WP T1 - Deliverable 3.1
SWOT Analysis of landfills investigation methods

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ACRONYMS AND DEFINITIONS

COCOON: "Consortium for a Coherent European Landfill Management Strategy", an INTERREG Europe-funded project, whose objective is to develop, integrate and improve relevant policy instruments, while increasing subsidies through operational programs for landfill mining projects, https://www.interregeurope.eu/cocoon/

DST: "Decision Support Tool", a tool that will rank landfills regarding landfill mining opportunities. The ranking is based on information following ELIF structure. It will operate at 2 levels: "Selection" (a first level of quick screening to identify landfills with a priori interesting potential but which need further historical investigations and geophysical survey) and "Ranking" (a prioritization tool to rank pre-selected and fully investigated landfills of economic interest for raw material recovery purposes).

ELFM: "Enhanced Landfill Mining", the safe exploration, conditioning, excavation and integrated valorisation of (historic, present and/or future) landfilled waste streams as both materials (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE), using innovative transformation technologies and respecting the most stringent social and ecological criteria).

ELIF : "Enhanced Landfill Inventory Framework", a landfill inventory structure that is focused on information regarding resources that can be extracted from a landfill (materials, energy carriers and land). The ELIF is used to describe landfills not only in terms of environmental and risk issues, but focuses on the quality and the quantity of dormant materials lying on them, in order to supply relevant data for stakeholders involved in ELFM projects.

LFM: "Landfill Mining", the safe exploration, conditioning, excavation and integrated valorisation of (historic, present and/or future) landfilled waste streams as both materials (Waste-to-Material, W2M) and energy (Waste-to-Energy, W2E), without specification of technologies.

RAWFILL: "Supporting a new circular economy for RAW materials recovered from landFILLs", an INTERREG North-West Europe-funded landfill mining project, launched in March 2017, www.nweurope.eu/rawfill

RDM: Resources Distribution Model, a 3D model based on historical documentary works, geophysics investigations on site and guides sampling/waste analysis that shows the distribution of homogeneous zones inside a landfill, and links these identified zones with information about the average waste composition and physical conditions (metal, organic materials, water content, etc.).

RECLAIM: "Landfill mining pilot application for recovery of invaluable metals, materials, land and energy", project funded by the European Commission through Life+ 2012 vehicle, contract LIFE12 ENV/GR/000427

SMART GROUND: "SMART data collection and inteGration platform to enhance availability and accessibility of data and information in the eU territory on secondary raw materials", an H2020-funded project aiming at improving the availability and accessibility of data and information on SRM (Secondary Raw Materials) in the EU territory, while creating collaborations and synergies among the different stakeholders involved in the SRM value chain, www.smart-ground.eu

PRESENTATION OF THE RAWFILL PROJECT

RAWFILL ("Supporting a new circular economy for RAW materials recovered from landFILLs") is an INTERREG EU-funded landfill mining project, gathering partners and associated partners of North-West Europe regions and supported by EURELCO. RAWFILL was launched in March 2017 and will end in March 2020.

The ultimate goal of RAWFILL is to allow North West Europe public & private landfills owners & managers to implement profitable resource-recovery driven landfill mining and enhanced landfill mining projects, hereunder named LFM or ELFM according to the context.

RAWFILL develops a cost-effective standard framework for creating landfill inventories (ELIF) based on existing experiences, an innovative landfill characterization methodology by geophysical imaging and guided waste sampling and an associated Decision Support Tool (DST) to allow smart ELFM project prioritization and sustainable landfill management. The whole concept was demonstrated in 8 pilot sites: two in Wallonia (Onoz and Bertrix), one in Flanders (Meerhout), two in UK (Emersons green and Stockley Park), one in Germany (Leppe) and two in France (Les Champs Jouault, Lingreville).

PRESENTATION OF WP T1 "ENHANCED INVENTORY FRAMEWORK"

One main challenge for stakeholders involved in ELFM operations is to evaluate the project profitability risk based on quantity and quality of dormant resources that can be excavated and recovered from a particular landfill site. Related reliable decision elements are missing in most of the landfill inventories we have reviewed, covering NWE region. The most advanced inventories describe landfills in terms of environmental and risk issues, but give no way to evaluate, even roughly, their dormant resources potential. In most cases, even the volume of waste remain unknown and only a very general information is given about waste type (which is very often a mixture of domestic, industrial and construction wastes).

The purpose of WP T1 is to supply ELFM stakeholders (public and private companies) with reliable and useful information by providing an exhaustive reliable and relevant Enhanced Landfill Inventory Framework (ELIF) that can be used for establishing any regional or trans-regional landfills inventories. RAWFILL provides only a database structure that has to be fed with information, coming from existing sources and in many cases from site survey (by using RAWFILL's geophysics multimethod approach and guided sampling). Regarding geophysics, waste sampling and waste analysis, RAWFILL provides also technical guidelines based on a SWOT analysis of the current waste characterisation methods.

Existing inventories, landfill mining experiences and accuracy of information

The first review of North-West Europe existing inventories (WP T1 – Activity A T.1.1) shows that most of these inventories describe their landfills in terms of generic information (name, location, ownership, sometimes periods of landfilling, sometimes waste volume estimation, etc.) and, for the most advanced of them, in terms of environmental and risk issues (type of wastes, physical state, presence of leachates and biogas, geology, hydrogeology and hydrology, environmental impacts surrounding population, etc.). Detailed information about the quantity, distribution inside the waste volume and composition of buried wastes is missing.

A T.1.1 analyses current situation in NWE countries by collecting structures of public & private available LFs databases/inventories. Supported by the WP Leader, each partner collects data from its region, while the WP leader uses the EURELCO network to gather additional information.

