LANDFILL MINER GUIDE


Re-use
Scan
Recover
RAWFILL
Describe
Prioritise

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This guide is the result of teamwork among the RAWFILL project partners. In detail, they respectively took responsibility for the following chapters: OVAM (Chapters 1, 2, 3 & 7), University of Liège and British Geological Survey (Chapter 4), ATRASOL (Chapters 5, 6, 8 & 9), SPAQuE (Chapters 9, 10 & 13) and VITO (Chapter 11).

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List of abbreviations

BTEX: mixture of benzene, toluene, xylene isomers, ethylbenzene
DST: Decision support tool
EC: European Commission
ELFM: Enhanced Landfill mining
$ELFM^2$: Enhanced Landfill management & mining
ELIF: Enhanced landfill inventory framework
EMI: Electromagnetic induction
ERDF: European Regional Development Fund
ERT: Electrical resistivity tomography
EU: European Union
GPR: Ground penetrating radar
GRA: Gravimetry
HVSRN: Horizontal to vertical spectral ratio of noise
IP: Induced Polarization
IU: Interim use
LFM: Landfill mining
MAG: Magnetometry
MASW: Multi-channel analysis of surface waves
MBT: Mechanical biological treatment
MSW: Municipal Solid Waste
OnToL: Online Tool for the Evaluation of Landfill Mining Projects
PAH: Polycyclic Aromatic Hydrocarbon
PCB: Polychlorinated biphenyl
RDF: Refuse Derived Fuel
RDM: Resource Distribution Model
SDG: Sustainable Development Goal
SP: Spontaneous potential
SRT: Seismic refraction tomography
UNFC: United Nations Framework Classification for Resources
VOC: Volatile Organic Compound
WtE: Waste-to-Energy
WtL: Waste-to-Land
WtM: Waste-to-Materials

Main introduction

With circular economy being one of the main priorities to the EU, Dynamic Landfill Mining is an efficient solution to the transition from traditional waste management to sustainable resource management. In the future, the recovery of resources from landfill mining will become essential as the reserve of primary natural resources are slowly being exhausted. Following this concept of circular economy, RAWFILL ("Supporting a new circular economy for RAW materials recovered from landFILLs") is an EU-funded landfill mining project, gathering partners and associated partners of Northwestern European regions, who focus on the remnants of the linear economy: former landfills. The aim of the RAWFILL project is to widely implement landfill mining in Northwest Europe. For that purpose, the RAWFILL project has faced several challenges:

1. The lack of reliable data regarding landfill content and its recovery potential;
2. The prohibitive cost of the traditional characterization methods;
3. The profitability assessment of LFM projects.

Through this landfill miner guide, written by the RAWFILL project partners, the reader will gain a deeper understanding of the landfill mining concept as well as the challenges tackled by the RAWFILL project.

This guide provides the reader with all the tools to understand the core concepts behind the term "landfill mining", the current challenges, and how to deal with them. Moreover, it provides a technical overview of a landfill mining project from the landfill content characterization, all the way to site restoration. The landfill miner guide was written based on scientific literature, experiences acquired during the project and exchanged knowledge during RAWFILL events. This guide is intended for a broader audience from landfill owners and project manager to regional authorities.

The guide is divided into twelve chapters summarizing the aspects of a landfill mining project. **Chapter 1** is dedicated to the rationales of the project. In this chapter, we introduce the concept of landfill mining and demonstrate the need to consider the landfill's dynamics features that can change over time. **Chapter 2** focusses on the dynamic waste management. The **third chapter** concerns the legal framework of landfill mining. The EU legislation in term of waste management is presented and its impact on regional level is discussed.

Chapters 4 and 5 are dedicated to the landfill characterization. **Chapter 4** focusses on the geophysical imaging. The principles on how to use geophysics and how to perform a geophysical survey on site are explained. The reader will discover the best way to select the geophysical methods depending on the landfill geometry and the type of landfilled waste. The innovative methodology developed by the RAWFILL project partners and based on the coupling between the waste sampling and the geophysical results are also presented. In **Chapter 5**, the traditional waste sampling methodology is presented. Research completed within the framework of the RAWFILL project showed a lack of consistency in waste description, therefore a new standard methodology to characterize the waste samples is also provided in this chapter.

To facilitate the implementation and the development of the landfill mining project across Europe, the RAWFILL partners developed:

1. An evidence-based, cost-effective enhanced landfill inventory framework (ELIF). This inventory combines all the aspects related to landfills: administrative, environmental, social, technical and economical. Its structure is described in detail in the **Chapter 6**;
2. An innovative landfill characterization methodology by combining geophysical imaging and targeted waste sampling (**Chapters 4 and 5**); and,
3. A two-step Decision Support Tool (DST) to allow smart landfill mining project planning, prioritization and interim use (**Chapter 7**).

The landfill miner guide also aimed to provide the outlines of the technical part of a landfill mining project. Recommendations for landfill mining works on site are presented in **Chapter 8**. The excavation of landfilled waste materials can help to recover land (Waste-to-Land). In addition, the excavated waste materials can be revalorized either into Materials (Waste-to-Materials) or Energy (Waste-to-Energy). In the **Chapter 9**, the potential valorization for each main type of waste is presented. The choice of site rehabilitation is a balance between the project's profitability, environmental, and social constraints. Guidelines for the site rehabilitation are provided in **Chapter 10** as well as an overview of the different possibility to rehabilitate a landfill site. The penultimate chapter (**Chapter 11**) explains how to deal with stakeholders and local population to get a landfill mining project accepted. The last chapter (**Chapter 12**) is dedicated to the presentation of landfill mining projects implemented in Europe, covering case studies are discussed.

1 Rationale of RAWFILL project

1.1 Introduction

The linear take-make-dispose model of the 20th century resulted in approximately 500.000 landfills in the EU (Hogland *et al.*, 2010). It expresses the belief that natural resources were abundantly available. Scarcity of materials and adverse environmental impacts of landfills set new standards on waste management and landfilling became the least preferable action. Better recycling rates could not avoid that critical raw materials were disposed of, leading to the question of how viable landfill mining can be and its place in a circular economy. Rethinking the static landfill concept and considering it as a dynamic storage of resources is necessary. To develop this concept, the RAWFILL project was created. The RAWFILL project aims at implementing the recovery of resources (waste material, energy and land) from landfills on a European scale. The project helps promoting a dynamic waste management which is fundamental for the circular economy.

1.2 Basic principles of the linear economy

During the first half of the 20th century, most society behaved as if all resources on our planet were infinite. Once enough materials were collected these would be turned into objects and tools. Until, it would turn out supply could no longer meet the expectations. Therefore, tools and objects were abandoned or collected and buried for eternity. However, most of this waste material did not disappear. The waste deposits made the land unsuitable for useful land use, like agriculture, economic activity or housing. It also affected the water. This is in brief, and slightly romanticized, the way a linear economy has worked for decades (**Figure 1-1**). The realization that something needed to be done found support step by step. In a period stretching from the early 80s (e.g. Flemish Waste Decree, Walloon Waste Decree) until the late 90s (e.g. EU Landfill Directive), waste streams and recycling were described into policies and legislative frameworks.

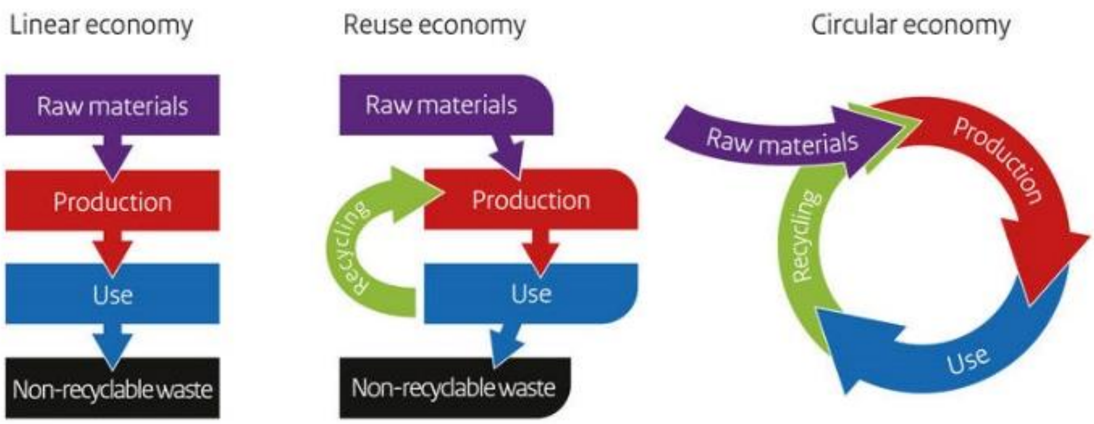

Figure 1-1 Diagram explaining the transition from a linear economy to a circular economy (source: government.nl).

In 2008, a consortium called EURELCO wanted to go a step further and developed the concept of Enhanced Landfill Mining (ELFM)[1], where old waste streams in landfills would be reactivated and reused in the current industrial processes as much as possible, effectively closing the circle and creating a circular economy (**Figure 1-1**). More recently, the concept was expanded and renamed Dynamic Landfill Management [2]. Current understanding determined that the most promising inactive landfills have the potential to be exploited or redeveloped because of the high-quality management in the past when they were still active.

1.3 Resources and reserves

The United Nations Framework Classification for Resources (UNFC) was created for the energy and mineral resources industry (UNECE, s.a.). The energy sources encompass fossil fuels (oil and gas), and renewable resources. The mineral resources consist of secondary resources recycled from residues and waste materials, among other principles as for instance regular mineral mining but also the more pioneering technique of storing carbon dioxide in porous rock beneath the planet's surface. These secondary resources are obviously complementary to the field of study of the RAWFILL project.

UNFC, in its core principles, includes the management of all socio-economical, technological and uncertainty aspects of energy and mineral projects. The main aspect of UNFC is to de-risk projects from costly failures by putting the project maturity and resource progression into the model of UNFC. It is a tool to protect the investments in the sector. UNFC fully integrates social and environmental considerations and the technology required to bring clean and affordable energy resource projects into the market.
The same methodology can be applied to landfill projects (Winterstetter *et al*., 2016) and therefore is an interesting system to involve in the used knowledge base of the dual Decision Support Tool developed by the RAWFILL project.

1.4 Scarcity, depletion and availability of resources: critical raw materials

Resources have been the object of research for classical economists, who started to explore the resource availability (especially land) with regard to human use and population growth (Malthus, 1798; Ricardo, 1817). In 1931, the economist Harold Hotelling in his paper "The Economics of Exhaustible Resources" launched a new research field of economy dealing with the management of natural resources by human societies (Hotelling, 1931).
An intense debate on the likelihood of resource depletion emerged in the mid-twentieth century. A well-known example of this concern is the book "Limits to Growth" (Meadows *et al*., 1972), in which the availability of finite resources was simulated in relation to the projections of exponential growth of population, industrialization, pollution and food production in a mathematical model.

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[1] See https://eurelco.org/definition/ for a complete definition.
[2] See https://eurelco.org/definition/ for a complete definition.

According to Mancini *et al.* (2013), the security of supply of raw materials has become a high-priority theme in the political agenda of the European Union (EU). To ensure access to resources and avoid supply shortages, the European Commission (EC) has taken action and set up the flagship initiative for a resource-efficient Europe under the Europe 2020 strategy. This initiative supports the shift towards a resource-efficient, low-carbon economy to achieve sustainable growth. The sustainable management of natural resources in societies, as well as their availability and access, are fundamental issues for ensuring the population's well-being.

Critical Raw Materials[3] have been identified with the aim of helping to anticipate/prevent supply shortages and focusing efforts and policy actions on materials whose supply interruption would have the most harmful consequences. The use of material resources is therefore depending on the geological availability as well as on the access to them. In this section the security of supply, the resource scarcity and their place in sustainability assessment practice are briefly described in **Figure 1-2**.

The broader perspective of criticality is well described by Myers *et al*. (2019). An overview is given in **Figure 1-2**. This approach is in line with the report titled "*Minerals, Critical Minerals, and the U.S. Economy*", the authors defined the criticality of minerals as a function of two variables: the importance of uses and availability (National Research Council, 2018). The availability can be described as the supply risk and is far more than an assessment of the depletion time of the ore deposits. As earlier indicated, the geological conditions are seldom the main risk for supply. The accessibility of the deposits and availability at the commodity markets are contributing as well to this supply risk. Legislation might also influence the presence/absence of raw materials. The supply risk is of minor concern if the resource can be easily substituted by another material or the importance of the produced goods is low. These parameters influence the prices of the raw materials and if criticality is high, mining landfills might lower the criticality.

[3] Antimony, Beryllium, Borates, Cobalt, (Coking Coal), Fluorspar, Gallium, Germanium, Indium, Magnesium, Natural Graphite, Niobium, Phosphate Rock, Silicon Metal, Tungsten, Platinum Group Metals, Light Rare Earths and Heavy Rare Earths, Baryte, Bismuth, Hafnium, Helium, Natural Rubber, Phosphorus, Scandium, Tantalum, and Vanadium (EU Commission, 2017).

