sampling and mapping of the contamination or eventually excavate more soil than strictly necessary according to the calculations.
Soil excavation is an intensive remediation technique, removing the soil contamination in a rather short time span. As a consequence, costs are also made in a short time span, which can result in problems with the cash flow. (E2)	Financial	0–20%	€18,720	Try to assess the financial risks by gathering information from a financial institution/bank and/or raise a loan.
The (<i>ex situ</i>) remediation technique applied on the excavated soil is not effective, another, more intensive technique has to be applied. (E3)	Soil-technical	0–20%	€93,600	Better characterisation of the soil contamination.
A commonly occurring technical defective results in an important delay in the remediation operation. (E4)	Technical	0–20%	€187,200	Invest in a better follow-up of the technical equipment and machinery and/or preventively add some extra working days in the work planning.

Table 2. Risk register for steam extraction as a remediation option.

Risk description	Category	Probability	Effect	Measure to be taken
The costs of the steam extraction strongly depend on the volume of soil that has to be treated. During or after remediation, it may appear that the contamination was underestimated. A bigger area/volume of soil has to be treated. (S1)	Organisational	20–40%	€62,000	Invest more in sampling for a better mapping of the extent of the contamination
The costs of the steam extraction per volume unit of soil are also dependent on the amount of steam and energy necessary to clean-up the contamination, which is mainly determined by soil permeability. When soil permeability is insufficient, costs can rise significantly. (S2)	Soil-technical	20–40%	€46,500	Invest more in soil testing to better estimate the permeability of the soil and eventual variations in permeability on the site.
The unknown effects of steam injection on mechanical soil properties can result in subsidence (especially in the case of peat soils). (S3)	Soil-technical	80–100% (in the case of the occurrence of a peat layer)	€37,200	Better assessment of the characteristics of the site and its contamination
After remediation, the contamination appears to be more mobile than initially estimated. (S4)	Soil-technical	0–20%	€27,900	Better assessment of the characteristics of the site and its contamination
Steam extraction is an intensive remediation technique, removing the soil contamination in a rather short time span. As a consequence, costs are also made in a short time span, which can result in problems with the cash flow. (S5)	Financial	0–20%	€3100	Try to assess the financial risks by gathering information from a financial institution/bank and/or raise a loan.
Acceptance by stakeholders may cause a delay in the remediation, both at the start and during the remediation project. (S6)	Organisational	0–20%	€35,000	Better project management and planning.
The treatment cost per unit of soil volume is underestimated because hydraulic permeability and the ratio between horizontal and vertical permeability are not correctly estimated. (S7)	Soil-technical	20–40%	€155,000	Better assessment of the properties of the contamination and of the soil composition
The required capacity of the water pumping and treatment installation is underestimated and has to be increased. (S8)	Organisational	0–20%	€93,000	Better project management and planning.

Probability of occurrence	Severity				
	Negligible (<30,000€)	Moderate (30,000€ → 100,000€)	Moderately critical (100,000€ → 200,000€)	Critical (200,000€ → 400,000€)	catastrophical (>400,000€)
Very likely to occur 80-100%		S3			
Likely to occur 60-80%					
Probable 40-60 %					
Possible 20-40%		S1 – S2	S7		
Very unlikely to occur 0-20 %	E2 – S4 – S5	E3 – S6 – S8	E4	E1	

Figure 4. Risk matrix indicating the financial risks for soil excavation (E-codes) and steam extraction (S-codes).

impact of the remediation. Based on the information deduced from the risk matrix (Figure 4), however, steam extraction represents the most important financial risk (i.e. because contaminant removal by steam extraction is much more affected by a heterogeneous soil composition). Because of the quite innovative character of this method, experience of it is limited in Belgium and it is difficult to rely on previous experience when (technical) problems arise during the remediation project. A successful soil remediation project that makes use of steam extraction requires a more detailed characterisation of the (sub)soil in comparison with soil excavation.