A short review of landfill mining experiences (WP T1 – Activity A T.1.2) and focused on the methodology applied to evaluate the landfill resources potential, shows that, in the studied cases, no specific particular attention was given to the precise evaluation of resources. Other important factors lead to the decision of mining the landfill, as solving an environmental issue, recovering valuable land or performing feasibility tests. This situation is expected to change as far as the ELFM market will grow and, within North-West Europe, because some mineral resources will request more attention. For sure, in a high density populated area, the economic value of the land that can be reclaimed trough an ELFM project will remain a key decision factor.

A T.1.2 performs a benchmark analysis of the existing LFM initiatives (+/- 20 in Europe), including legal, technical & economic issues, focusing on how the raw material content of the LFs was estimated, the accuracy of the evaluation and its economic impact in the (positive or negative) results.

Regarding existing information, the level of accuracy of some data is sometimes difficult to estimate, for example the indicated surface of the landfill which is mixed with the total surface of the site, the volume of waste which can be just a draft estimation based on a mean height, the type of waste which remain generic in uncontrolled landfills, etc. As this precision is very important for launching a LFM feasibility study, our ELIF should specify for each DST-relevant field an accuracy estimation that will be taken into account for the ranking. The simplest one will be a classification as "poor/average/good/unknown".

The ELIF structure

Analysis of A T.1.1 and A T.1.2 will lead to establish a list of suitable fields for our ELIF, which is part of the 4th activity of the WP T1:

A T.1.4 supplies the enhanced ELIF, i.e. a database structure taking into account LFs resources, under the form of a list of fields ("indicators").

The ELIF ambition is to supply stakeholders with an inventory framework that can be filled with suitable data, in order to evaluate the ELFM potential of the site. We are aware that this information, based on some general documentary studies completed by on-site geophysics investigation, will demand lots of efforts to be found, validated and encoded. We also know that this information will remain on general level and, for a particular given project, will not be sufficient to design a detailed and precise business case model. But ELIF is expected to be useful to 1) demonstrate to stakeholders the interest of reliable, enhanced inventories seen from a perspective of material and energy recovery, which is a quite recent approach; 2) do not invest time and money on sites with obviously limited ELFM potential and 3) select the most promising sites where further investigations can be concentrated.

SWOT analysis of landfills characterisation methods

Even if landfill mining operations are not economically viable in the present context[1], we can logically consider that the EU prices of materials and energy carriers will increase in the future, while landfill mining, sorting and materials preparation operations will become more effective and cheaper. Landfilled materials can be seen as potential anthropogenic "resources" (reasonable prospects for eventual economic extraction in the foreseeable future) or "reserves" (current economic extraction possible). In any case, a deep and relevant knowledge of what lies in landfills is essential: what are the waste, in which quantities and under which form? How can they be excavated? Which precautions should be taken? The ambition of RAWFILL is to give some suitable answers to these questions, by supplying a whole integrated methodology taking into account historical studies of the landfills, geophysical investigations, guides sampling and relevant waste analysis.

A T.1.3 analyses available technical & financial aspects of classical landfill and waste characterization methods by boreholes, trenches and former geophysics experiences. The best practices results will be used to fill the ELIF related fields, tested in the 2 Investment WPs, and highlighted through the WP T3 Demonstration. Financial data will also be gathered to show the value-for-money of the geophysics vs. traditional characterization methods.

Most of the time, characterization of landfills and waste is not directly related to ELFM projects and has been/is performed for environmental monitoring or rehabilitation procedures, or geotechnical stability checks (as settlements and landslide risk).

Specific attention is given to waste composition but also to the landfill existing conditions that can influence ELFM projects: biogas, leachates, temperature, settlements, stability, etc.

A T.1.3 supplies the results of the SWOT analysis and technical guidelines summarizing best practises for waste sampling and site characterisation.

[1] See for instance "Framework for the evaluation of anthropogenic resources: A landfill mining case study – Resource or reserve?", Winterstetter & Al., 2014

ELIF is divided into five main sections:
- ✓ Generic information
- ✓ Landfill ID card
- ✓ Landfill in its surroundings
- ✓ Landfill geometry
- ✓ Specific waste information

Section	**Definition**	**Fields examples**
0. Generic information	Information about datasheet creation and maintenance	Date of creation, updating and who is responsible
1. Landfill ID Card	All administrative information about a given landfill	Name, location, owner, operator, monitoring, aftercare, legal status, permits
2. Surroundings	All relevant data about the landfill's surroundings	Land planning, territorial strategy, current use, specific risks, geology, groundwater, access
3. Geometry	Landfill geometry, regardless waste information	Surface, volume, depths, stability, bottom, capping, biogas network
4. Waste	Specific information about the landfill's waste streams	Types, density, water and gas content, temperature estimated composition from the site Resource Distribution Model (RDM).

Section 4. "Waste" will contain all relevant information about the waste streams identified in the landfill. This information can come from various sources:
- ✓ Historical studies of the landfill
- ✓ Geophysical imaging
- ✓ Guided sampling
- ✓ Waste analysis on-site and in laboratories

All information regarding waste will be described in the ELIF under the form of 4 to 5 main layers, forming the 3D RDM when taken all together.

The landfill is intended to be divided into 4 or 5 homogeneous and contrasted zones, for example the bottom layer (the oldest part of the landfill), the top layer (most recent – and probably most documented – part) and 2 or 3 other volumes in between. Ideally, we should measure and calculate for each part precise data about surface, volume, in-situ density, tonnes buried, water content, temperature as well as some indication about the waste composition, including the % of fine materials that are useless in many separation and valorisation processes. This information regarding waste composition will be evaluated on site and in laboratories. To be sure it is relevant and useful, sampling and analysis methods should be taken from the best practises, so selected from the results of the SWOT analysis.

A T.1.3 SWOT analysis of landfills and waste characterisation methods

Overview of landfills and waste characterisation methods

The study of landfills is conventionally carried out using intrusive methods such as core drilling or trenching, combined with various laboratory analysis (e.g. composition, humidity, temperature, organic content, microbiology (e.g. Reddy *et al.*, 2011; Zornberg *et al.*, 1999). This methodology is time-consuming and costly. It often provides sparse and local information which is difficult to extrapolate between boreholes located less than 30 m apart (Zornberg *et al.,* 1999).