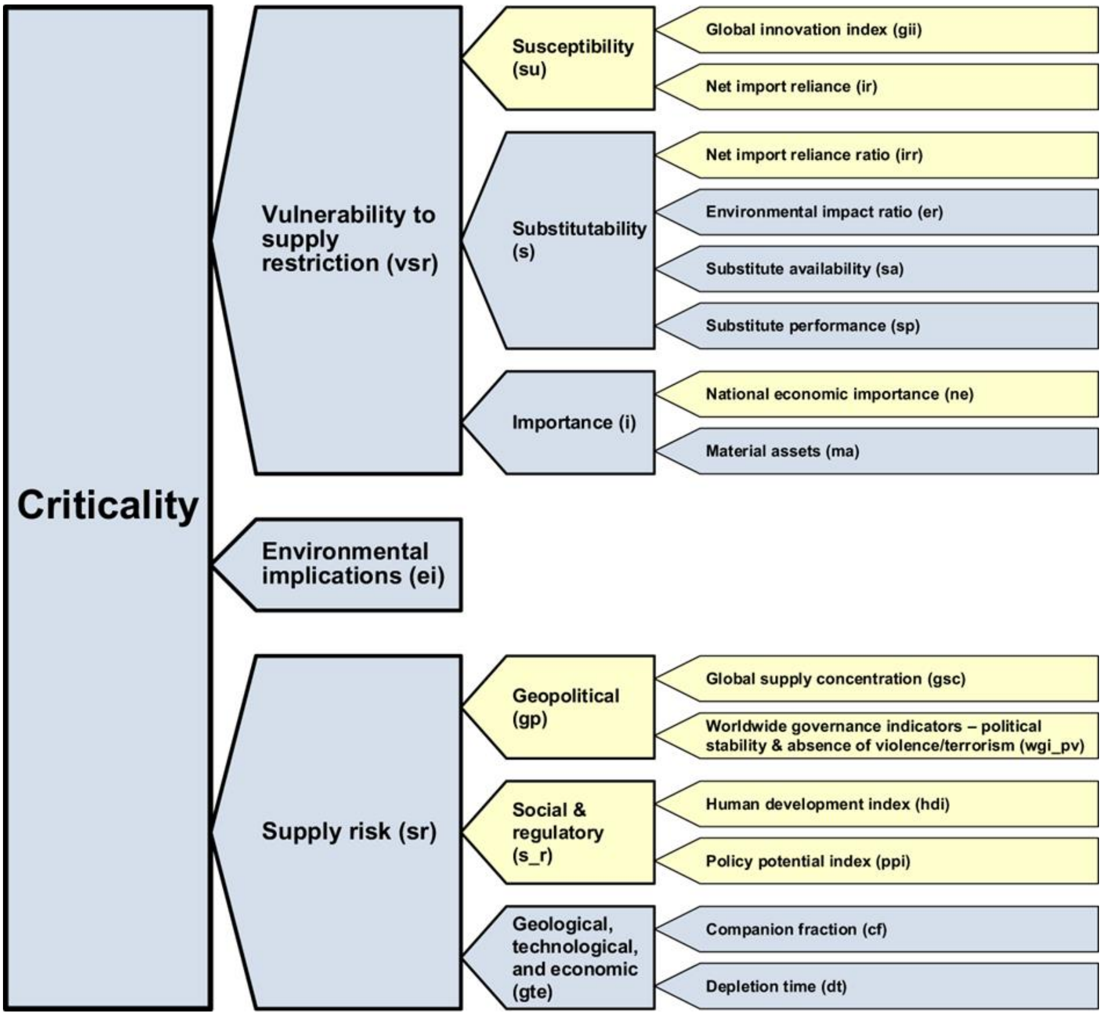

Figure 1-2 Criticality methodology developed by Myers et al. (2019).

1.5 EU Flagship on resource efficiency

In 2011, the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions launched a communication called the Roadmap to a Resource Efficient Europe.

The flagship initiative for a resource-efficient Europe under the Europe 2020 strategy supports the shift towards a resource-efficient, low-carbon economy to achieve sustainable growth. Natural resources underpin our economy and our quality of life. Continuing our current patterns of resource use is not an option. Increasing resource efficiency is key to securing growth and jobs for Europe. It will bring major economic opportunities, improve productivity, drive down costs and boost competitiveness. The flagship initiative for a resource-efficient Europe provides a long-term framework for actions in many policy areas, supporting policy agendas for climate change, energy, transport, industry, raw materials, agriculture, fisheries, biodiversity and regional development. This is to increase certainty for investment and innovation and to ensure that all relevant policies factor in resource efficiency in a balanced manner.

Resource efficient development is the route to this vision. It allows the economy to create more with less, delivering greater value with less input, using resources in a sustainable way and minimising their impacts on the environment. In practice, this requires that the stocks of all environmental assets from which the EU benefits or sources its global supplies are secure and managed within their maximum sustainable yields. It will also require that residual waste is close to zero and that ecosystems have been restored, and systemic risks to the economy from the environment have been understood and avoided. A new wave of innovation will be required.

1.6 Geogenic and anthropogenic resources

Classical mining is the extraction of geogenic materials (minerals and other geological materials) of economic value from deposits on the Earth. Mining activities adversely affect the environment by inducing loss of biodiversity, soil erosion, and contamination of surface water, groundwater, and soil. Moreover, during processing and refining, leakage of chemicals from mining sites can have negative effects on the health of the population living in the vicinity.

The increasing population during the twentieth century is also reflected by the enormous increase in production of food and other products. The mining industry provided vast amounts of raw materials which were introduced in the production chains. At the end of use phase, discarded products became waste and were stored in landfills (principle of linear economy).

Since the 1960s, more attention was paid to waste management. The first objective was the protection of the environment which was often limited to safeguarding a healthy residential area and waste was evacuated to landfills outside the city. Biodiversity and resource-efficiency were of minor concern. However, this changed rapidly, and a waste hierarchy was introduced. This waste management was aiming at minimizing landfilling and maximizing reintroduction of waste in the material cycle (**Figure 1-3**). New concepts of mining were developed such as Urban Mining and Landfill Mining, providing man-made or anthropogenic resources. These resources increase the potential stock.

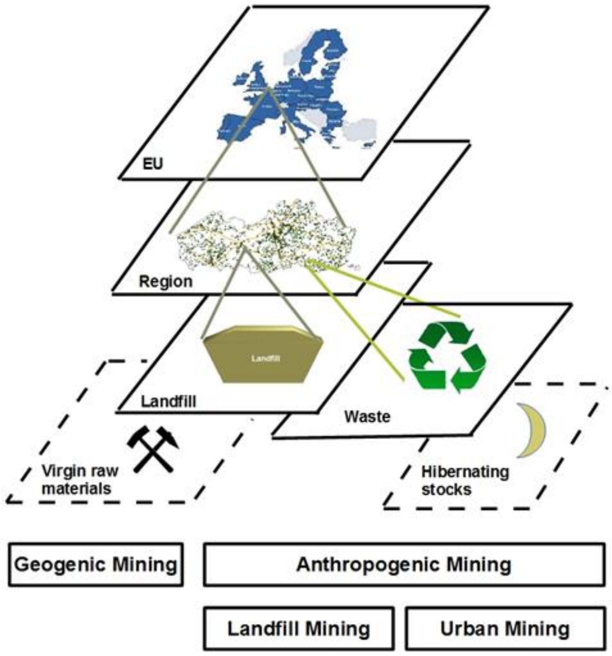

Figure 1-3 Development of new mining concepts (Wille, 2019).

1.7 Landfills and landfilling in a circular economy: ELFM as an innovative concept

Where landfills used to be the final and eternal disposal site of waste, it is nowadays considered to be a long-term and dynamic stock of resources, the so-called circular economy. Two main reasons are the driver for this mind shift:

- In times of geopolitical tensions, these landfills could provide the necessary materials for continuing economic activities, or at least for a short amount of time.
- Resources are finite, recycling is a must if we do not want to be in need of a second planet.

Some policies are already adapted to these insights and changed the way how and what is still landfilled. On the highest geopolitical level, there is the EU Landfill Directive which is mandatory for EU members to implement in their national or regional legislation (COCOON, 2018). The set of rules builds further on the principle of the Lansink's Ladder (**Figure 1-4**), directs to landfill as few materials as possible while protecting that what still needs to be landfilled from the surrounding environment. The ELFM can be integrated in four out of seventeen UN Sustainable Development Goals (UN General Assembly, 2015; see **Chapter 2**) showing an increasing willingness to develop the circular economy and the recovery of resources from landfill on a worldwide scale.

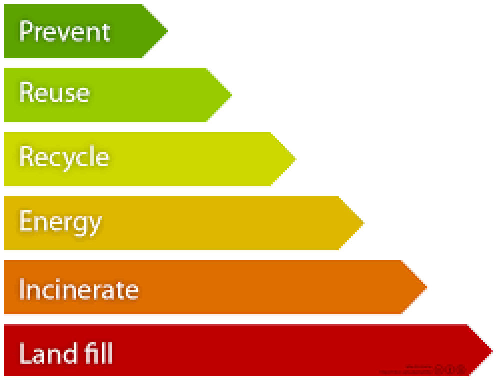

Figure 1-4 The Lansink's ladder (translated from recycling.nl).

Nationally or even regionally, a specific set of rules exists to take landfill management even further. For instance, in Flanders, a policy already exists since the early eighties to promote monolandfilling as much as possible, because the future costs to mine/remove/reuse the site would be much cheaper (EMIS, 1981). Monolandfills are currently the most promising landfills to redevelop, a major advantage for the region. In Wallonia, the concept of landfill mining is mentioned in the waste resource plan, showing a political will to implement the resource recovery from landfills, especially critical raw material (Service Public de Wallonie, 2018). A green deal promoting the development of landfill mining project was also signed in 2018 in the framework of the RAWFILL project. The landfill site of Onoz (see **Chapter 12.1**) will be the first test site for landfill mining in Wallonia. Germany has one of the most comprehensive legislation on landfill sealing (Bundesamt für Justiz, 2009). Specific procedures and quality standards were introduced to guarantee a reliable long-term containment. Currently, testing methods aim at a 100-year period of safe sealing conditions. But what after 100 years? The Netherlands apply an eternal monitoring and aftercare on current landfills. In view of this long-term perspective, they started the project "Sustainable Landfill Management" to investigate accelerated decay and immobilization at three test case landfills.

1.8 Dynamic Landfill Management as an innovative concept

European waste management has evolved to sustainable material management and the initial 3 R's (Reuse, Recycling and Recovery) were extended to a 5 R's (Refuse, Reduce, Reuse, Repurpose and Recycle) or even a 7 R's (Rethink, Refuse, Reduce, Repurpose, Reuse, Recycle and Rot) concept. Especially for landfills, "Rethink" is applicable. The traditional paradigm of the linear economy resulted in landfills as the final waste disposal sites, aiming at an eternal safe situation. This results in static landfills with often low valuable use. The containment and monitor model is gradually coming under pressure because maintaining a static situation in a dynamic environment is not easy to obtain nor is it free of charge. At the 2nd ELFM Seminar in the European Parliament on 20th November 2018, there was an overwhelming consensus that the landfill paradigm needs to change from the static view to a comprehensive, long-term, multi-phased Dynamic Landfill Management vision. This dynamic view on landfill management implies the management of landfills needs to be smartly adapted over time. The Dynamic Landfill Management objectives are multiple ranging from pollution prevention, land reclamation and restoration, creation of new landfill void space, interim use of the landfill surface, to the recovery of materials and energy resources (Jones *et al*., 2018). The concept of Interim use is an inherent part of the Dynamic Landfill Management and consists of finding a suitable land use valorization for the landfill site. The duration of the interim use strongly depends on two key parameters: (1) the time needed for the landfill to reach appropriate mining conditions (e.g. no more biogas production, waste pile stability); and (2) the market price evolution for the landfilled waste resource.

Such a new Dynamic Landfill Management paradigm should have strategies and solutions for not only the (minority of) Landfill Directive-compliant operational and recently closed sanitary landfills but also for the historic landfills and waste dumps predating the Landfill Directive. This is key as the latter form the majority of Europe's >500,000 landfills. This paradigm should be aligned with the Circular Economy paradigm, rather than opposing it.

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2 Recall of the concept of Enhanced landfill mining[4], conceptual site model

2.1 Introduction

All mining projects start with an exploratory phase to detect and characterize ore bodies. The data collection should allow decision making on the feasibility of the project. A conceptual site model offers a good visualization, helps understanding the local situation and serves as a framework for incorporating new data. Quite often the conceptual site model is limited to the local settings while the whole valorization process is depending on regional and even global settings. The relevance of the various system conditions is explained in this chapter.

2.2 The use of conceptual site models in traditional soil remediation projects

In the development process of a Decision Support Tool for Landfill Valorization (**Chapter 7**), the use of a Conceptual Site Model contributes to a good visualization of the problem and points out additional elements of concern. The Conceptual Site Model is one of the primary planning tools that can be used to support the decision-making process of managing contaminated land and groundwater on a large scale.

An analysis of currently applied Conceptual Site Model in the EU and the USA pointed out that the basic constraints of the Conceptual Site Models (**Figure 2-1**) are related to the traditional risk assessment of contaminated sites. This practice is described as a source-pathway-receptor model wherein the characteristics of the source are often limited to the mobile parameters which could impact the vulnerable receptors. In case of landfills, these parameters are landfill gases and leachates. Run-off of solid particles (waste material) is seldom considered as an important contributor. This approach is, however, too limited in view of the RAWFILL objectives which aims at the potential valorization of the landfill in terms of resource recovery (waste and energy) and reclaimed land.

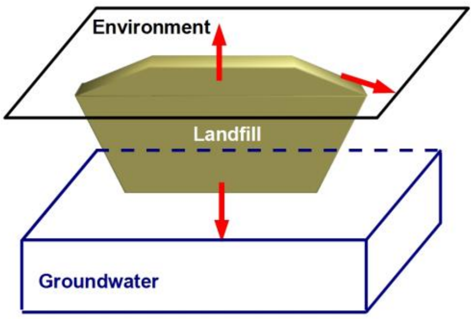

Figure 2-1 Schematic overview of a conceptual site model for a landfill.

[4] See https://eurelco.org/definition/ for a complete definition of ELFM.