3.3.3. How to reduce the financial risks of soil remediation projects

The consequences of missing or incorrect data concerning the contaminated site (characterisation of soil and subsoil) carry an important financial risk. The selection of steam extraction as a remediation technique requires investment in a more detailed characterisation of the contamination and the site characteristics in order to minimise the financial risks. Nevertheless, in the case of soil excavation too, a proper estimation of the amount of contaminated soil to be removed and cleaned remains essential. The design of the sampling programme is usually based on cost-effectiveness (Back 2007), but missing information burdens the outcomes of site investigations with a large degree of uncertainty. Geostatistical tools can be used both to quantify the volume of contaminated soil to be excavated/treated and the cost associated with the remediation project (Demougeot- Renard, de Fouquet, and Renard 2004; D’Or, Demougeot-Renard, and Garcia 2009), including cost optimisation under conditions of uncertainty (Cardiff *et al.* 2010; Horta and Soares 2010).

3.4. Combining risk reduction, environmental merit and cost

In the present study, we did not quantify weighting factors, nor did we apply an economic valuation method to come to an overall evaluation of both soil remediation technologies. As a consequence there is no final choice presented between the two remediation technologies. Instead, we used a graphical interface to simplify and clarify the discussion about the superiority of remediation options (Hofstetter *et al.* 2000). The weighting triangle can display the result of the REC analysis without knowing the weighting factors and shows under which conditions (which weighting factors) product/process A is better than B (Hofstetter *et al.* 2000). The presentation by means of the Triangle Tool is useful

to enhance the transparency of the weighting process. The different stakeholders involved in the soil remediation project do not have to set discrete weights, but they have to agree whether a combination of weight factors is plausible or not. The decision maker has to choose between minimising the financial risk and damaging human health and environmental quality to an acceptable level.

Aggregating the three scores from the REC assessment in the mixing triangle is presented in Figure 5. The grey area indicates the combinations of weighting factors that will result in a better appraisal of steam extraction compared to soil excavation, while the white area indicates the combination of weighting factors, making soil excavation the superior option. In general, a weighting score below 35% has to be attributed to the cost of the remediation project in order to select steam extraction as the most feasible remediation option. Whether such a weighting could be reasonable is rather unlikely, since cost is still considered a key factor in the selection of soil remediation options. Analogously, because risk reduction is one of the primary goals of a soil remediation project, a low weighting score for risk reduction cannot be considered realistic. In a realistic scenario, in which, for example, a weight of 40% is attributed to risk reduction, 40% to costs and 20% to environmental merit, soil excavation is the preferred remediation option (Figure 5). Even

Figure 5. Weighting triangle for the indices calculated using the REC method. Sub-areas indicate where soil excavation is superior to steam extraction (in white) and vice versa (in grey). W_R , W_E , W_C are the weighting factors for Risk reduction, Environmental merit and Cost, respectively.

with a somewhat more idealistic attitude, in which environmental merit counts for 40%, and risk reduction and cost only for 30% each, soil excavation is still superior to steam extraction. It can be concluded that soil excavation will most probably be selected as the most feasible remediation option. Only when additional financial resources become available, for example, from funding received for innovative demonstration projects, one may consider to attribute a low weight to the costs (e.g. 20%), attaching more importance to risk reduction and environmental merit (e.g. 40% each) of the remediation project, making steam extraction the preferred remediation option.

Although the REC methodology takes into account three important aspects with regard to soil remediation, no explicit decision regarding the best choice between different remediation alternatives can be made, unless there is an overall best option, with the best score for human health, environmental and financial aspects. Moreover, the REC method does not cover all relevant concerns with regard to decision making, especially with regard to people living in the neighbourhood of the contaminated site. Nuisance caused by noise, traffic and odour are difficult to quantify, but economic valuation methods offer possibilities here. Sorvari and Seppälä (2010) developed a decision support tool based on the REC software, but extended it in order to include land-use and socio-cultural aspects (loss of cultural heritage, visual aspects). In future research, the opportunities for using this tool will be assessed.