The major problem of landfill and waste characterisation methods is indeed the heterogeneity of the waste, which can be identified at various levels. Similarly to geotechnical and hydrogeological properties as porosity and permeability that vary depending on the size of the soil or rock mass, we will distinguish 2 levels of heterogeneity:

- At the level of the whole landfill (10^3 to 10^6 m³ or more): different waste streams have been landfilled in different places at the same time or at different moments. When their composition is different and lead to a geophysical contrast (i.e. domestic waste vs construction waste), RAWFILL landfill content characterization methodology (i.e. coupling geophysics and targeted waste samples) will bring a way to quickly identify these zones ("layers") with reasonable costs, and describe them in the RDM. When everything has been mixed, the whole mass can be considered as "homogeneous" with local disparities that will not easily be explained.
- At the level of the waste (1 m³): a single m³ of waste can be homogeneous (i.e. containing only one material as lime, ashes, slags and other industrial waste streams) or heterogeneous (i.e. containing several different elements as metal, cardboard, glass, wood, plastics…). However, even heterogeneous waste can have a particular signature and can be described with a single label (i.e. "domestic waste") and considered as homogeneous at small scale.

When waste are heterogeneous, it is quite difficult to extrapolate the content of materials lying in a given layer of a landfill.

	Homogeneous	Heterogeneous
At large scale (macro)	Only one layer of waste can be distinguished: - One single waste stream (mono-landfill) - Several waste streams, totally mixed Any taken sample will have a similar composition	More than one layer of waste can be distinguished, each layer has a relatively homogeneous composition
At small scale (micro)	Only one waste stream can be found in any sample	More than one waste stream can be found in any sample

Four combinations are possible:

- Homogeneous at large scale and homogeneous at small scale (e.g., industrial landfill of gypsum);
- Homogeneous at large scale and heterogeneous at small scale (e.g., mixed domestic waste with a composition that do not vary in time);
- Heterogeneous at large scale and homogeneous at small scale (e.g., a cell for construction waste and another for earth, each of them being homogeneous);
- Heterogeneous at large scale and heterogeneous at small scale (e.g., mixed domestic waste with a composition that varies in time because of landfill ban).

Please note that this criteria is not absolute: even a mono-landfill can contain some small quantities of waste that should normally not be there. Some appreciation is left to the responsible of the waste description.

Boreholes

Boreholes are performed with drilling machines normally used for civil engineering, hydrogeology, geotechnical survey and environmental survey. Diameter varies between 50 mm (small machines as Geoprobe used for environmental survey) and 1,2 m (casing oscillating piling machines used for large drilling gas extraction shafts up to 4 or 50 m depth). Depth depends on the power of the engine, fixing the torque that can be generated to overcome friction of the waste mass while drilling or pressing a metallic casing into the landfill. Domestic waste, for instance, are known to generate very strong friction forces (that’s why most of the trenches can hold vertical or subvertical slopes on several meters). Different methods can be used to drill, as rotary drilling or percussion drilling (down-the-hole hammer drilling, pulse drilling). Drilling heads are of different kinds as well (hollow augers, etc.). Diameter must be compared to the size of the waste elements because it will define the maximum size of sample that can be extracted from the waste mass. A specific attention has to be given to explosive properties of the mixture of biogas with oxygen (explosion limits between 5 and 15%): the dry contact between the metallic part of the drilling equipment and metallic waste must be avoided in order to avoid sparks production, especially when using down-the-hole hammer drilling. Most of the time, remaining water content of the waste will reduce the risk to a low level, but it may be necessary to use water drilling – that will disturb the samples.
The difficulty is to extract undisturbed samples from the landfill: the smaller the diameter, the less representative the sample will be.Access of the machines is a major issues: width of the access roads, width of the landfill road and their maximum slope, compaction level of the upper soil, etc. It may requires preparation works that can be expensive. A major element regarding pricing is the transport and the installation of heavy machines (a piling machine with casing oscillating system can weight more than 50 T and require consequent installation surfaces)

The list hereunder summarizes main aspects of investigation boreholes in a landfill:

Advantages/strengths

- The only method to take deep samples and to reach the bottom of a landfill if depth is > 5 – 6 m
- No depth limitation
- Well-known technique with a great diversity of machines and tools
- Large variety of diameters
- Possible to take not too disturbed samples
- Odours and dust problems are limited

<u>Disadvantages/Weaknesses</u>

- Quite expensive
- Cost of bringing and removal of the machines can be very high, so the method may be very expensive when only a few boreholes are requested
- Quite slow method
- Access to the site and from one borehole to another one can be difficult especially on slopes and/or on slippery or soft soils
- Heavy machines for large diameter drilling request good soil compaction
- Small diameter do not allow to take undisturbed, large-scale samples
- Special attention must be given to biogas problems
- In case of capping restoration, digging will be necessary to give access to sufficient space (for welding a new geomembrane by extrusion, etc.)

Trenches

Trenches performed by traditional civil engineering equipment as crawler excavators; wheel diggers, etc. are the most easy and common way to analyse the first meters of waste.

Advantages and disadvantages are quite obvious:

<u>Advantages/strengths</u>

- Easy to realize
- Give access to large, undisturbed samples
- Well-known technique with a great diversity of machines
- Fast
- Low cost
- In case of capping restoration, easy to repair it as access is given to sufficient space (for welding a new geomembrane by extrusion, etc.)

<u>Disadvantages/Weaknesses</u>

- Access must be difficult especially on slopes and when slippery or soft soils
- Depth usually limited to 4 -5 m
- Requires more safety measures than boreholes
- Special attention must be given to stability problems

- Odours and dust problems may occur
- Special attention must be given to biogas problems
- In case of capping restoration, digging will be necessary to give access to sufficient space (for welding a new geomembrane by extrusion, etc.)