Landfills were the end points of the linear economy, but doubts occur on how robust landfills are in a (global) dynamic system. This opens the discussion between the use of a Conceptual Site Model and a Complex Adaptive System.

A Conceptual Site Model aims to provide a schematic overview of specific features of soil contamination and its impacted media in order to assess the risks and determine appropriate remediation measures. From this perspective, landfills are generally described as a (mixed) source of pollution with exposure pathways through soil, air and water. The model mostly simplifies the contaminants of concern to hazardous particles, landfill gas and leachate. Seldom a detailed characterization of the landfilled waste is executed, and the aforementioned risk models take only the "mobile" fractions into account. This risk-based approach is not an appropriate method with regard to resource management of landfills because basic information to evaluate the resource potential is unavailable.

By contrast, Dynamic Landfill Management puts landfills in a broader Complex Adaptive System considering several geometrical scales, timeframes, multiple systems and actions (**Figure 2-2**). The final goal is the optimal reintroduction of a landfill in its environment. This can vary from a total removal of the landfilled waste deposits (including the impact on adjacent zones) to a monitoring system of low maintenance.

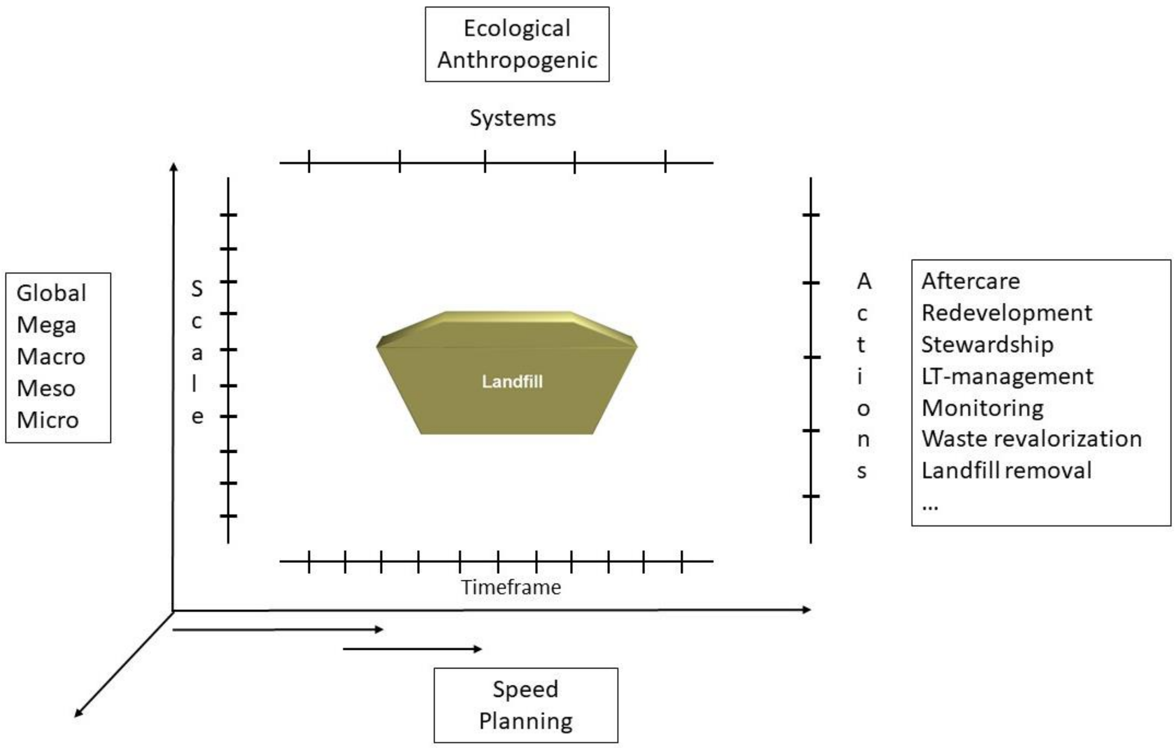

Figure 2-2 Representation of a landfill in a complex adaptive system.

A Dynamic Landfill Management - oriented Complex Adaptive System takes into account the broader context of the circular economy and Sustainable Development Goals (SDGs; UN General Assembly, 2015), addressing the following features should be addressed:

- Defining the levels and impact ranges:
    - Internal processes of the landfill and their impact: site specific – **content**
    - External processes impacting the landfill: spatial aspects - **context**
- Concentric model (geographical characteristics):
    - Microscale: particle level
    - Mesoscale: landfill level
    - Macroscale: landfill and its immediate surroundings
    - Mega scale: landfills at a regional scale
    - Global scale: landfill in a global context
- Systems and Barriers (ranking according to Timbre, 2012):
    - Economics
    - Legislation
    - Procedural administrative
    - Political
    - Information and know-how
    - Technological
    - Social cultural
- Actions and Positive impacts (ranking according to Timbre, 2012):
    - Restore environment *(Link with the SDG 15.3; UN General Assembly, 2015)*
    - Raise local economic development
    - Reduce development pressure on green fields *(Link with the SDG 11; UN General Assembly, 2015)*
    - Increase employment
    - Attract new investors
    - Dispose of negative stigma

Introducing these factors and indicators in any Decision Support Tool (e.g. RAWFILL DST 1 – Cedalion and DST 2 - Orion) requires a comprehensive collection of site and context-specific data. Europe faces a potential stock of 500,000 landfills, most of them dating from before the EU Landfill Directive implementation in 2001. This implies not only a diversity of the installed protecting measures, but also on the availability of data of the landfill features and its waste content. Data collection will differ between the member states and additional information will be required to set up a management plan.

A quick survey of all these landfills will result in a huge financial effort (500,000 sites x 10,000 €site[5] ≈ approximately 5 billion euro) and a short execution period will also pose capacity problems on available experts. In order to tackle this financial and operational problem, RAWFILL provides a Decision Support Tool built on a two-step approach (see **Chapter 7**), aiming at building up data capacity based on accessibility of the data and the relevance for further investigation, and waste revalorization planning.

2.3 Alternative models and flow schemes: The Doughnut-model

From the sixties onwards, when mass production became standard for many large economies, landfills functioned as some form of last frontier for products or packaging material that no longer had any use or economic value.
Since then, society and industry have evolved and learned to make use of every piece or gram of some raw materials and started recycling. Still, it was not before the early 90s that, for instance, electronics started to be recycled.

In today's world, economic factors are beneficial enough to look at landfills as a potential and cheap(er) source of basic components to create new products. The RAWFILL project among other parties sees a landfill as part of a future circular economy, since it is one of the last missing links between the disposal of an old product and the creation of a new one.

An interesting point of view concerning the creation of a circular economy is the doughnut-theory (**Figure 2-3**) as developed by Raworth (2012). In this theory, Raworth (2012) formulates that circular economy has boundaries: (1) a shortfall when specific basic needs (e.g. water, food) and rights (e.g. education, equality) are not met; (2) and an overshoot when too much stress is put on Earth's system. The latter is a good argument for the reuse of landfills.

[5] Based on OVAM experience and expert advice on landfill management.

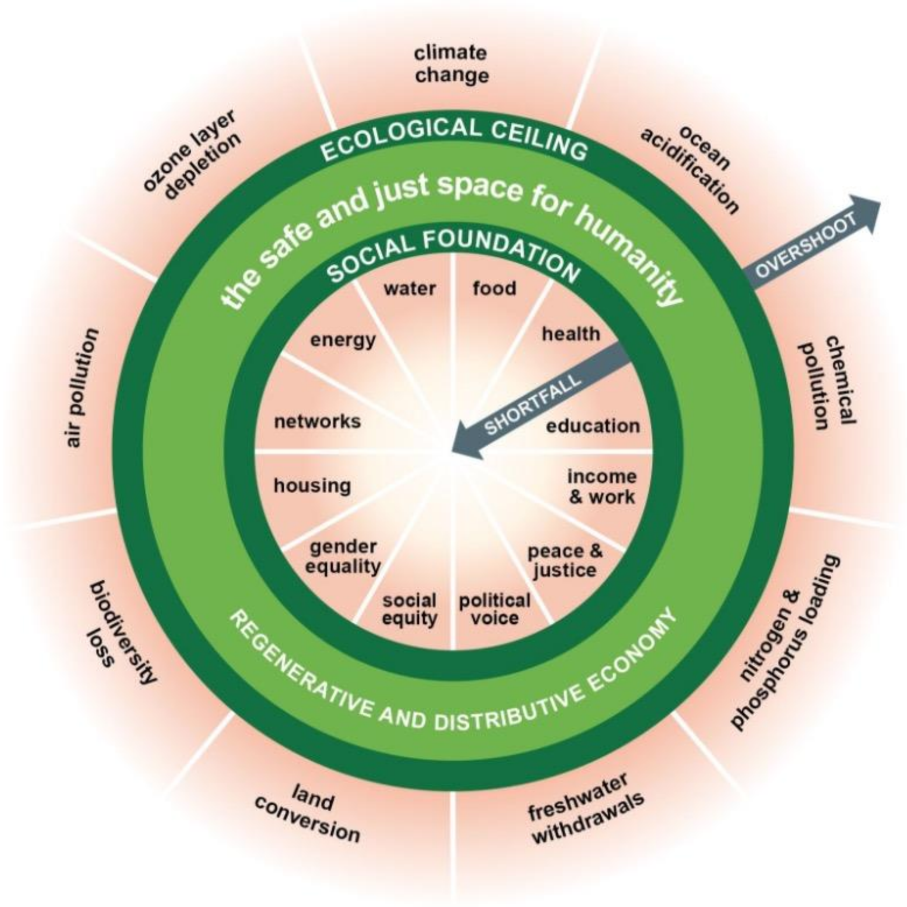

Figure 2-3   Visual presentation of the doughnut-shaped economy of Raworth (2012).

2.4 Challenges and goals: climate change, soil sealing, water scarcity, Sustainable Development Goals

Landfills tend to be seen as a static body of waste deposits, safe forever on the spot where it was chosen. However, the environment is a dynamic feature and many factors, many triggered or induced by man, can lead to detrimental effects on the landfill body.

Climate change

The bioreactor of a landfill produces several gases, including methane. Methane is a well-known greenhouse gas, 28 times more powerful than carbon dioxide. In this case, the actual management of the landfill is related to its impact on the environment. Landfills created after the EU Landfill Directive must be sealed completely so the produced landfill gas can be collected and processed, preferably with energy recuperation. However, since the majority of the landfills predate 1999, most methane has already found its way into the atmosphere and the bioreactor has shut down or is very weak due to a lack of actors in the overall chain of events. Questions rise on the effects of prolonged periods of inundation e.g. flooding due to changing precipitation patterns and form a new opportunity of research.

Soil sealing

The vast majority of landfills currently have no real land use[6] and are often covered with herbs, shrubs and sometimes trees together with various degrees of equipment typically associated with landfill aftercare monitoring (e.g. gas collecting pipes, leachate treatment plant). Because of the green environment which often occurs on top of landfills, the impression is given that these terrains are "open" i.e. have unhindered soil respiration.

In case of landfills with a sealing, or landfills created in old quarries, water cannot escape into the direct environment. This is a good thing since landfill contain contamination. However, the consequence in modern landfill design is that meteoric water is also captured in the quarry or the drainage system. In both cases this water is removed, treated and led to the closest river system without having the chance to accumulate in the aquifer.
Additionnally, climate change causes more periods of extended drought, with the result of very low or record low ground water levels. This is for instance the case in Belgium: in 2020, the groundwater levels still have not recovered yet from the exceptionally dry year 2018 (DOV, 2020).

Water scarcity

The relation between water scarcity and landfills follows more or less the same principle as with soil sealing: water from the landfill itself and surface water run-off are captured, purified and subsequently discharged into a local river or stream. However, it can also be an opportunity. From a historical perspective, every village, town and city had one or more landfills for their municipal solid waste. Landfills are therefore scattered around the area as long as there is civilization present. The trigger for a landfill mining project could be partially recycling to win terrain. When this is done, the positive return on available space could be used for residential projects, but also to create basins to store excess meteoric water as a reserve in times of drought.

Sustainable Development Goals

Four out of seventeen UN Sustainable Development Goals (SDGs; UN General Assembly, 2015) are directly applicable to the concept of landfill mining (**Figure 2-4**). Goal 9[7] contains the strive for innovation, Goal 11[8] the creation of sustainable cities. In the "section water scarcity", it was already mentioned that many landfills are nowadays located in cities, not on the edge, due to urban sprawl. Innovation will make it possible to find a solution for landfills to re-enter the (economic) society, at the same time actively contributing to the sustainability of the surrounding community. Goal 12[9], responsible consumption and production, will have an effect on the amount of waste that still will need to be landfilled. Finally, Goal 13[10] - climate action, is applicable on the way landfills are constructed. A good

[6] Landfill sites are usually integrated in a regional land use planning. However, due to the potential risks related to the presence of landfills, the lands are often abandonned and not revalorized. In some cases, the real land use can differ from the regional land use planning.
[7] Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
[8] Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable.
[9] Goal 12 : Ensure sustainable consumption and production patterns.
[10] Goal 13 : Take urgent action to combat climate change and its impacts.

cover and degasification installation will not allow the escape of methane into the atmosphere. More specifically, Goal 14[11] – conservation of the marine resource and its aim to prevent and the reduce the marine pollution can be indirectly linked with the concept of landfill mining. Around the world, landfills were built along the shore, which constitute a serious threat for marine resource due to the coastal erosion and the transportation of waste materials and contaminant directly into the sea. Therefore, there is a clear link between the removal of these landfills and the long-term reduction of the marine pollution.