4. Conclusion

The different tools applied in this study resulted in individual indices or scores for the environmental impact, human health impact and costs/financial risks of two soil remediation options. However, based on all these indices and scores, it is still difficult to make a best choice between different remediation alternatives, unless there is an overall best option, with the best score for human health, environmental and financial aspects. The environmental and health impact calculated using the ReCiPe method are consistent with the results for risk reduction (R) and environmental merit (E) obtained using the REC method. In the present case study, steam extraction was preferred as a remediation technology compared to soil excavation with regard to environmental and human health impact, regardless of the applied evaluation tool (in REC or ReCiPe). Unfortunately, steam extraction is the most costly option and also carries the highest financial risk, which makes steam extraction not automatically the overall best option when human health, environmental impact and financial risk have to be considered together.

Whether or not steam extraction is preferred as a remediation technology will depend on the stakeholders: the companies in charge of the soil remediation project will most probably prefer the financially more secure situation, whereas people living in the neighbourhood of the site and future residents on the site will be more attracted by a remediation technology that has a lower impact on the environment and that results in a lower risk for human health.

Concerning the applicability of the tools analysed in this paper, we can conclude that, in the REC method, environmental merit (E) is defined in such a manner that it can be clearly distinguished from risk reduction (R) (Beinat *et al.* 1997). This is necessary, because the main goal of most soil remediation projects is to reduce the risk of the contamination. In contrast, LCAs are not specifically designed as decision support tools for soil remediation; they do not clearly distinguish between environmental merit and risk reduction. Therefore, it should be taken into account that including LCA together with human health risk assessment (e.g. with RISC-HUMAN, a risk assessment model

that is specifically designed for soil and groundwater remediation; Environment Agency 2003) in the decision-making process of site remediation would entail an overlap with regard to human health aspects. Although LCA offers some possibilities to include environmental impact assessment in soil remediation projects, the REC tool seems more appropriate for the evaluation of soil remediation options in daily practice. An assessment of the financial risk of soil remediation options, as exemplified in this paper, also deserves some consideration and should be integrated in any decision support tool. There is clearly a need for practical tools that help practitioners in choosing the correct technology that will not only be effective but will also minimise the financial risk associated with the clean-up.

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References

- AF Centre for Engineering and the Environment. 2010. *SRT, Sustainable Remediation Tool, User Guide*. San Antonio, TX.
- APM Group. 2011. *Managing a Successful Project Using PRINCE2TM. Syllabus*, version 1.3. Buckinghamshire: The APM Group.
- Back, P-E. 2007. "A Model for Estimating the Value of Sampling Programs and the Optimal Number of Samples for Contaminated Soil." *Environmental Geology* 52 (3): 573–585.
- Bardos, P., B. Bone, R. Boyle, D. Ellis, F. Evans, N. D. Harries, and J. W. N. Smith. 2011. "Applying Sustainable Development Principles to Contaminated Land Management Using the SuRF-UK Framework." *Remediation Journal* 21(2): 77–100.
- Beinat, E., M. A. van Drunen, R. Janssen, M. H. Nijboer, J. G. M. Koolenbrander, J. P. Okx, and A. R. Schütte. 1997. *The REC Decision Support System for Comparing Soil Remediation Options; A Methodology Based on Risk Reduction, Environmental Merit and Costs*. September. Gouda, The Netherlands: CUR/NOBIS.
- Brand, E., P. F. Otte, and J. P. A. Lijzen. 2000. *CSOIL 2000: An Exposure Model for Human Risk Assessment of Soil Contamination. A Model Description*. RIVM report 711701054/2007. Bilthoven, The Netherlands.
- Cappuyns, V., and B. Kessen. 2012. "Evaluation of the Environmental Impact of Brownfield Remediation Options: Comparison of Two Life Cycle Assessment-Based Evaluation Tools?" *Environmental Technology* 33 (21): 2447–2459.
- Cardiff, M., X. Liu, P. K. Kitanidis, J. Parker, and U. Kim. 2010. "Cost Optimization of DNAPL Source and Plume Remediation Under Uncertainty Using a Semi-Analytic Model." *Journal of Contaminant Hydrology* 113 (1–4): 25–43.
- Chen, Y-C., and H-W. Ma. 2007. "Combining the Cost of Reducing Uncertainty with the Selection of Risk Assessment Models for Remediation Decision of Site Contamination." *Journal of Hazardous Materials* 141 (1): 17–26.
- Davis, E. L. 1998. *Steam Injection for Soil and Aquifer Remediation*. EPA/540/S-97/505. Ada, OK: Robert S. Kerr Environmental Research Laboratory.
- Demougeot-Renard, H., C. de Fouquet, and P. Renard. 2004. "Forecasting the Number of Soil Samples Required to Reduce Remediation Cost Uncertainty." *Journal of Environmental Quality* 33: 1694–1702.
- D'Or, D., H. Demougeot-Renard, and M. Garcia. 2009. "An Integrated Geostatistical Approach for Contaminated Site and Soil Characterisation." *Mathematical Geosciences* 41 (3): 307–322.
- Environment Agency. 1999. *Cost Benefit Analysis for Remediation of Land Contamination*. R&D Technical Report P316. Prepared by Risk Policy Analysts Ltd. and WS Atkins. Swindon: Environment Agency R&D Dissemination Centre.
- Environment Agency. 2003. *Fact Sheet for RISC-HUMAN 3.1*. Fact Sheet No. FS-03 April. Rotherham: UK EA.