Geophysical imaging

For a detailed analysis of SWOT of different geophysical imaging methods, please refer to the SWOT Analysis of geophysical methods available on the RAWFILL website.

Here are the main aspects of geophysical imaging:

Advantages/strengths

- Easy to realize
- Non-destructive, non-invasive, do not harm capping layers
- Fast-developing method with an increasing number of complementary techniques
- Fast
- Low cost
- Cost of bringing and removal of the equipment is very low
- Large coverage
- Gives a 3D image of the different layers in the landfill

Disadvantages/Weaknesses

- Access must be difficult especially on slopes, heavy vegetation, and presence of aerial biogas networks…
- Gives only bulk properties that must be correlated to useful waste properties
- Single method cannot supply enough information
- Do not allow to take samples
- Prone to modelling errors (artefacts)
- Depth limited to horizontal length of the lines (so the size of the site)
- Resolution and precision decreases with depth

Please note that in any case, some sampling by trenches and/or boreholes will be necessary to calibrate the measures, and to supply useful information related to landfill mining projects.

CONSIDERATIONS ON SAMPLING PLANS

An appropriate sampling plan for a solid waste must be responsive to both regulatory, scientific objectives and landfill mining objectives. Once those objectives have been clearly identified, a suitable sampling strategy, predicated upon fundamental statistical concepts, can be developed. Regarding ELFM, scientific objectives are related to the evaluation of materials that can be recovered as well as the evaluation of environmental impacts and potential health issues. Analysis of micro pollutants (chemicals) has few interest regarding ELFM potential, however it can be required in some cases related to regional regulations or health issues (protection of workers against chemicals when performing the works) or for specific cases as bioleaching projects, that are not part of ELFM as we understand it.

Samples must be representative[2] of the waste (i.e. reflect average properties of the whole waste) and must describe the variability of the waste (i.e. describe all relevant waste streams). The results of the measurements must be accurate and precise (regarding statistical definitions: accurate means closeness of a sample value to its true value and precise means closeness of repeated sample values).

Sampling precision is most commonly achieved by taking an appropriate number of samples from the population. Another technique for increasing sampling precision is to maximize the physical size (weight or volume) of the samples that are collected. Increasing the number or size of samples taken from a population, in addition to increasing sampling precision, has the secondary effect of increasing sampling accuracy.

Sampling methods

This section only describes the most usual methods that can be applied, depending on the particular context of the site. More practical details are given in RAWFILL landfill miner guide, where we will focus on practically applicable methods.

Random sampling: every unit in the population (e.g., every location in a landfill) has a theoretically equal chance of being sampled and measured. One of the commonest methods of selecting a random sample is to divide the population by an imaginary grid, assign a series of consecutive numbers to the units of the grid, and select the numbers (units) to be sampled through the use of a random-numbers table (such a table can be found in any text on basic statistics). It is important to emphasize that a haphazardly selected sample is not a suitable substitute for a randomly selected sample. That is because there is no assurance that a person performing undisciplined sampling will not consciously or subconsciously favour the selection of certain units of the population, thus causing the sample to be unrepresentative of the population.

[2] The term "representative sample" is commonly used to denote a sample that (1) has the properties and chemical composition of the population from which it was collected, and (2) has them in the same average proportions as are found in the population

Simple random sampling: all units in the population (essentially all locations or points in all batches of waste from which a sample could be collected) are identified, and a suitable number of samples is randomly selected from the population.

Stratified random sampling: if a batch of waste is known to be no randomly heterogeneous in terms of its chemical properties and/or non-random chemical heterogeneity is known to exist from batch to batch. In such cases, the population is stratified to isolate the known sources of non-random chemical heterogeneity. After stratification, which may here occur over space (locations or points in a batch of waste) and not over time (each batch of waste), the units in each stratum are numerically identified, and a simple random sample is taken from each stratum. As previously intimated, both simple and stratified random sampling generate accurate estimates of the chemical properties of a solid waste.

Systematic random sampling: the first unit to be collected from a population is randomly selected, but all subsequent units are taken at fixed space or time intervals. An example of systematic random sampling is the sampling of a waste lagoon along a "transect" in which the first sampling point on the transect is 1 m from a randomly selected location on the shore and subsequent sampling points are located at 2-m intervals along the transect. The advantages of systematic random sampling over simple random sampling and stratified random sampling are the ease with which samples are identified and collected (the selection of the first sampling unit determines the remainder of the units) and, sometimes, an increase in precision. In certain cases, for example, systematic random sampling might be expected to be a little more precise than stratified random sampling with one unit per stratum because samples are distributed more evenly over the population.

Authoritative sampling: an individual who is well acquainted with the solid waste to be sampled selects a sample without regard to randomization. The validity of data gathered in that manner is totally dependent on the knowledge of the sampler and although valid data can sometimes be obtained for our purpose (good knowledge of the content of a landfill by a former worker for instance), authoritative sampling is not recommended for the chemical characterization of most wastes, but can be used in an ELFM point of view.
Selection of a method: If little or no information is available concerning the distribution of chemical contaminants of a waste, simple random sampling is the most appropriate sampling strategy. As more information is accumulated for the contaminants of concern, greater consideration can be given (in order of the additional information required) to stratified random sampling, systematic random sampling, and, perhaps, authoritative sampling.

Composite sampling: a number of random samples are initially collected from a waste and combined into a single sample, which is then analysed for the chemical contaminants of concern. The major disadvantage of composite sampling, as compared with non-composite sampling, is that information concerning the chemical contaminants is lost, i.e., each initial set of samples generates only a single estimate of the concentration of each contaminant.