Figure 2-4 UN Sustainable Development Goals. Goals 9, 11, 12 and 13 are linked directly with the concept of landfill mining. Goal 14 - conservation of the marine resource is indirectly linked with the landfills present along the shore which constitute a significant threat for the marine life. Landfill mining projects can help to reduce the pollution related to these landfills.

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[11] Goal 14 : Conserve and sustainably use the oceans, seas and marine resources for sustainable development.

3 Legal framework and perspectives

3.1 Introduction

In the linear take-make-dispose model, all measures are undertaken from the perspective of an eternal and safe storage of waste. This final disposal is the less favourable option according to the Waste hierarchy in the EU[12]. In waste management, the Lansink's Ladder principle aim at an optimal closure of the materials cycle. Avoiding waste is the first option and landfilling the last preferable.

3.2 EU-legislation and impact on regional level

Waste management and/or Material management

The transition to a sustainable material management goes beyond the border of waste avoidance, treatment, and emphasis on the way products are made. Ecodesign is a step forward in creating products which are more dematerialized, built for reuse & recycling requires less energy, and is less toxic. This transition is also described as a part of Urban mining: the products of tomorrow are made of the materials collected today. An additional source of potential materials which can be introduced in the material cycle, is the content of the former landfills.

Landfilling and landfill aftercare

Operational standards for landfilling became more stringent since the 1980s and waste dumps were phased out[13]. Sanitary landfills are preferably sited at locations with a low vulnerable natural environment. Precautions measures are taken to prevent leakages. This involves protective liners and drainage infrastructure but also operational restrictions on the types of landfilled waste. The principle of limited mobility often results in (pre)treatment of landfilled waste to lower its leaching capacity. After closure of the landfilling activities, a final cover is installed and if landfill gas is still produced, an extraction unit evacuates these gases. This extraction unit is commonly combined with an energy-producing facility. This kind of landfill management does not emphasize on the potential valorization of the landfilled waste and its land surface although the stock is rather immense. Estimations pointed out that Europe has a potential stock of more than 500,000 landfills (Hogland *et al*., 2010). The existing environmental policies are solely addressing the adverse impacts of these disposal facilities. Contaminated land management is the basic approach and disregards the resource potential. The current operational conditions even inhibit future mining.

Sanitary landfills are operated under such conditions that they result in final waste disposal sites, therefore creating a steady state landfill within a dynamic environment. All measures are (and should be) put in place to avoid adverse impact and interaction with the environment.

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[12] 2008/98/EC, Waste Framework Directive; amended by Directive 2018/851 of the European Parliament and of the Council of 30 May 2018.
[13] 1999/31/EC, Landfill Directive; amended by Directive 2018/850 of the European Parliament and of the Council of 30 May 2018.

The dynamics of the adjacent media are not only limited to physical-chemical processes but also triggered by economic and social drivers. From that perspective, setting up a final disposal facility requires severe boundary conditions which are mostly attained by introducing containment measures resulting in an isolated volume of waste. This approach is in line with the conceptual site models and risk assessments in order to eliminate the exposure pathways and potential hazards for human health and the environment. To guarantee the environmental safety of the landfill site, long-term aftercare monitoring must be performed. The duration of the aftercare period is fixed by regional legislation (e.g. 30 years in Wallonia). However, some landfill sites still remain problematic after 30 years and there are still currently no solutions on how to deal with them in the near future.

The contained source of pollutants (waste) remains a potential threat and reducing the landfilled waste is a more effective measure. At first, the waste treatment hierarchy points out the basic views on prevention, reuse, recycling and final disposal. During the last decade, the policy transition from waste to sustainable materials management was introduced and fitted in the broader concepts of resource efficiency and circular economy.

EU policies on natural resources and land use

Under the Europe 2020-programme, the EC introduced a strategy for smart, sustainable and inclusive growth. Europe 2020 puts forward three mutually reinforcing priorities:

- Smart growth: developing an economy based on knowledge and innovation.
- Sustainable growth: promoting a more resource efficient, greener and more competitive economy.
- Inclusive growth: fostering a high-employment economy delivering social and territorial cohesion.

The Flagship initiative for a Resource Efficient Europe supports the shift towards a resource-efficient and low-carbon economy. The Roadmap to a Resource Efficient Europe outlines how we can transform Europe's economy into a sustainable one by 2050, taking into account the interdependencies.

The General Union Environment Action Programme to 2020 “Living well, within the limits of our planet” emphasizes the transition to a circular economy. On the 2nd of December 2015, the EC adopted a new Circular Economy Package to stimulate this transition. In a circular economy, the value of products and materials is maintained for as long as possible. Minimizing waste production and reducing the mining of virgin natural resources contributes to this objective and lowers the externalities on the different levels.

Land is a multifunctional resource and the amount available to be used for different purposes is relatively fixed (EIEP, 2013). Mark Twain already noticed this reality when he stated: “Buy land, they ain’t making it anymore”. Land take is a process of significant relevance in the countries of the EU. Land take is defined as the “Change of the amount of agriculture, forest and other semi-natural and natural land taken by urban and other artificial land development” (EEA, 2013). In 2011, the European Commission put in evidence that an important milestone for the EU should be to reach the goal of no net land take by 2050, and to take under strict control the impact on land taking processes of the EU policies in the new Structural Funds programming period (2014–2020).

During the conference "Land as a resource" (June 19, 2014), the EU-commissioner of environmental affairs declared: "Efficiency in land and soil management is one of the main challenges facing our society. This challenge can only be met if we act to address the factors underlying it. In particular, we need to acknowledge that land is a finite resource and use it first and foremost for as many purposes as possible – economic, social and environmental. Secondly, we need to avoid its wastage, including by preventing land degradation. Thirdly, we actively need to restore its functions once the land is degraded and encourage land recycling, in particular by supporting the regeneration of brownfields." Landfill sites as a specific kind of brownfields, could be addressed within that regeneration process.

The European Parliament resolution of July 9th, 2015 on "Resource efficiency: moving towards a circular economy (2014/2208(INI))" clearly indicates the necessity of innovation and policy transition when it comes to resource management. This resolution states that unsustainable use of resources is the root cause of various environmental hazards. Parliament fully supports the transition towards a circular economy and point attention to 80 measures to the European commission in view of this policy change. Measure 40 calls on the EC to further investigate the feasibility of proposing a regulatory framework for enhanced landfill mining (ELFM) so as to permit the retrieval of secondary raw materials that are present in existing landfills. Recent research pointed out that ELFM should be considered as mining of anthropogenic resources but also contributes to sustainable land use. The transition to a circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized, is an essential contribution to develop a sustainable, low carbon, resource efficient and competitive economy. The European Commission adopted a Circular Economy Package[14], which includes revised legislative proposals on waste to stimulate Europe's transition towards a circular economy. This plan establishes a concrete and ambitious programme of action, with measures covering the whole cycle (production and consumption to waste management and the market for secondary raw materials). However, in this package landfill mining was not explicitly mentioned. In May 2014, the EC decided to withdraw the proposal for a Soil Framework Directive but also mentioned that current soil degradation trends both in Europe and globally, present future challenges to ensure protection. The contribution of the EC to the conference "Land as a resource" (June 19, 2014) stated clearly that sustainable resource management is essential and broad defined concept. From this perspective, landfills and landfilling are included.
Landfills can contribute to the supply of resources such as materials, energy and land. The introduction of Enhanced Landfill Mining (ELFM) necessitates a specific approach compared to traditional geogenic mining. ELFM is situated at the crossroads of waste and resource management, and contaminated land management. Multiplicity is the major characteristic, and the interconnection of multiple levels, disciplines and actions demands an appropriate management: Enhanced Landfill Management & Mining (ELFM²).

Figure 3-1 provides an overview of all these aspects and the relationships between them. While Waste management is focusing on the treatment of the generated waste and a safe

[4] COM(2015) 614/2, December 2, 2015.

storage in landfills, ELFM² puts emphasis on Closing the loop and the reintroduction of the landfilled waste in the economic and ecological cycle. The latter requires a comprehensive approach and uses concepts from traditional mining (mapping and surveying), but also decision making, as not only the "grade" (resource potential) is relevant. Land as a resource is an important driver as well as the environmental impact causing deterioration of land and groundwater. Consequently, rehabilitation and valorization of landfills is a complex issue and involves multiple partners, disciplines and timeframes.

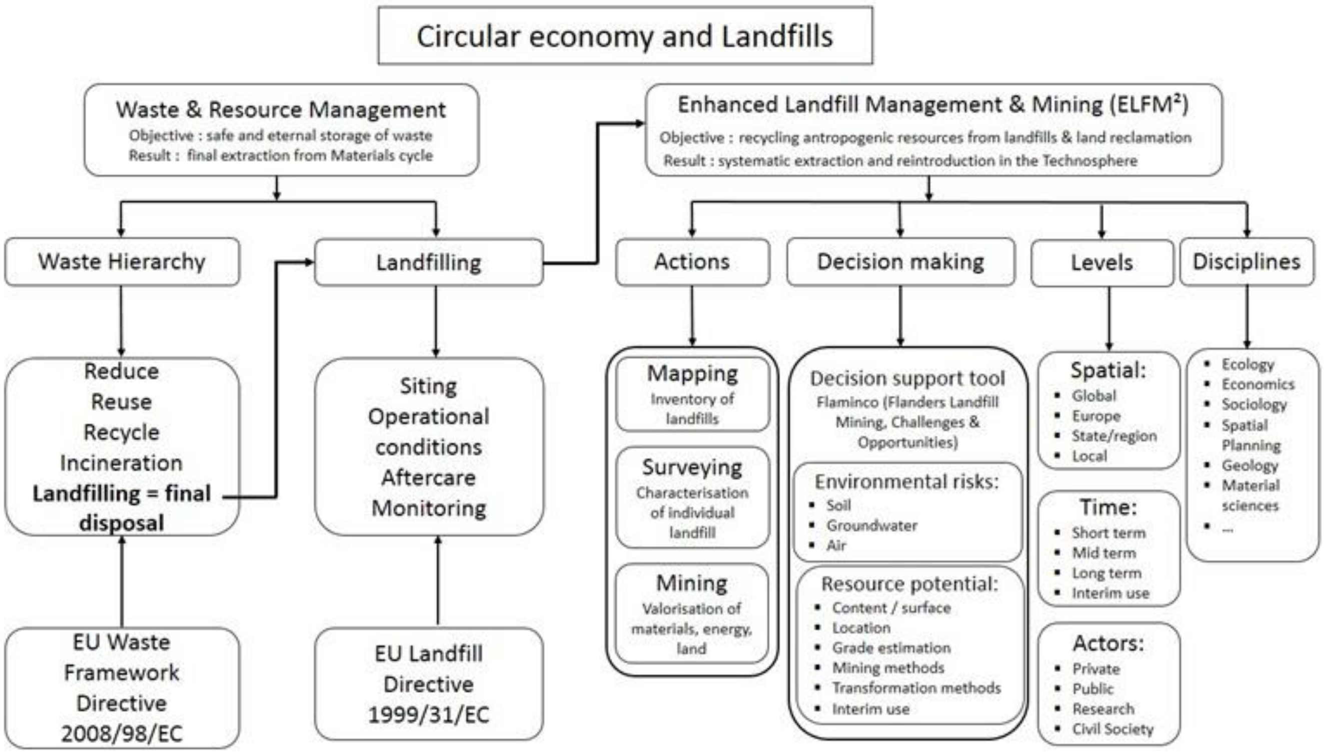

Figure 3-1 Multiple aspects of ELFM².

Specific regulations on ELFM

The 1999/31/EC, Landfill EU Directive does not include specific operational standards for landfill mining. Nevertheless, the directive does not prohibit landfill mining and according to EURELCO and COCOON data, a few projects were executed and/or are ongoing. EU legislation has been addressed in the Circular Economy Package (Waste sub package) and included the proposal on amending the Landfill Directive with regard to ELFM. No specific ELFM-amendment was included.

The applicable regulations differ by member state. Most customize regulations on environmental permits or use the laws on soil remediation. In Germany, for instance, there are no general consistent national legislative frameworks and approval procedures for landfill mining. In fact, the authorities define assessing procedures for permissions on landfill mining projects in each of the 16 federal states. In general, German authorities consider landfill mining on operational landfills as an alteration in the practice of landfilling, which is why landfill mining projects ought to be planned and conducted according to the circular economy and waste legislation as well as in compliance with the legal framework of national emission control. However, approval for landfill mining projects based on the circular economy and waste legislation is yet an exception and is mostly applied to small landfills with low environmental impact (Gäth & Nispel, 2012). Moreover, concerning energetic valorization of recovered resources from landfills that cannot be used for raw material recovery, the excavated waste has to have at least 11,000 kJ/kg according to the circular economy and waste legislation. The legal framework of national emission control is mostly applied once the waste is sorted and processed at a different location than the mined landfill (Gäth & Nispel, 2012). In North-Rhine Westphalia for instance, landfill mining studies and projects are commonly permitted according to waste or soil legislation. On operational landfills, regulations according to waste legislation will be applied to landfill mining projects. Once a landfill was released from aftercare, landfill mining projects will be performed in compliance with soil legislation. Moreover, sorting, recycling and treatment plants for excavated waste will be regulated under national emission control legislation.

In Belgium, the regions are the competent authorities on environmental policies and legislation. The Walloon region introduced the concept of the Green Deal to promote Landfill Mining at the Onoz site, which will be the first landfill mining project in Wallonia. In this particular case, the involved stakeholders at the local and regional level signed an agreement with the private company on the realization of the ELFM project. This contract, signed within the framework of the RAWFILL project, is setting the scene of their cooperation: a commitment of efforts, but not results at any price. The concept of landfill mining is also mentioned in the waste resource plan, showing a political will to implement the resource recovery from landfills (Service Public de Wallonie, 2018). The Walloon government is currently working on the establishment of a regional strategy for the circular economy, which should be ready by the end of 2020.