- Goedkoop, M., A. De Schryver, M. Oele, S. Durksz, and D. de Roest. 2010. *Introduction to LCA with SimaPro 7*. Report version: 4.5, November.
- Goedkoop, M., R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. van Zelm. 2012. *ReCiPe 2008. A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at The Midpoint and the Endpoint Level*. 1st ed. (revised). Report I: Characterisation. The Netherlands: RIVM.
- Goovaerts, L., R. Lookman, K. Vanbroekhoven, J. Gemoets, and K. Vrancken. 2007. *Best beschikbare technieken (BBT) bij het uitvoeren van bodemsaneringsprojecten en bijgrondreinigingscentra (Best Available Techniques for Soilremediations Projects and Centres for Soil Remediation and Cleaning)*. Gent: Academia Press.
- Hetterschijt, R., C. te Stroet, M. van Zutphen, W. Schlebaum, M. Nijboer, H. de Sain, and J. Hartog. 2000. *Financiële risico's van saneringsvarianten – kwantitatieve risicoanalyse (QRA) ter ondersteuning bij variantkeuze*. Gouda, The Netherlands: CUR/NOBIS.
- Hofstetter, P. 1998. *Perspectives in Life Cycle Impact Assessment: A Structured Approach to Combine Models of the Technosphere, Ecosphere and Value Sphere*. Dordrecht: Kluwer.
- Hofstetter, P., A. Braunschweig, Th. Mettler, R. Müller-Wenk, and O. Tietje. 2000. "The Mixing Triangle: Correlation and Graphical Decision Support for LCA-based Comparisons." *Journal of Industrial Ecology* 3 (4): 97–115.
- Horta, A., and A. Soares. 2010. "Uncertainty Assessment for Soil Remediation projects." Paper presented at the Accuracy 2010 Symposium, July 20–23, Leicester, UK.
- Huijbregts, M. A. J., U. Thissen, J. B. Guinée, T. Jager, D. Van de Meent, A. M. J. Ragas, A. Wegener Sleeswijk, and L. Reijnders. 2000. "Priority Assessment of Toxic Substances in Life Cycle Assessment, I: Calculation of Toxicity Potentials for 181 Substances with the Nested Multi-Media Fate, Exposure and Effects Model USES-LCA." *Chemosphere* 41: 541–573.
- Huijbregts, M. A. J., J. Struijs, M. Goedkoop, R. Heijungs, A. J. Hendriks, and D. Van de Meent. 2005. "Human Population Intake Fractions and Environmental Fate Factors of Toxic Pollutants in Life Cycle Impact Assessment." *Chemosphere* 61 (10): 1495–1504.
- IARC. 1999. "Re-Evaluation of Some Organic Chemicals, Hydrazine and Hydrogen Peroxide." *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 71*, 1189–1208. Lyon: IARC Press.
- IARC. 1984. "Polynuclear Aromatic Hydrocarbons, Part 2, Carbon Blacks, Mineral Oils (Lubricant Base Oils and Derived Products) and some Nitroarenes. Summary of Data Reported and Evaluation." *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 33*, 87–168. Lyon: IARC Press.
- Irvine, R., and T. Denne. 2010. *Cost-Benefit Analysis of the Proposed NES for Assessing and Managing Contaminants in Soil to Protect Human Health*. Report prepared for the Ministry of Environment, August.
- Lemming, G., M. Z., Hauschild, and P.L. Bjerg. 2010. "Life Cycle Assessment of Soil and Groundwater Remediation Technologies: Literature Review." *International Journal of Life Cycle Assessment* 15: 115–127.
- Naval Facilities Engineering Command. 2011. *SiteWise™ Version 2, User Guide*. Ohio: Batelle Memorial Institute.
- Nijhof, A. G., R. Theelen, A. Weenk, R. Janssen, E. Beinat, C. E. H. M. Buijs, and A. J. M. Schelwald. 1996. *Risk Reduction, Environmental Merit and Costs; REC-Method, Phase 1*. Amsterdam: NOBIS.
- Pollard, S. J. T., A. Brookes, N. Earl, J. Lowe, T. Kearney, C. P. Nathanail. 2004. "Integrating Decision Tools for the Sustainable Management of Land Contamination." *Science of the Total Environment* (1–3): 15–28.
- Pré Consultants. 2011. *SimaPro 7.3*. Pré Consultants. <http://www.pre-sustainability.com/software>
- Schmidt, R., J. Gudbjerg, T. Sonnenborg, and K. Jensen. 2002. "Removal of NAPLs from the Unsaturated Zone Using Steam: Prevention of Downward Migration by Injecting Mixtures of Steam and Air." *Journal of Contaminant Hydrology* 55: 233–260.
- Schnoor, J. L., L. A. Licht, S. C. McCutcheon, N. L. Wolfe, and L. H. Carrier. 1995. "Phytoremediation: An Emerging Technology for Contaminated Soils." *Environmental Science and Technology* 29: 318–323A.
- Scholz, R. W., and U. Schnabel. 2006. "Decision Making Under Uncertainty in Case of Soil Remediation." *Journal of Environmental Management* 80 (2): 132–147.