Sampling Objectives

The primary objective of any waste sampling effort is to obtain information that can be used to evaluate a waste regarding ELFM purposes and/or environmental purposes. It is essential that the specific information needed and its uses are defined in detail at this stage.
The information needed is usually more complex than just a concentration of a specified parameter; it may be further qualified (e.g., by sampling location or sampling time.) The manner in which the information is to be used can also have a substantial impact on the design of a sampling plan. (Are the data to be used in a qualitative or quantitative manner? If quantitative, what are the accuracy and precision requirements?)
All pertinent information should be gathered. For example, if the primary objective has been roughly defined as "collecting samples of waste which will be analysed to comply with environmental regulations," then ask the following questions:

1. The sampling is being done to comply with which environmental regulation? Certain regulations detail specific or minimum protocols (e.g., CWEA in Wallonia for polluted soils); the sampling effort must comply with these regulatory requirements.
2. The collected samples are to be analysed for which parameters?
Why those and not others? Should the samples be analysed for more or fewer parameters?
3. What is the end-use of the generated data base? What are the required degrees of accuracy and precision?

By asking such questions, both the primary objective and specific sampling, analytical, and data objectives can be established.

Sampling plan considerations

The sampling plan is a document that describes the objectives and details the individual tasks of a sampling effort and how they will be performed.
The more detailed the sampling plan, the less the opportunity for oversight or misunderstanding during sampling, analysis, and data treatment.
To ensure that the sampling plan is designed properly, it is wise to have all aspects of the effort represented. Those designing the sampling plan should include the following personnel:

1. An end-user of the data, who will be using the data to attain program objectives and thus would be best prepared to ensure that the data objectives are understood and incorporated into the sampling plan.
2. An experienced member of the field team who will actually collect samples, who can offer hands-on insight into potential problems and solutions, and who, having acquired a comprehensive understanding of the entire sampling effort during the design phase, will be better prepared to implement the sampling plan.
3. A materials specialist and/or an analytical chemist, because the analytical requirements for sampling, preservation, and holding times will be factors around which the sampling plan will be written. A sampling effort cannot succeed if an improperly

collected or preserved sample or an inadequate volume of sample is submitted to the laboratory for chemical, physical, or biological testing. The appropriate analytical chemist should be consulted on these matters.

4. A statistician, who will review the sampling approach and verify that the resulting data will be suitable for any required statistical calculations or decisions.

5. A quality assurance representative, who will review the applicability of standard operating procedures and determine the number of blanks, duplicates, spike samples, and other steps required to document the accuracy and precision of the resulting data base.

At least one person should be familiar with the site to be sampled. If not, then a presampling site visit should be arranged to acquire site-specific information. If no one is familiar with the site and a presampling site visit cannot be arranged, then the sampling plan must be written so that it can address contingencies that may occur.

Even in those cases in which a detailed sampling plan is authored and a comprehensive knowledge of the site exists, it is unusual for a sampling plan to be implemented exactly as written. Waste-stream changes, inappropriate weather, sampling equipment failure, and problems in gaining access to the waste are some reasons why a sampling plan must be altered. Thus it is always necessary to have at least one experienced sampler as a member of a sampling team.

Waste properties

The following waste properties are examples of what must be considered when designing a sampling plan (please see next section for more detailed information):

1. Physical state of the waste: it will affect most aspects of a sampling effort. The sampling device will vary according to whether the sample is liquid, gas, solid, or multiphasic. It will also vary according to whether the liquid is viscous or free-flowing, or whether the solid is hard or soft, powdery, monolithic, or clay-like. Wide-mouth sample containers will be needed for most solid samples and for sludge's or liquids with substantial amounts of suspended matter. Narrow-mouth containers can be used for other wastes, and bottles with air-tight closures will be needed for gas samples or gases adsorbed on solids or dissolved in liquids. The physical state will also affect how sampling devices are deployed. A different plan will be developed for sampling a soil-like waste that can easily support the weight of a sampling team and its equipment than for a lagoon filled with a viscous sludge or a liquid waste.

2. Volume: the volume of the waste, which has to be represented by the samples collected, will have an effect upon the choice of sampling equipment and strategies.

3. Hazardous properties : safety and health precautions and methods of sampling and shipping will vary dramatically with the toxicity, ignitability, corrosiveness, and reactivity of the waste.

4. Composition: the chosen sampling strategy will reflect the homogeneity, random heterogeneity, or stratification of the waste in time or over space.

Site-specific factors must be considered when designing a sampling plan.

A thorough examination of these factors will minimize oversights that can affect the success of sampling and prevent attainment of the program objectives. At least one person involved in the design and implementation of the sampling plan should be familiar with the site, or a presampling site visit should be arranged. If nobody is familiar with the site and a visit cannot be arranged, the sampling plan must be written to account for the possible contingencies.

Examples of site-specific factors that should be considered follow:

1. Accessibility: The accessibility of a waste at the chosen sampling location must be determined prior to design of a sampling plan.
2. Waste generation and handling: The waste generation and handling process must be understood to ensure that collected samples are representative of the waste.
3. Hazards: Each site can have hazards -- both expected and unexpected. A thorough sampling plan will include a health and safety plan that will counsel team members to be alert to potential hazards.

LOG DESCRIPTION OF WASTE

Here is a list of major elements to be defined when describing
a trench or a pit, or waste extracted from a large borehole. These elements are interesting for a landfill mining point of view. Most of them are visually measurable and do not require any specific equipment nor specific technical knowledge. That's why some objective way of establishing them must be applied.

- Water content
- Consistency
- Degradation index
- Temperature
- Specific odours
- Colours
- Homogeneity
- Composition (by elements sizes and globally)
- % of fine materials
- Other relevant elements (depending also of the kind of waste that can be valorised, i.e. lime, ashes, slags, etc.)

We will not go deep in details regarding special analysis methods and standards. Our goal is to supply a practical tool that a technician can apply on site in order to analyse waste and deliver relevant information on a very concrete basis. More details are given in RAWFILL Landfill Miner Guide.

These methods are especially valid when describing a trench or a borehole, but can be applied off-site if the waste are transported elsewhere. Some attention must be given to parameters that may change during transportation and pre- or post-transportation storage, as consistency, % of fine materials, water content, temperature (irrelevant if not measured in-situ), etc.