In Flanders, OVAM started an operational programme in 2011 (Wille, 2016) on Enhanced Landfill Mining (ELFM) over the period 2011 – 2015. The main goal of this programme was the development of a comprehensive policy dealing with the issue of more than 2,000 former landfills in the region of Flanders (Belgium). On October 16, 2015, the Flemish Government approved the OVAM-memorandum on the new concept of Sustainable Resource Management of Landfills, as introduced by the minister of Environmental Affairs. This concept, also described as Enhanced Landfill Management & Mining (ELFM²), aims at a sustainable long-term management of (mostly former) landfills, including interim use, and the valorization of its content and surface. This concept was further developed in the Interreg Europe COCOON-project and renamed as Dynamic Landfill Management (Jones *et al*., 2018).

The region of Flanders has taken specific legislative initiatives to promote and implement Dynamic Landfill Management. An amendment on the Soil Act was approved by Flemish Parliament on November 29, 2017[15]. The aim of the modification is collecting more and better data on landfills by introducing the obligation to conduct a preliminary soil investigation at landfill sites according following rules :

- Before 31.12.2021: industrial and MSW landfills;
- Before 31.12.2023: inert landfills;
- Before 31.12.2027: if exemption is acquired : OVAM will execute investigation

In order to streamline these investigations, OVAM will provide specific guidelines. The Environmental Permitting Act was amended on May 3, 2019[16] and introduced a specific framework for large scale mining-projects with regard to landfills and the ELFM concept.
In the Sustainable Materials Act (former Waste Management Act), the chapter on Levies & Environmental taxes was modified and resulted in zero taxation on the landfilling of residual waste coming from accredited ELFM projects (approved July 2018). Since former landfill sites can be considered as brownfields (neglected or under-used sites that have been damaged in such a way that they can only be reused through structural measures), the Brownfield covenant Act is also applicable. Since the 7th call launched in May 2017 specific emphasis on landfill (site) projects was set.

These examples point out that the competent authorities can customize their legislative frameworks on waste, landfills, environmental permits, soil remediation and brownfield rehabilitation in order to promote Dynamic Landfill Management. Additional drivers can be detected in policy domains such as flooding risk management, climate change, soil sealing and circular economy.

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4 Geophysical imaging

4.1 Introduction

The purpose of this chapter is to provide guidance on the application of geophysical survey methods. Specifically, on how geophysical survey methods may be used to enhance the characterization of landfill sites, in terms of spatial extent, volume and/or composition/distribution of waste materials across a site. Rather than providing a detailed description of individual techniques (e.g. Reynolds, 2011 and corresponding applications on landfills: Soupios & Ntarlagiannis, 2017), this document presents a high-level approach for the design of a geophysical survey through the development and subsequent improvement of a conceptual ground model. The final aim of the process described is to construct a Resource Distribution Model (RDM) of a given site, which describes the spatial and volumetric distribution of indicative parameters of the landfill materials, at a scale suitable to assess the economic viability of landfill mining operations.

4.2 Why geophysics?

Geophysical prospecting methods are rapid, non-invasive, surface-based techniques, used to measure bulk ground properties, such as electrical conductivity (or its inverse, electrical resistivity), density or stiffness. The most effective use of geophysical surveying relates to the ability to investigate relatively large areas, in order to delineate (map) areas of contrasting material properties. In addition, geophysical methods are largely non-invasive and do not present the same risk of cross-contamination or damage to contamination barriers associated with conventional invasive sampling such as trial pitting and drilling.

Geophysical surveying can capture much greater information concerning spatial heterogeneity across a site and is more cost effective than point measurements alone (e.g. intrusive boreholes/trenches or point sensors - **Figure 4-1**). For example, to identify anomalies of a minimum area of 25 m^2 (at ~1 m depth) with confidence within a site of dimensions 100 * 100m, using intrusive methods alone would require over 600 trial pits of 1 m^2 to be dug - a significant cost, both financial and in terms of the time/resource required. In comparison, multiple geophysical mapping techniques could be undertaken across the site in a fraction of the time and at vastly reduced cost. Select areas for verification through a small number of trial pits could then be chosen, based on previous results.

Geophysical methods, when correctly applied, help to better understand landfills. Combined with a priori information and targeted sampling (e.g. boreholes, trenches), they can help to identify the landfill's extent and to characterize and identify changes in waste composition.

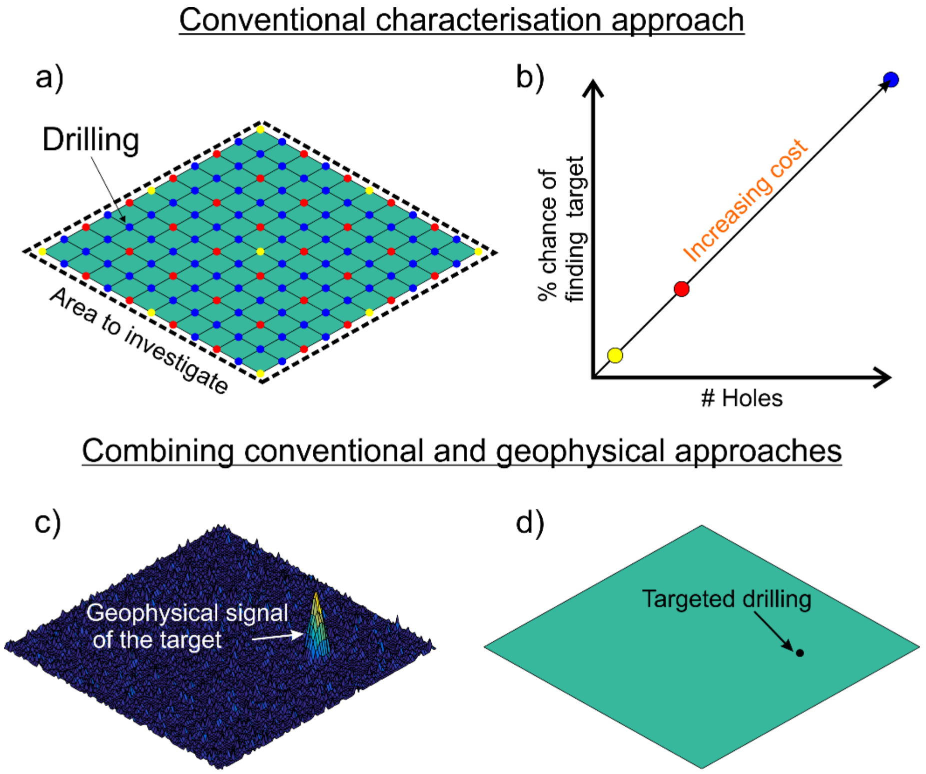

Figure 4-1 Sampling provides direct information of the material. Uncertainty remains about the area between boreholes or trial pits and a specific target might be missed if sampling is done too sparse (a). However, the highest the grid resolution, the fastest sampling costs increase (b). Geophysical methods can help to "fill" the gaps (c) and guide invasive investigations reducing the number of "holes" required to characterize the area (d).

4.3 Principles on how to use Geophysics

A correct application of a geophysical survey is critical in order to achieve reliable results. It should be kept in mind that geophysical methods are indirect techniques and the measured physical property might point to different possible interpretations. For example, high conductivity indicates either increased leachate or increased metal content. Therefore, in order to reduce this uncertainty, it is highly recommended to apply a combination of complementary geophysical methods, which measure different (and unrelated) material properties. Due to the highly heterogeneous structure of landfills, it is necessary to use targeted intrusive samples (e.g. boreholes, trenches; see **Chapter 5** for further information) both in order to verify the geophysical results and to calibrate the geophysical processing and modelling

Principle 1: Never use a single geophysical technique on its own.
Combining complementary geophysical techniques is highly recommended in order to: - Calibrate the geophysical processing and reduce interpretation uncertainties. Targeted sampling is required in order to: - Calibrate the geophysical data processing to produce unambiguous results; - Verify the results and minimize interpretation uncertainties.

A geophysical technique is only able to detect a target if it causes a significant contrast in the measured material property. Conductivity maps measured with electromagnetics will only efficiently delineate a waste body if the conductivity contrast between the waste and the host material is high enough (e.g. increased conductivity of waste due to the high content of metallic scraps). Furthermore, every geophysical method has its own advantages and limitations. Some methods are better to map lateral changes whereas other methods are able to measure up to greater depths. Therefore, it is crucial to choose the primary geophysical technique(s) and the associated measurement parameters based on a priori knowledge of the site conditions (expected heterogeneities in material properties) and the intended objective of the survey.

Principle 2: A geophysical survey needs to be planned based on a priori site information and in accordance with the objective/target[17].
This information is essential to: - Choose the best combination of geophysical methods; - Choose the adequate measurement parameters; - Define the required extent/resolution of the survey.

A workflow suggesting how to use geophysical techniques in order to build a RDM for a potential landfill mining project has been proposed, based on the development and subsequent improvement of a conceptual ground model. The main steps are summarized in **Figure 4-2**. The following sections describe each step in further detail.

[17] In this case, landfill mining operations.

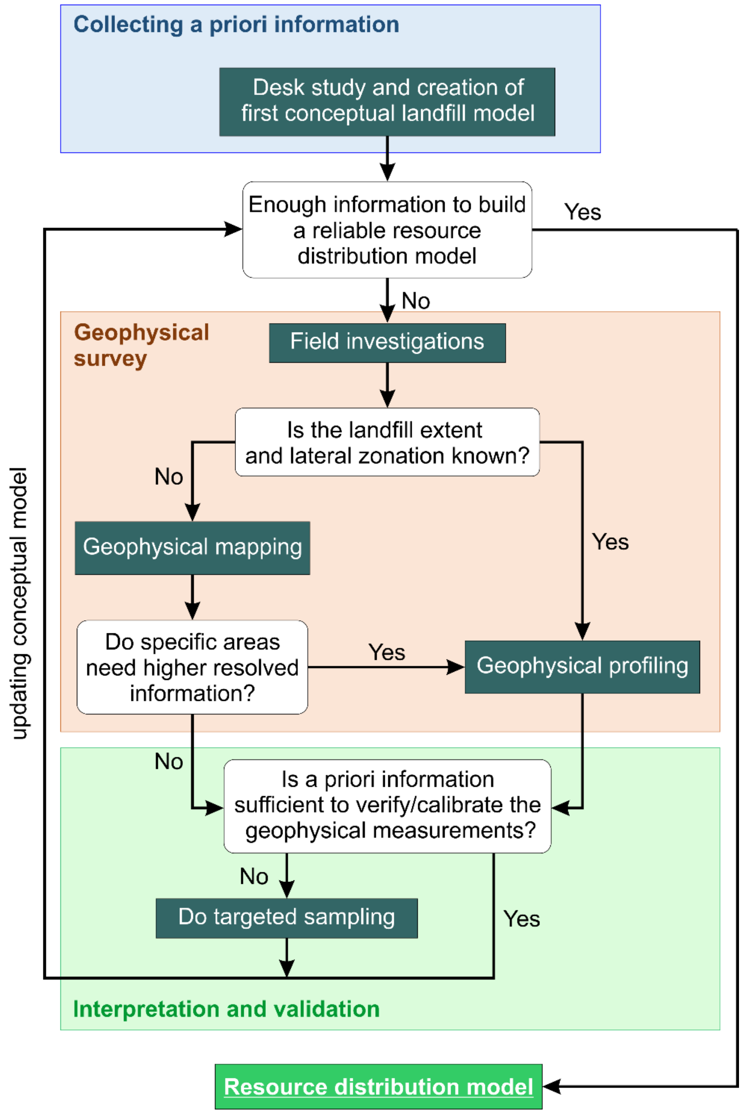

Figure 4-2 Main steps of the suggested workflow. Each step is explained in more detail in the following sections.

4.4 A priori information and identification of knowledge gaps

A first step in the planning of a geophysical survey is the collection of already available a priori site information. This information can range from landfill extent, structure (e.g. presence of waste cells or HDPE membrane) to waste composition and can come from various sources as described in **Table 4-1**. The available information should allow creating a preliminary conceptual model of the landfill as shown in **Figure 4-3**. Depending on the available information, the degree of detail of this conceptual model can vary. Based on the conceptual model, "knowledge gaps" can be identified and the objective/target of the geophysical survey can be defined. Furthermore, the conceptual model is vital in order to select the appropriate combination of geophysical techniques, delineate areas of interest, and define required survey resolution and parameters.

Table 4-1 Sources and types of a priori landfill information.