- Singh, A., and O. P. Ward, eds. 2004. "Biodegradation and Bioremediation." Series: *Soil Biology*, Vol. 2, 2004, XVIII. The Netherlands: Springer.
- Sorvari, J., and J. Seppälä. 2010. "A Decision Support Tool to Prioritize Risk Management Options for Contaminated Site Management." *Science of the Total Environment* 408: 1786–1799.
- van Wezel, A. P., R. O. G. Franken, E. Driesen, and C. W. Versluijs. 2007. *Maatschappelijke Kosten-BatenAnalyse van de Nederlandse bodemsaneringsoperatie*. MNP Report 500122002/2007. The Netherlands: Milieu- en Natuurplanbureau.
- van Zelm, R., M. A. J. Huijbregts, H. A. den Hollander, H. A. van Jaarsveld, F. J. Sautere, J. Struijs, H. J. van Wijnen, and D. van de Meent. 2008. "European Characterization Factors for Human Health Damage of PM10 and Ozone in Life Cycle Impact Assessment." *Atmospheric Environment* 42: 441–453.

Appendix A. Input for the calculation of environmental merit in the REC model

Soil characteristics and pollution status (before remediation)				
Pollutant	Mineral oil	Benzene	Toluene	Ethylbenzene
Contaminant content of soil [mg/kg]	10,000	2	15	50
Pollutated surface area [m ²]	1,325	4,800	4,800	4,800
Depth polluted soil layer [m]	2	1.5	1.5	1.5
Contaminant content of groundwater [μg/l]	7,000	100	—	—
Volume of polluted groundwater	332	225	—	—
Soil density [kg/m ³]	1,700			
Organic matter content (%)	2			
Remediation actions		Units		
Soil excavation				
Supplemented soil		m ³	6,500	
Re-used soil		m ³	6,500	
Used groundwater		m ³	12,000	
Re-infiltrated groundwater		m ³	0	
Soil excavated		ton	11,050	
Soil to be transported away from the site		ton	11,050	
Distance transport away		km	20	
Soil to be transported to the site		ton	11,050	
Distance transport to site		km	20	
Groundwater extraction		m ³	12,000	
Pump height		m ³	2	
Water to be purified		m ³	12,000	
Water to sewer		m ³	0	
Natural gas use		m ³	0	
Diesel used for other processes		ton	0.37	
Electricity used for other processes		MJ	32,400	
Waste soil that can not be treated		m ³	0	
Sludge from waste water purification		m ³	0.11	
Other waste (activated coal)		m ³	5.79	
space use in each phase		m ²	4,800	
time occupation of the phase		years	0.22	

(continued)

Appendix A. Continued

Steam extraction

Supplemented soil	m ³	0
Re-used soil	m ³	0
Used groundwater	m ³	18,898