Water content

We propose to classify the water content of the waste in 5 categories:

- Dry
- Low water content
- Medium water content
- High water content
- Saturated waste

Dry waste No humidity is observed in the large particles and in the matrix of fine material Low water content Large elements are dry but the fine matrix is slightly wet. This matrix is slightly clustered, forming larger elements, but these elements can easily be fragmented.

Medium water content
Large elements and fine matrix are clearly wet. The matrix forms clusters separated from each other but more and more coherent and more difficult to fragment as far as water content increases
High water content
All the waste mass, large elements and matrix, is soaking wet (soggy). Leachates drops are visible, although no percolation is observed. The fine matrix is plastic and forms a muddy mass.
Saturated waste
All the waste mass, large elements and matrix, is completely soggy. Leachates percolation is observed. The fine matrix forms a liquid sludge. A groundwater table, that can be local or with large extension, is suspected.

Waste consistency

Waste consistency is related to physical state of the waste and can be evaluated regarding 3 stages. Larger elements may be removed from evaluation.

- Brittle (friable)
- Coherent
- Compact

Brittle
Waste clusters are loose and can be easily fragmented and deagglomerated.
Coherent
Waste clusters can be partially deagglomerated and some parts are dropping when forming a waste pile
Compact
Waste clusters cannot be deagglomerated without substantial effort.

Degradation index

This property is linked to waste degradation, especially organic material degradation: is it still possible to recognize the nature of organic elements, i.e. to still read newspapers or recognize fruit species? As this property is very difficult to evaluate, only a description will be given while establishing the log and no specific scaling will be proposed for now.

The remaining degradation potential of the waste has to be considered carefully, as it will continue to increase with time. Methodologies to evaluate how the identified resources will age in the next decades should be developed.

Waste homogeneity

Waste will be briefly described as homogeneous and heterogeneous, regarding composition and particle sizes. This should be specified in the description.

Homogeneous composition

The waste mass has a similar composition in the whole observed surface and no layers can be visually distinguished.

- Homogeneous composition and homogeneous element size: should we take different samples at different places of the layer, we will always have a similar particle size distribution
- Homogeneous composition and heterogeneous element size: particle size distribution can considerably vary from one place to another one

Heterogeneous composition

The waste mass has a different composition in the whole observed log and some horizontal or sloping layers or lenses can be visually distinguished. Each different layers can be analysed separately if they have sufficient extension, i.e. if it will be possible to dig them separately with usual civil engineering equipment

Waste composition

Composition of each identified waste layer can be described by weighting, for each different elements sizes, the following elements:

- ferrous metals
- non-ferrous
- cardboard and paper
- plastics
- glass/ceramics
- minerals (stones & concrete)
- rubber
- textiles
- wood
- organic materials
- hazardous waste (i.e. batteries)
- others/not visually identifiable (fine materials/matrix)

A short description of the physical state and origin of these elements can be given.
This list is related to typical domestic waste content and can be adapted regarding the type of waste, especially industrial waste.

As far as sieving/screening is concerned, here is a proposed mesh sizes list that is used for evaluation of the interest to recover waste in order to produce secondary fuels:

- 0 – 2 mm
- 2 – 4 mm
- 4 – 25 mm
- 25 – 50 mm
- >= 50 mm

Other meshes can be used for more general waste recovery uses:

- 0 – 40 mm ("fine materials)

- 40 – 150 mm
- 150 – 300 mm
- >= 300 mm

Of course, mesh sizes can be adapted if some general idea of the recovery process is already known when performing the sampling. It can also be adapted to the waste themselves after historical study or some preliminary sampling campaigns. So, it is sometimes not relevant to distinguish different sizes in the fine fraction (< 40 or 50 mm) when no specific use of it is expected.

Of course, weight percentages should be given for any of these fractions, but a way to sum up each waste stream should be foreseen in order to know the global part of a given waste stream of the waste, regardless size (except maybe fine materials)

% of fine materials

For each layer, an idea of the % of fine materials (matrix) should be given. This % is difficult to establish as it may be very heterogeneous, but an indication should be precised, at least:

- < 20%
- 20 to 50%
- 50 to 80%
- > 80%

This % is already recorded when describing the waste composition, but as it is very important, a recall must be made in order to make it appear clearly.

W2E: NET CALORIFIC VALUE

This parameter should be measured in case of expected use of waste as secondary fuels, by applying bomb calorimetry. Please refer to RAWFILL landfill miner guide for more information.

A NOTE ON WASTE CHEMICAL ANALYSIS

Chemical analysis of prepared waste sample is often requested, when studying a rehabilitation process on a risk-based methodology, when considering a bio-leaching operation or when evaluating the possibility to use some waste fractions as secondary fuels in installations with limit values. Chemical analysis will consider a wide range of substances and preparations considered as contaminants: heavy metals, polyaromatic hydrocarbon, BTEX compounds, PCB/Dioxin, etc.

They have no direct interest for "classical" landfill mining operations as they will be taken from fine materials fractions and will not give suitable information on the chemical form and size of the elements. However, they can lead to some health and safety measures when working on the waste mass, when burning waste in a W2E perspective, etc. They can also be useful for specific industrial waste streams.