	Information source	Information type
Reports and maps	Historical reports	- Landfill extent - Landfill structure - Waste composition
	Aerial photography archives	- Landfill extent and operation times which might be linked to waste type and landfill engineering design
	Groundwater maps	- Presence of groundwater table at depth
	Geological maps	- Host material
Interviews	Interviews and discussions with landowners, neighbours and local authorities	- Landfill extent and operation times which might be linked to waste type - Landfill structure
Observations / site visits	Topographical changes	- Potential indication of landfill extent
	Vegetation cover	- Current landfill state and accessibility
	Geological outcrops	- Host material
	Cover layer	- Type of cover material
	Superficial waste	- Presence of waste at the surface - Expected buried waste type
Ground truth data	Nearby boreholes	- Groundwater table depth - Host material
	Available sampling data	- Presence of gas and potential pollution - Waste type - Water content

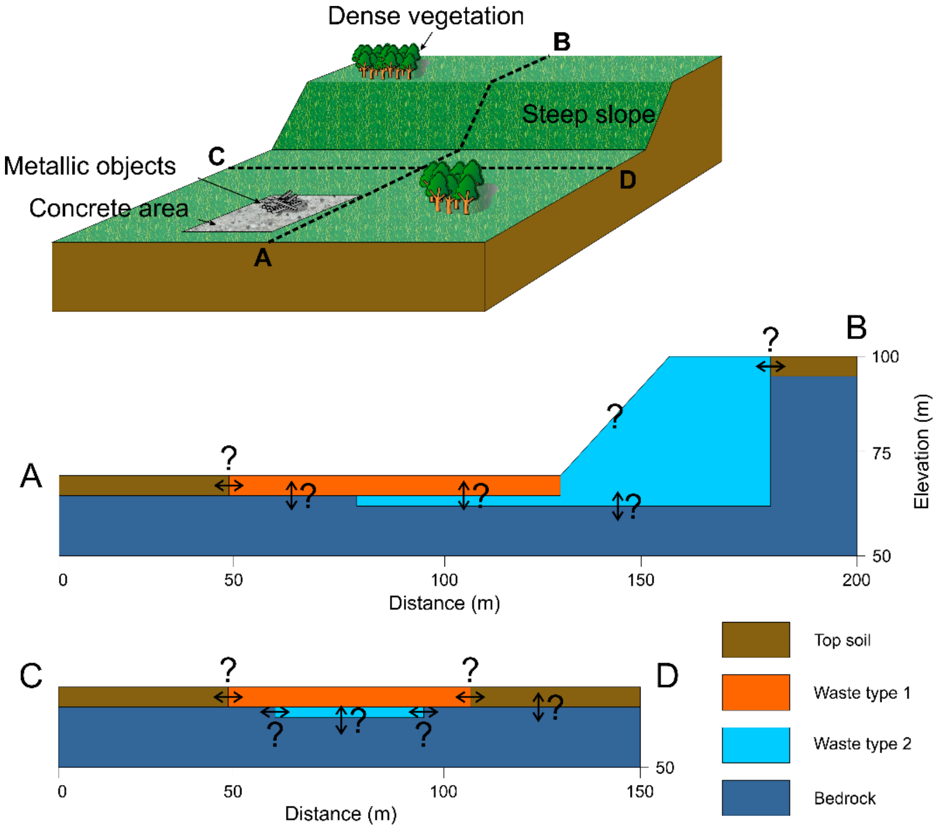

Figure 4-3 Example of a conceptual model built from a priori site information, including information such as landfill extent, host material, waste body, cover layer.

4.5 Geophysical survey

The effectiveness of any geophysical survey is related to the overall size of a field site and the scale of heterogeneity encountered. A survey should be designed to capture information at a scale appropriate to characterize any variations in material properties throughout a field site, or to resolve anomalies/features of a desired size/volume. Survey planning should therefore take into account any pre-existing information regarding the site, such as construction information, records of waste and any intrusive information (e.g. description of boreholes) that may have been collected previously, specific site constraints such as accessibility or presence of disturbing structures (e.g. metallic objects as illustrated in **Figure 4-3**). This is particularly important for deciding which geophysical techniques may be of most relevance.

The choice of primary geophysical technique(s) used will likely be related to the type of property of interest (i.e. if a particular material such as metal or plastic is to be recovered preferentially), but it is recommended that multiple techniques are applied, preferably measuring a range of different (and unrelated) properties. Changes in the bulk properties of landfill materials relating to variation in the types of waste deposited (e.g. low resistivities = high leachate content or high metal content) may mean that a particular technique(s) (e.g. electrical or electromagnetic) is most appropriate, but a secondary technique (e.g. relating to material stiffness or density), may help to further refine the interpretation of the collected geophysical dataset.

A direct result of combining geophysical methods which measure different but complementary physical properties is the significant increase in the level of confidence placed in any final interpreted RDM. Geophysical methods, when correctly applied, help to better understand landfills. Combined with a priori information and targeted sampling (see **Chapter 5** for further information), they can help to identify and characterize the landfill extent, and waste composition.

The following paragraphs introduce a suggested process through which a geophysical survey may be designed. The types of existing data discussed are not exhaustive and any source of information available should be utilized where possible.

Geophysical methods can be divided into two categories (see **Figure 4-4**):
- **Mapping methods:** These methods provide rapid overall knowledge of extent, structure or lateral changes in composition or thickness of cover and waste layers.
- **Profiling methods**: These methods are less cost effective but provide more detailed information about changes with depth. High-density surveys can be combined to create a 3D model of the landfill.

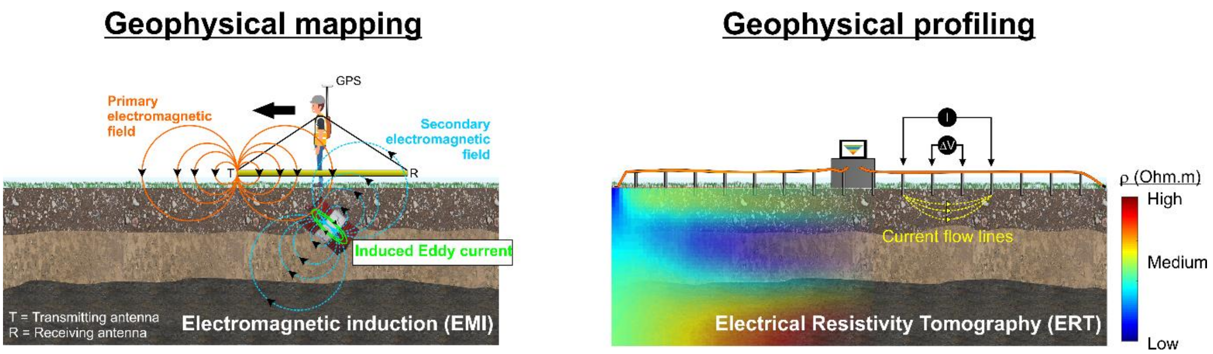

Figure 4-4: Examples of mapping (left) and profiling (right) geophysical methods. The geophysical mapping method illustrated is the electromagnetic induction (EMI) which uses electromagnetic fields to measure electrical conductivity and magnetic susceptibility of the subsoil. The geophysical profiling method shown is the electrical resistivity tomography (ERT) which allows to image (in 2D or 3D) the electrical resistivity distribution of the subsoil by injecting electrical current and measuring the resulting difference in electrical potential via buried electrodes.

Often mapping methods are applied first in order to gain an overall view of the landfill extent and structure. The profiling methods are generally used afterwards for more detailed studies. Either they are used for targeted investigations on areas which require additional information based on a priori information or/and on the results of the mapping methods. Or they can be used as single profiles gaining an overview of the depth/structure of the landfill. A proposed workflow is schematically illustrated in **Figure 4-5** & **Figure 4-6** used a synthetic case study. Mapping methods (here electromagnetic induction and magnetometry) are first used to delineate the lateral extent of the landfill and gain an overview of lateral heterogeneities within the landfill. Once the lateral zonation is observed, the vertical extent of the landfill and the waste zonation can be investigated by applying profiling methods (here electrical resistivity tomography and induced polarization). In the top profile (**Figure 4-6**), the model resolution at depth is not sufficient to reliably estimate the total thickness of the landfill, but the homogeneity of the observed electrical properties (i.e. resistivity and chargeability) suggests the presence of a single type of waste. In the bottom profile, the model resolution and electrical contrast are sufficient to map the interface between the host geology and the waste at depth. Given the observed electrical signatures, two layers within the landfill can be identified suggesting the presence of two different types of waste deposits.

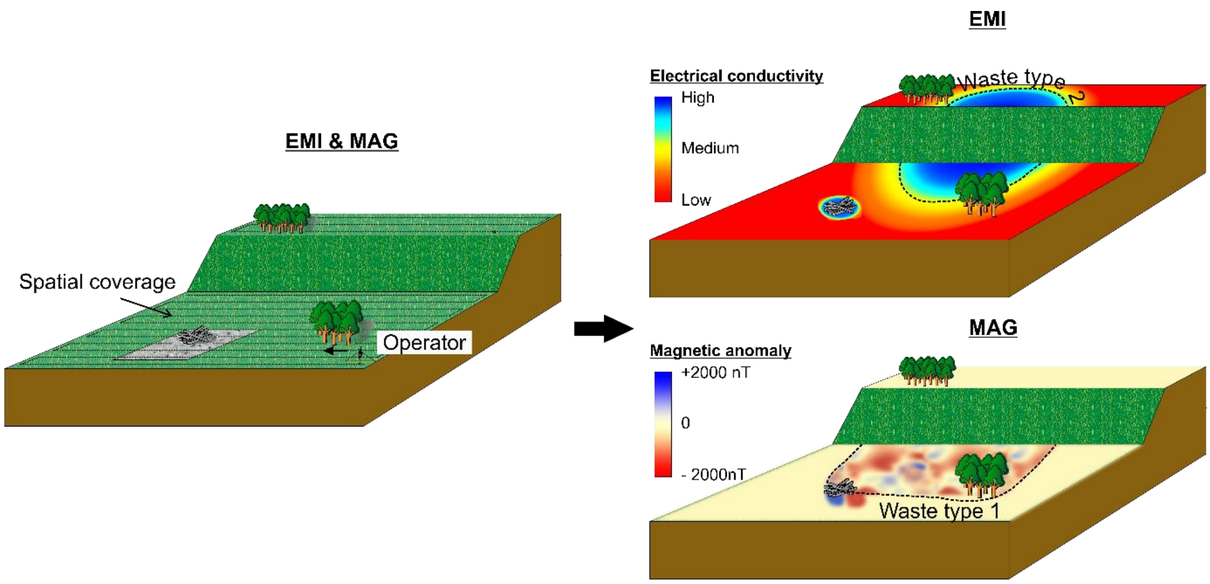

Figure 4-5 Application of mapping methods to the synthetic case study. The spatial coverage of electromagnetic induction (EMI) and magnetometry (MAG) is shown on the left (dotted lines). The survey is generally carried out along a grid with an interline spacing that should ideally not be too coarse to capture site heterogeneity. After data processing, the results can be displayed as maps showing the physical properties targeted by the methods (here electrical conductivity for EMI and magnetic field anomaly for MAG). In this case, it is possible to estimate the lateral extent of the landfill and to identify two areas related to the different types of waste material.

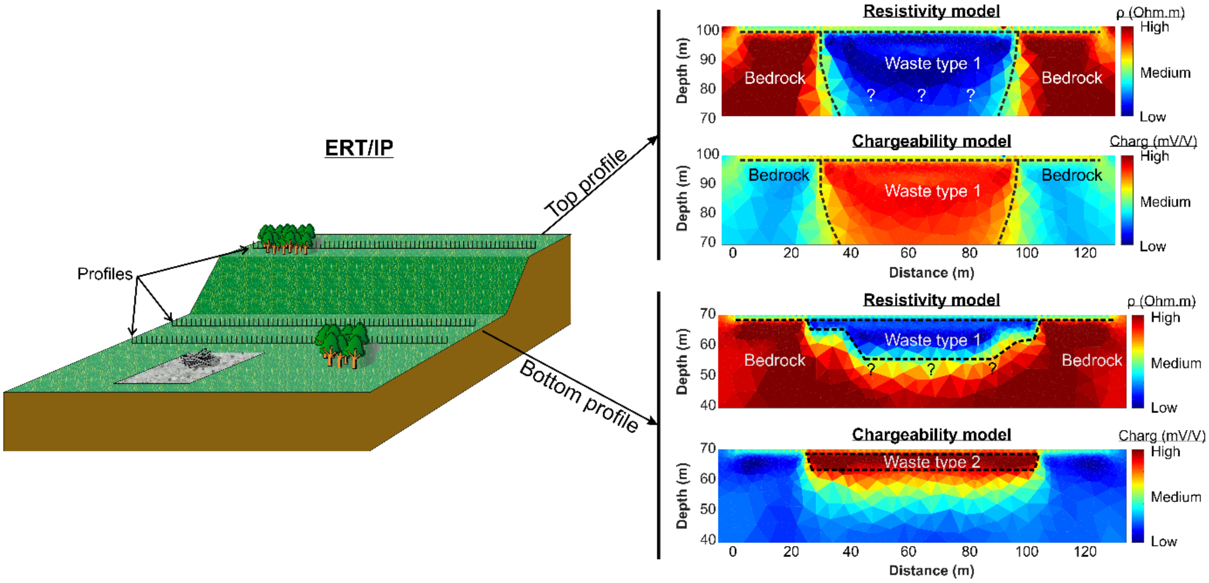

Figure 4-6 Application of profiling methods (here electrical resistivity tomography – ERT and induced polarization – IP) to the synthetic case study. The principle is similar to the seismic profiling methods. Such methods are generally applied along 2D lines (see left figure) or 3D grids. They provide information about the vertical and horizontal zonation of the landfill. When only applied at the soil surface, the resolution of such methods generally decreases with depth making the interpretation of deep structures difficult (see resistivity and chargeability models corresponding to the upper profile).

4.5.1. Selection of appropriate geophysical methods & feasibility study

Geophysical methods measure different physical properties. In order to detect and map the target, the property contrast between the target and the surrounding must be high enough. Moreover, geophysical methods differ in investigation ranges, resolution and applicability in different environments (e.g. limitation of very conductive ground or HDPE membrane). Similarly, required time and staff for data acquisition and processing can vary significantly. **Table 4-2** gives a quick overview of possible applications of main near-surface geophysical methods for landfill characterization together with the staff required to deploy them, acquisition and processing times. However, the correct choice of methods is site dependent and should therefore be done by a geophysicist who should answer the following questions:

1. Physical properties and expected contrasts:
   What physical property could provide sufficient contrast between the waste and the surrounding?
2. Type, scale and position of objective:
   Would lateral mapping methods allow delineating the target (e.g. landfill boundary, different waste zonation)?
   Are methods which cover higher vertical resolutions or larger depths required?
3. Site limitations:
   Are there specific site conditions which would limit the use of a specific method (e.g. ERT cannot be used if HDPE membrane is present)?