Re-infiltrated groundwater	m ³	0
Water to be purified	m ³	18,898
Water to sewer	m ³	18,898
Natural gas use	m ³	0
Diesel used for other processes	ton	59
Electricity used for other processes	MJ	195,931
Waste soil that can not be treated	m ³	10.47
Sludge from waste water purification	m ³	1.20
Other waste	m ³	10.32
Space use in each phase	m ²	267
Time occupation of the phase	years	0.25

Appendix B. Input in SimaPro model (ReCiPe)

Soil excavation

Process	Quantity
Excavated soil	15,145 m ³
Occupation, construction site	210 m ² per day, 12,645 m ² in total
Transformation, from industrial area	12,645 m ²
Excavation, hydraulic digger	15,145 m ³
Excavation, skid steer loader	15,145 m ³
Transport, passenger car	2 persons, 40 km/day for 60 days = 4,800 personkm
Transport, lorry, 25t (away from site)	25,747 tons, 25tons/time, 40km/time = 1029,880 tkm
Disposal, inert material, 0% water, to sanitary landfill/CH S	25,747 ton
Groundwater pumping, electricity	14,400 kWh
Electricity, supplementary	18,000 kWh
Pumped water + disposal to surface water	31,600 m ³
Disposal of mineral oil	38,3 (0.514) kg (m ³)
Use of active carbon + disposal	2,000 kg
Refilled soil	15,145 m ³
Occupation, construction site	632 m ² per day, 12,645 m ² in total
Transformation, from industrial area	12,645 m ²
Ground for refill, example: sand at mine	15,145 m ²
Transport, lorry, 25t (towards the site)	25,747 tons, 25tons/time, 40km/time = 1029,880 tkm
Excavation, skid steer loader	15,145 m ²
Transport, passenger car	2 persons, 40 km/day for 20 days = 1,600 personkm
Operation, lorry >32t, EURO3/RER S	200 km

Steam extraction

Process	Quantity
Steam extraction of soil	
Steamgenerator	
• Input of energy (diesel)	64 ton
• Input of water	1,638 m ³
Well drilling	
• Input of energy (diesel)	0.9984 ton
• Disposal, inert material, 0% water, to sanitary landfill/CH S	20 ton

Groundwaterpump	
• Input of energy	16,380 kWh
Transport, passenger car	1 person, 13,000 km = 13,000 personkm
Occupation, construction site	300 m ²
Transformation, from industrial area	300 m ²
Vacuum pump	
• Input of energy	12,012 kWh
Condensor	
• Input of energy	32,760 kWh
Water cleaning	
• Disposal of water to sewer	21,294 m ³
• Disposal of mineral oil	1,000 kg
Air cleaning	
• Input of active carbon	5,000 kg
Operation, lorry >32t, EURO3/RER S	1,500 km