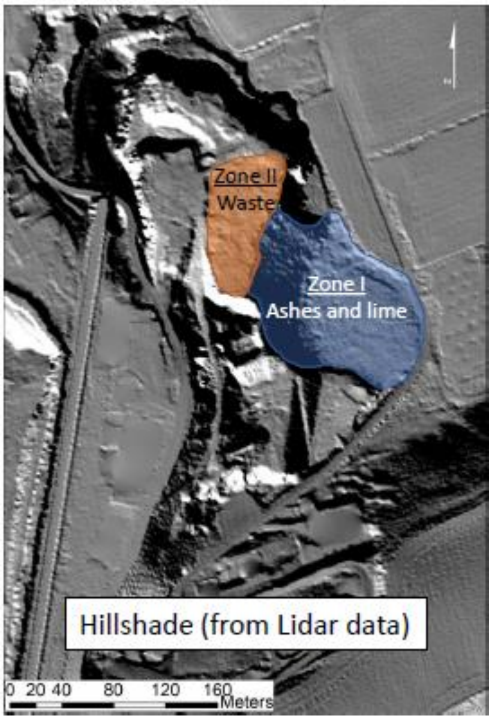
VALUE FOR MONEY OF GEOPHYSICAL IMAGING: CASE STUDY

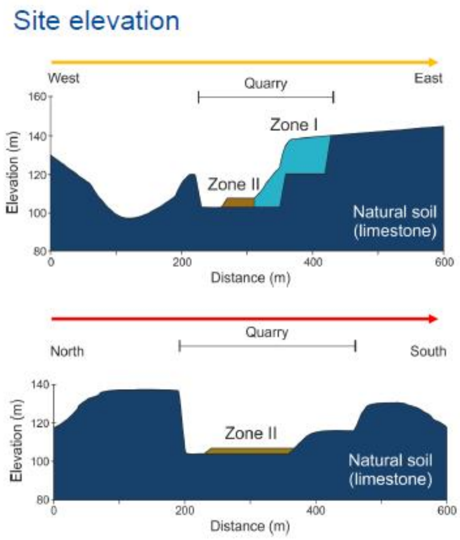
Let's take an example, coming from one's RAWFILL sites investigations: a mixed- waste landfill containing domestic waste, industrial waste and construction waste of 14000 m² divided in 2 zones:

- an upper part of 8000 m², 10 to 30 m of waste with an average thickness of 20 m (Zone 1)
- a lower part of 3500 m², 5 m of waste above the bed rock (Zone 2)

A steep slope of 2500 m², difficult to access, separates Zone 1 and 2 and has not been investigated either by geophysical imaging nor trenches of boreholes.

The goal is to define the bed-rock level everywhere under the mass of waste and to search for homogeneous zones with similar waste composition in order to define the feasibility of a landfill mining project.





Traditional survey by boreholes and trenches should require:

- In the upper part (Zone 1):
  - 1 borehole per 500 m² = 16 boreholes of 20 m = 320 m of boreholes
- In the lower part (Zone 2):
  - 2 days of trenches = 1 trench per 500 m² = 7 trenches
  - 1 borehole per 500 m² = 8 boreholes of 6 m (in order to reach the bed-rock) = 48 m of boreholes

Geophysical imaging confirmed by control boreholes and trenches requires:

- In the upper part (Zone 1):
    - 3 boreholes of 20 m = 60 m of boreholes
- In the lower part (Zone 1):
    - 1 days of trenches = 1 trench per 1000 m² = 4 trenches
    - 2 borehole of 6 m (in order to reach the bed-rock) = 12 m of boreholes

Draft pricing (tax excluded) for boreholes and trenches can be estimated as follows:

- 1 day of trenches digging = 800 € (tax excluded)
- Bring a drilling machine of 16 T (down to the hole hammer) = 1000 €
- 1 m of borehole diameter 200 mm = 100 €

Cost of one multimethod geophysical imaging campaign (electrical resistivity tomography/induced polarization, electromagnetic and magnetic mapping, seismic refraction) prior to boreholes and trenches control is estimated as:

- Equipment	3000 €
- Field works	5000 €
- Processing interpretation and reporting	6000 €

Traditional survey by boreholes and trenches should cost:

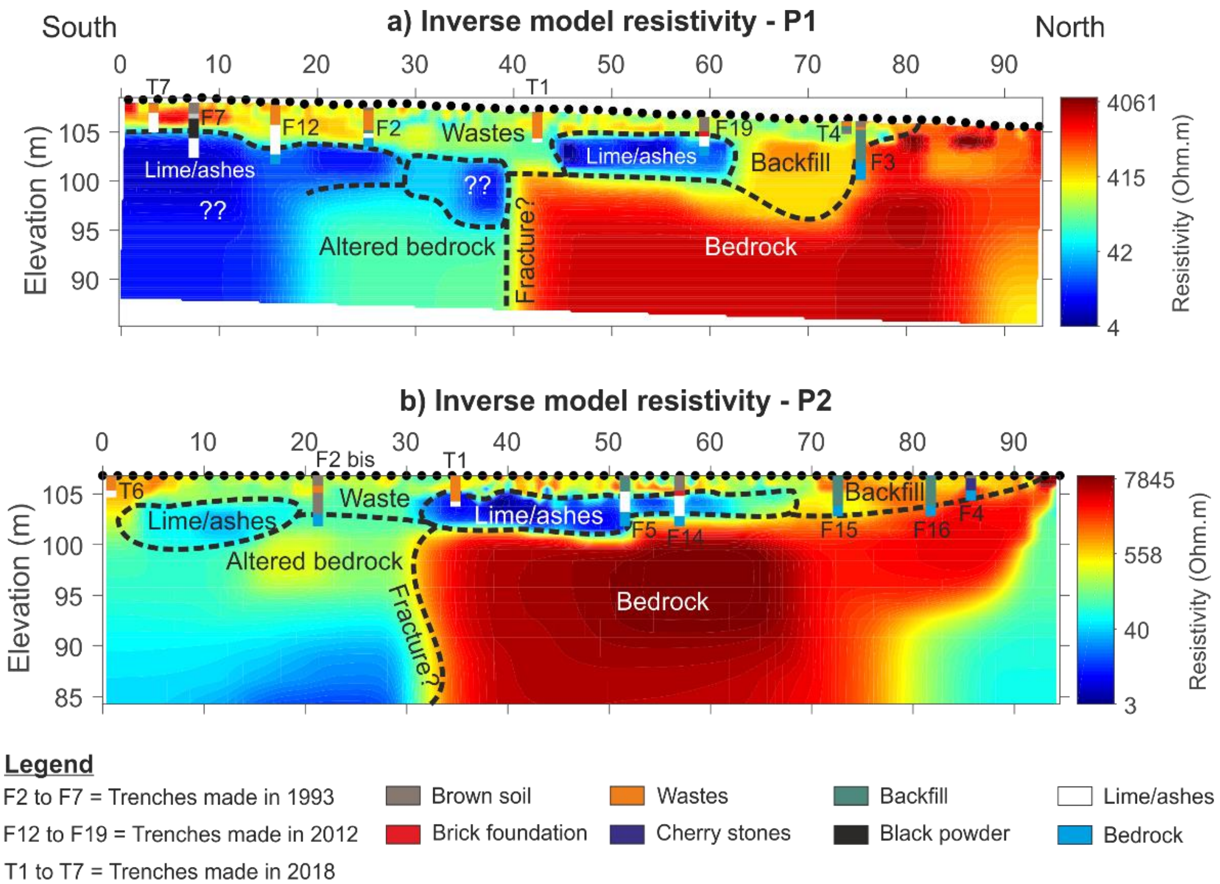
- In the upper part (Zone 1):
    - Machine 1000 €
    - Boreholes 32000 €
- In the lower part (Zone 2):
    - 2 days of trenches = 1600 €
    - Boreholes 4800 €
- **Total for traditional survey: 39 400 €**