4.5.2. Survey design and selection of measurement parameters

The geophysical survey should be designed to capture information at a scale appropriate to characterize the full area of interest. Surface-based geophysical methods are only able to characterize the ground directly below the area covered by the measurements. Therefore, in order to characterize the landfill extent for example, the whole potential landfill area would need to be covered by a grid of parallel measurement lines as displayed in **Figure 4-5**. Areas which are not accessible for measurements (e.g. due to steep topography or dense vegetation) will lead to a blank, filled by an interpolation of geophysical properties from the measured surrounding areas. Similarly, the resolution of a survey should be in accordance with the expected heterogeneities (e.g. diameter of waste type zonation) and the required precision of the measurements. Thus, the line spacing in **Figure 4-5** for example should be smaller than the diameter of an expected target (e.g. waste zonation).

In terms parameters, each geophysical technique has its own limitation. For example, to resolve the thickness of a thin clay cap with ERT/IP the electrode spacing would need to be small. However, a small electrode spacing would limit the investigation depth.

Finally, since some techniques take longer and are more expensive. Available resources, staffing and site accessibility times need to be considered.

For an ideal survey design to weigh trade-offs (e.g. between resolution and coverage), a geophysicist would require the following information:

1. Required resolution:
   What is the expected size of waste zonation? Up to which level of detail does a waste zonation need to be resolved?
2. Required investigation depths:
   What is the expected thickness of the landfill? Up to which depth does the landfill site need to be characterized with high-resolution data?
3. Specific zones of interests, already known zonation and features:
   Are there any areas of particular interest that require higher resolution?
4. Resources, staffing and accessibility time:
   What resources and staff are available? Is the site accessible at all times? Is there any other work done during the study? Some methods may be negatively influenced by the presence of nearby metal objects (e.g. EMI or MAG) or by vibrations induced by other works (seismic methods).

Table 4-2 Suitability of geophysical methods for different applications related to landfills study. Abbreviation list: EMI – Electromagnetic induction, MAG – Magnetometry, ERT – Electrical resistivity tomography, IP – Induced Polarization, MASW – Multi-channel analysis of surface waves, SRT – Seismic refraction tomography, GPR – Ground penetrating radar, HVSRN – Horizontal to vertical spectral ratio of noise, SP – Spontaneous potential, GRA – Gravimetry. Please note that it is impossible to provide the exact duration required for survey and processing as they are site specific. Therefore, the time provided here is only indicative.

		Mapping		Profiling							
		EMI	**MAG**	**ERT**	**IP**	**MASW**	**SRT**	**GPR**	**HVSRN**	**SP**	**GRA**
Landfill structure	**Lateral extent**	Primary method	Primary method	May be used but not the best method	May be used but not the best method	May be used but not the best method	May be used but not the best method	Unsuited	May be used but not the best method	May be used but not the best method	May be used but not the best method
	Cover Layer thickness	May be used but not the best method	Unsuited	Primary method	Primary method	May be used but not the best method	May be used but not the best method	Primary method	May be used but not the best method	Unsuited	Unsuited
	Vertical extent	May be used but not the best method	May be used but not the best method	May be used but not the best method	Primary method	Primary method	Primary method	Unsuited	Primary method	Unsuited	May be used but not the best method
	Buried utilities	Primary method	Primary method	May be used but not the best method	May be used but not the best method	Unsuited	Unsuited	Primary method	Unsuited	May be used but not the best method	Unsuited
Landfill characterisation	**Waste zonation**	Primary method	Primary method	Primary method	Primary method	Primary method	May be used but not the best method	Unsuited	May be used but not the best method	May be used but not the best method	Primary method
	Leachate content	May be used but not the best method	Unsuited	Primary method	May be used but not the best method	May be used but not the best method	May be used but not the best method	Unsuited	Unsuited	May be used but not the best method	Unsuited
Environmental conditions	**Host material**	Unsuited	Unsuited	Primary method	May be used but not the best method	Primary method	Primary method	Unsuited	May be used but not the best method	Unsuited	May be used but not the best method
	Groundwater table	Unsuited	Unsuited	Primary method	May be used but not the best method	May be used but not the best method	May be used but not the best method	May be used but not the best method	Unsuited	May be used but not the best method	Unsuited
Staff required for survey		2	1	2	2	3	3	1	1	2	1
Required time for survey		1	1	2	3	3	3	1	1	2	2
Required time for processing		1	1	2	2	3	3	3	1	2	2

Primary method | May be used but not the best method | Unsuited

4.6 Calibration and validation through targeted sampling

The joint interpretation of geophysical data, together with the prior knowledge of the investigated landfill, should allow to update the conceptual site model. At this stage, there should remain some uncertainty given the indirect nature of the information provided by geophysics. To validate and calibrate the conceptual site model, ground truth data is generally required (see **Chapter 5**). An example of a sampling plan based on the conceptual site model is presented in **Figure 4-6**.

The sampling plan is expected to be site dependent, but should target the following:

1. Areas characterized by different geophysical signature ;
2. The background conditions ;
3. Areas where geophysical method cannot provide any or enough coverage/differentiation.

At least one sample should be collected in each of the aforementioned zones. Increasing the number of samples collected in each of these zones will improve the statistical robustness of the resulting ground truth data. If the sampling plan allows a large number of samples to be collected, statistical tools such as Latin Hypercube Sampling informed by the geophysical data could be considered (more information in Minasny & McBratney, 2006).

After the joint interpretation of geophysical and sampling data, it must be decided whether the information available on the site is sufficient to establish a reliable RDM or whether further studies are necessary in which case it is possible to iterate on geophysical and sampling investigations (see **Chapter 5** for further information) as illustrated in the proposed workflow (**Figure 4-2**).

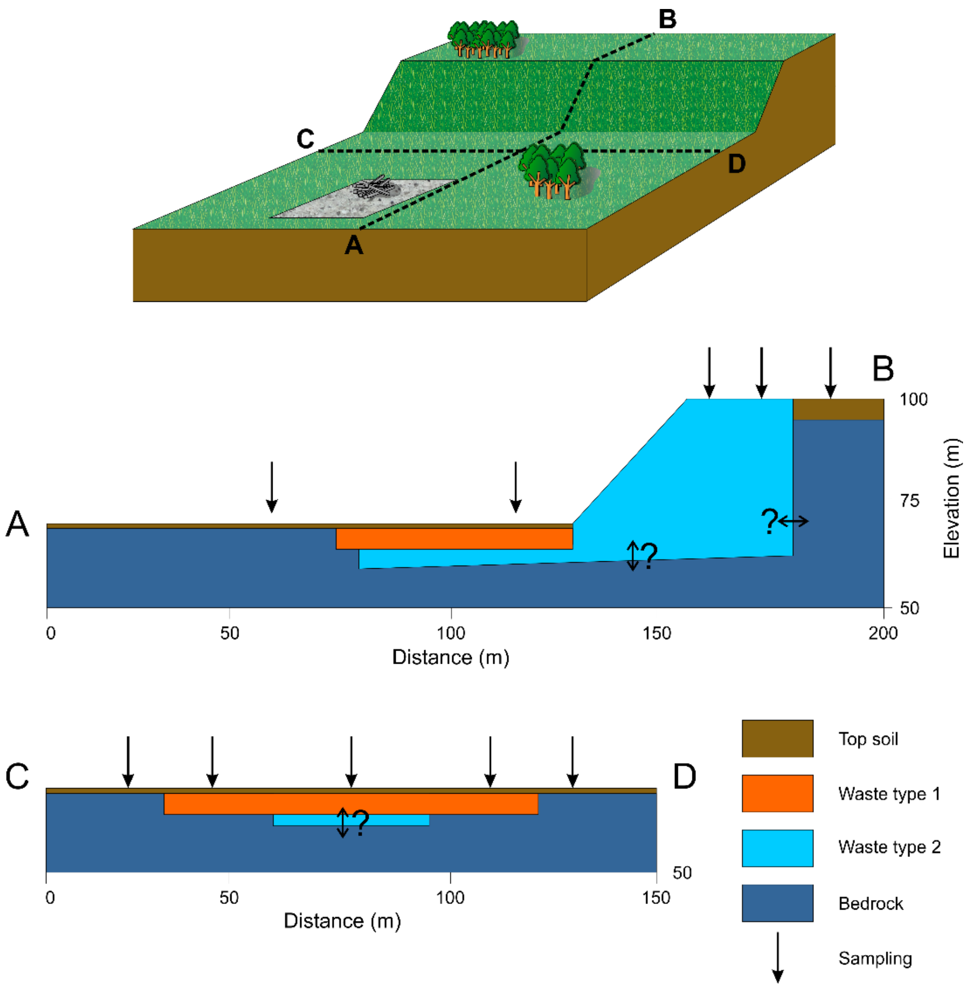

Figure 4-7 Updated conceptual site model after interpretation of geophysical results and proposed sampling plan for validation and calibration.

4.7 Building of a resource distribution model (RDM)

Building an RDM is the final step of the proposed workflow (see **Figure 4-2**). It is a crucial step to assess the economic viability of potential landfill mining operations via the developed ELIF (Enhanced Landfill Inventory Framework) and DSTs (Decision Support Tools – Cedalion and Orion) (see **Chapters 6 and 7** respectively for more information). The delivered RDM should contain the spatial and volumetric distribution of indicative parameters of the landfill materials. In RAWFILL two approaches are commonly used to build the RDM. The first is relatively simple and consists of building the RDM by "visually" comparing geophysical and ground truth data. In such an approach, ground truth data (see **Chapter 5**) is used to constrain the model whereas geophysical data is used to ensure spatial continuity. Such an approach is illustrated in the synthetic case presented in **Figure 4-8**. The second approach uses co-located geophysical and sampling data to produce probability models belonging to a predefined waste facies. Such an approach offers the advantage of providing models which take into account uncertainty and loss of resolution occurring with depth but are somewhat more complex to produce than those provided by the first approach. For more information on the probabilistic approach, the reader is referred to Hermans & Irving (2017). For both approaches, multivariate clustering methods can be applied prior to building the RDM with the aim of reducing the number of dimensions of the geophysical dataset to compare with the ground truth data.

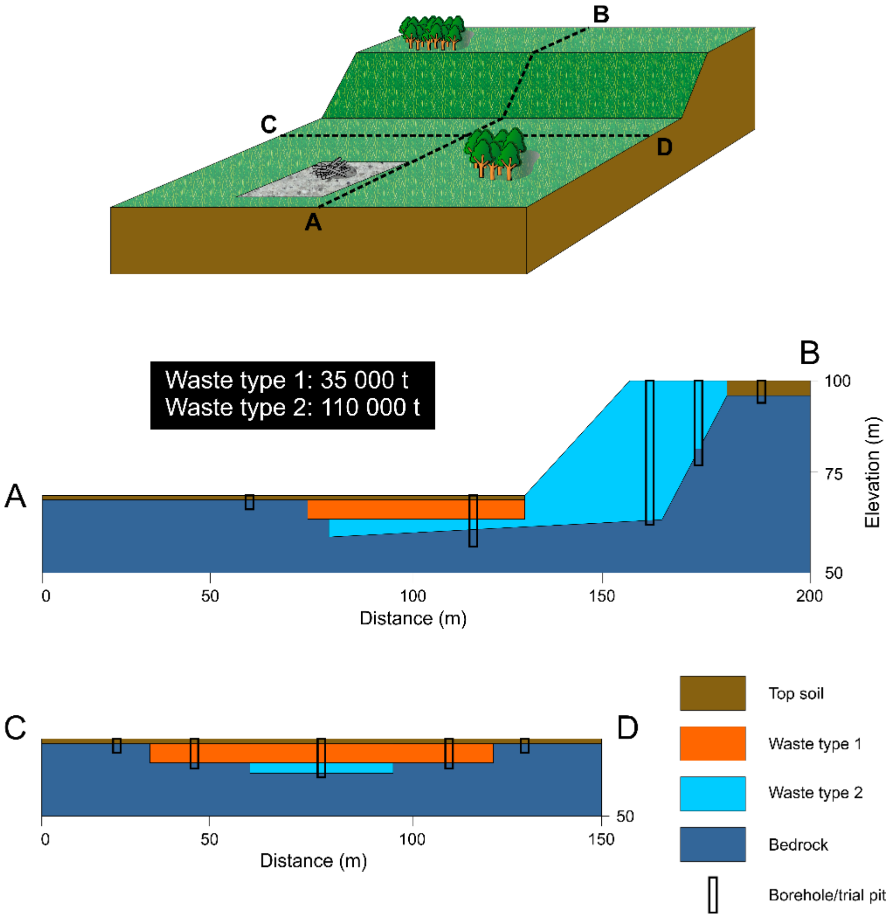

Figure 4-8: RDM of the site obtained using the first approach. The proposed model provides a spatial view of the different waste facies identified together with their estimated volumes. The mass of the waste deposits is estimated based on the waste density (measured in laboratory or in the literature) and the volume of waste deposits given by the RDM. Other relevant information such as the presence of a groundwater table, the composition of the waste facies or the presence of contamination may also appear in the RDM.

4.8 Conclusions

This chapter presents a proposed workflow for the use of geophysical survey techniques to characterize landfill deposits in order to guide resource mining activities. Geophysical survey techniques provide many advantages over traditional, "intrusive" investigative methods and should always be considered at the outset of a project when trying to establish the resource potential of an existing landfill.