Geophysical imaging confirmed by control boreholes and trenches requires:

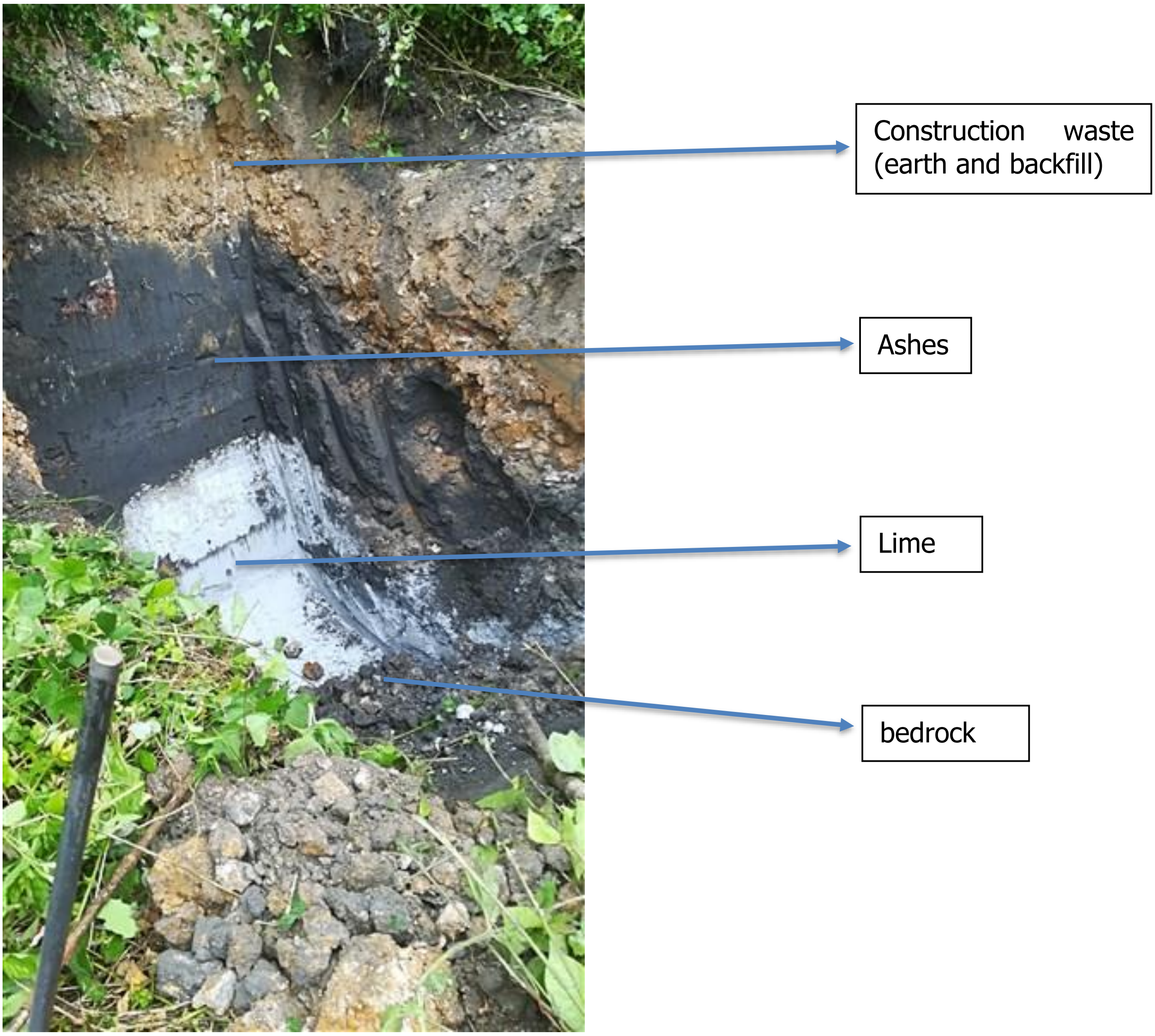
- In the upper part (Zone 1):
    - Machine 1000 €
    - Boreholes 6000 €
- In the lower part (Zone 1):
    - 1 days of trenches = 800 €
    - Boreholes 1200 €
- **Total for RAWFILL survey: 9000 € + geophysical imaging 14000 € = 23 000 €**

In this particular case, the use of RAWFILL geophysical imaging and guided sampling can reduce the survey costs by 40%, for obtaining the same quality of information. Please note that cost of samples analysis is not integrated in the comparison.

Here are 2 section of the RDM that will be established:



And some confirmation by trenches:



A more detailed value for money analysis is provided in the Deliverable WP T3.2.1. Cost benefit analysis of landfill content characterization methods.

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