Advantages of geophysics:

- **Fill gaps**: Reduced risk to miss the target, providing information between boreholes.
- **Reduced risk of damaging structures (non-intrusive)**: No risk of reducing integrity of structure or ground (e.g. damaging contamination barrier).
- **Cost effective & rapid:** geophysical mapping methods are cost effective and can be applied in a rapid manner.

The process described in this document focuses on the development of an initial conceptual ground model of a site, which is then used to plan a geophysical survey to addresses any gaps in information concerning geometry & extent of the landfill, as well as identifying areas of contrasting geophysical properties. Such constraints relate to changes in composition of fill and are indicative of different types of materials, changes in relative concentrations of particular (recoverable) materials. All are factors that will affect the overall economic viability of future resource recovery/material processing. It is important that any geophysical surveying undertaken should incorporate more than one technique, such that measurements are made of different, but complimentary material properties, in order to increase confidence in any interpretation derived from the survey.

Having planned and executed a geophysical survey based on the conceptual ground model developed from the existing data, it should be possible to refine with regard to the overall extents and any structure within the landfill. It is also possible to attach measured (or modelled) geophysical parameters to estimate the distribution of recoverable materials throughout the asset, transforming the conceptual ground model into an RDM, and including data acquired from subsequent intrusive surveys where appropriate.

What specific information can geophysics provide to assist producing a Resource Distribution Model:

- Landfill extent (depth and lateral extent)

Compared to surrounding/underlying host materials

- Landfill structure (clay cap thickness, HDPE membrane, clay boundaries etc.)
- Changes in waste composition

Discriminate areas/zones of differing material properties

- Changes in water content (ground water or leachate saturation)
- Position of buried utilities

A final note regarding the validity of an RDM derived from geophysical data, any interpretation should always have some element of ground-truthing through intrusive sampling. Also, it should be borne in mind that the geometry of any survey will necessarily limit the scale at which spatial heterogeneity is captured. For this reason, when constructing an RDM, it is important to not overinterpret areas covered by sparse data, where the potential exists to miss rapid lateral changes between data points/profile. As such the level of confidence in the RDM must be estimated to include any uncertainty associated with survey geometry.

4.9 References

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5 Waste sampling and analysis

5.1 Introduction

The traditional landfill characterisation (i.e. content in raw materials and energy carriers) is conventionally carried out using intrusive methods such as core drilling or trenching, combined with various laboratory analyses which are more environmentally oriented than ELFM oriented. This methodology is time-consuming, expensive and provides sparse and local information which is difficult to extrapolate to the whole waste body. Which is why the RAWFILL partners developed a methodology based on multi-method geophysical imaging coupled with guided sampling and adapted analysis to supply useful data for landfill mining developers. This chapter summarizes the common waste sampling and analysis methods. Please refer to **Chapter 4** for further information about geophysical imaging.

5.2 Waste homogeneity and heterogeneity

The major problem with landfill and waste characterisation methods is the heterogeneity of the waste. Similarly, to geotechnical and hydrogeological properties (e.g. porosity, permeability) which vary depending on the particle size distribution, or rock type, we will distinguish two levels of heterogeneity:

- **At the level of the whole landfill** (Scale: 10^3 to $>10^6$ m³): different types of waste materials have been landfilled in several parts of the landfill at the same time or during different periods of time. If the landfilled waste has been mixed, the whole mass can be considered as "homogeneous" with local disparities that will not easily be identified.
- **At the level of the waste** (Scale: 1 m³): a single cubic meter of waste materials can be considered as homogeneous (i.e. containing only one material such as lime, fly ash, slags and other industrial waste streams) or heterogeneous (i.e. containing several types of waste material such as metal, cardboard, glass, wood and plastics). However, even heterogeneous waste deposits can have a specific signature and therefore be described with a single label (e.g. municipal solid waste/domestic waste).

Note that when waste deposits are heterogeneous, it is more difficult to extrapolate the landfill content.

Table 5-1 defines more precisely the concept of homogeneous and heterogeneous waste at small and large scale:

Table 5-1 Definitions of the homogeneous and heterogeneous waste deposits based on the scale.

	Homogeneous	Heterogeneous
At large (macro) scale = at landfill level	Only one layer of waste can be distinguished with geophysical imaging: - One single waste stream (monolandfill) - Several waste streams, totally mixed **Any taken sample will show a similar composition.**	More than one layer of waste can be distinguished with geophysical imaging, each layer has a relatively homogeneous composition. **Samples taken at different places will show different composition.**
At small (micro) scale = at one waste layer level	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:

1. Homogeneous at large scale and homogeneous at small scale (e.g. industrial monolandfill of gypsum);
2. Homogeneous at large scale and heterogeneous at small scale (e.g. mixed domestic waste with no (a few) spatial variation);
3. Heterogeneous at large scale and homogeneous at small scale (e.g. a cell for construction/demolition waste and another for soil, each of them being homogeneous);
4. Heterogeneous at large scale and heterogeneous at small scale (e.g. mixed domestic waste with a composition that varies very much from place to place because of landfill ban or any other specific reason).

Please note that this criterion is not absolute: even a monolandfill can contain some small quantities of waste materials that should normally not be there.

5.3 Sampling methods

5.3.1 Boreholes

Boreholes are made using drilling rigs usually used for civil engineering, hydrogeology, geotechnics and environmental surveys. The diameter of the boreholes varies between 50 mm (e.g. small machines like Geoprobe used for environmental survey) and 1.2 m (e.g. casing oscillating piling machines used for large drilling gas extraction shafts). The borehole depth depends on the power of the engine, fixing the torque that can be generated to overcome the friction of the waste mass while drilling or pressing a metallic casing into the landfill. Domestic waste, for instance, is known to generate very strong friction forces (that is why most of the trenches can hold vertical or subvertical slopes on several meters depth).

Different methods can be used to drill, such as rotary drilling or percussion drilling (down-the-hole hammer drilling, pulse drilling; **Figure 5-1**). Drilling heads are of different kinds as well (hollow augers, etc.). A specific attention should be given to explosive properties of the mixture of biogas with oxygen (explosion limits between 5 and 15% v/v of methane in air). The dry contact between the metallic part of the drilling equipment and metallic waste should be avoided to avoid sparks production, especially when using down-the-hole hammer drilling. Most of the time, the water content of the waste material will lower the risk of explosion, but in some cases, it may be necessary to use water for drilling – that will disturb the waste samples.

Access by the rigs is a major issue and may require preparation works prior to the sampling investigations: e.g. increase the width of the access roads, the width of the landfill road and their maximum slope, compaction level of the upper soil. These preparation works can be expensive.

Figure 5-1 Down-the-hole hammer drilling in the fly ash deposits of the Onoz industrial landfill, one of the RAWFILL pilot site (Credit Photo: Atrasol).

5.3.2 Trenches

Trenches (**Figure 5-2**) are dug using traditional civil engineering equipment, such as crawler excavators, wheel diggers, etc, and are the easiest and most common way to analyse the first meters of waste deposits.

Figure 5-2 Trench performed at Onoz landfill showing inert waste, fly ash and lime (Credit Photo: Atrasol).

Advantages and disadvantages of both waste sampling techniques (borehole and trench) are summarized in **Table 5-2**.

Table 5-2 Comparison of the waste sampling techniques advantages and disadvantages.

	Advantages/strengths	Disadvantages/Weaknesses
Borehole	• Allows to take samples at depth and to reach the bottom of a landfill when the thickness of the waste deposits is higher than 5 – 6 m[18]. • Virtually no depth limitation if suitable equipment is used. • Well-known technique with a great diversity of equipment and tools. • Large variety of diameters (from 50 mm up to 1.2 m). • Reduces sample disturbance during sampling. • Odours and dust problems are limited.	• Expensive • Relatively slow method. • Access to the site; access from one borehole to another one can be difficult especially on slopes, slippery or soft soils. • Heavy machines for large diameter drilling request good soil compaction. • Special attention must be given to biogas problems. • In case of capping restoration, digging will be necessary to give access to enough space (for welding a new geomembrane by extrusion, etc.). • Provides only point information.
Trench	• Easy to realize. • Give access to large, undisturbed samples. • Well-known technique with a large 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.). • Provides actual cross-sectional information.	• Access can be difficult especially on slopes, slippery or soft soils. • Sampling 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 such as the risk of explosion. • In case of capping restoration, digging will be necessary to give access to enough space (for welding a new geomembrane by extrusion, etc.). • Provides only punctual information.

[18] Otherwise, trenches are prefered.

5.4 Sampling strategy

An appropriate landfill sampling plan must comply to both regulatory requirements, scientific objectives and landfill mining objectives. Once those objectives are 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. Chemical analysis of micro-pollutants has few interests regarding ELFM potential. However, it can be required in some cases depending on regional regulations or health issues (protection of workers against chemicals when performing the works) or for specific cases as bioleaching projects (out of scope of ELFM).

Samples should be representative[19] of the waste deposits (i.e. reflect average properties of the whole waste deposits) and describe the variability within the landfilled waste (i.e. describe all relevant waste streams). Sampling precision is primarily 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. Sampling should be performed in each zone preliminary defined by geophysical imaging. Within each zone, suitable survey methods should be applied to define the required sample number to calibrate and validate the conceptual site model (see section 4.6).

If the landfill site is not investigated using geophysics coupled with targeted waste sampling, other sampling strategies can be applied: random sampling, simple random sampling, stratified random sampling, systematic random sampling, authoritative sampling. These sampling strategies are explained in details in the *Deliverable WP T1 3.1 SWOT Analysis of landfills investigation methods*, available on the NWEurope project website for the RAWFILL project.

5.5 Log description of the waste deposits

In this section, our goal is to supply a practical description methodology that any technician can apply on site to describe waste and deliver relevant information on a very concrete basis. In order to standardize the waste description and to provide useful data for future ELFM project, RAWFILL selected a list of main waste parameters that should be taken into account during the sampling investigations on site:

- Water content
- Consistency
- Degradation
- Homogeneity
- Composition
- Proportion of fine materials
- Temperature

[19] 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 properties and composition in the same average proportions compared to the population.

- Specific odours
- Colours
- Other relevant parameters[20]

These parameters are interesting from a landfill mining point of view. Most of them can be visually determined and therefore do not require any specific equipment nor specific technical knowledge. However, a standardisation of the definition of each parameter is required[21].

The description of the relevant parameters should preferably be done on site during the waste excavation (e.g. **Figure 5-3**) but can also be performed off-site if the waste is transported elsewhere. Some attention must be given to parameters that may evolve during transportation and storage such as consistency, proportion of fine materials, water content, and temperature[22].

Figure 5-3 Extraction of waste materials from the Onoz Landfill (Credit photo: Atrasol).

[20] Depending on the kind of waste that can be valorised (e.g. lime, fly ash, metal slags).
[21] The definitions are provided in the sections below.
[22] Irrelevant if not measured in-situ.

5.5.1 Water content

The following categorization for water content of waste deposits is proposed (**Table 5-3**).

Table 5-3 Description of waste water content.

Water content category	Definitions
Dry waste	No humidity is observed in the large particles and in the matrix of fine materials.
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). Leachate 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. Leachate/percolation is observed. The fine matrix forms a liquid sludge. A groundwater table, which can be either local or extended, is suspected.

5.5.2 Waste consistency

Waste consistency is related to the physical state of the waste and can be evaluated regarding three stages: Brittle, Coherent, Compact (**Table 5-4**). Larger waste materials may not be taken into account in the description.

Table 5-4 Waste consistency definitions.

Waste consistency	Definitions
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.

5.5.3 Degradation

This property is linked to waste degradation, especially organic material degradation. As this property is difficult to evaluate, only a description will be given while establishing the log. No specific scaling will be proposed here. The remaining degradation potential of the waste materials should be considered carefully, as it will continue to increase with time.

5.5.4 Waste homogeneity

Waste deposits can be briefly described as homogeneous and heterogeneous, regarding composition and particle sizes. These two aspects should be specified in the description.

Homogeneous composition
The waste sample has a similar composition in the whole observed area and no layers can be visually distinguished.

- Homogeneous composition and homogeneous grainsize: Regardless of the sampling part, same particle size and distribution is expected.
- Homogeneous composition and heterogeneous grainsize: particle size distribution can considerably vary from one part of the sample to another one.

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

5.5.5 Waste composition

Composition of each identified waste layer can be described by assessing the relative contribution (in weight) of the following elements:

- Ferrous/non-ferrous metals
- Cardboard and paper
- Plastics
- Glass/ceramics
- Minerals (stones & concrete)
- Rubber
- Textile
- Wood
- Organic materials
- Hazardous waste (e.g. batteries)
- Other/not visually identifiable (fine materials/matrix)

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

Another way of classifying waste, in case it is intended for Waste-to-Energy valorisation (WtE), is to consider a specific grainsize so as to distinguish different combustible elements (such as plastics, cardboard and paper, wood, textiles and rubber). According to this methodology, three streams can be defined:

- Fine materials
- Residue derived fuel
- Coarse non-combustible materials

As far as sieving/screening is concerned, a mesh size list is proposed to evaluate the waste potential for secondary fuel production: 0–2 mm, 2–4 mm, 4–25 mm, 25–50 mm, > 50 mm.

Mesh sizes can be adapted if some general idea of the recovery process is already known at the time of performing the waste description. It can also be adapted to the waste itself after historical study or preliminary sampling campaigns. It may not be relevant to distinguish different sizes in the fine fraction (< 40 or 50 mm, sometimes up to 90 mm) when no specific use of it is expected. Moreover, weight percentages should be given for any of these fractions.

5.5.6 Proportion of fine materials

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

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

While this percentage is already assessed when describing the waste composition, it must be confirmed here. The proportion of fine materials within the landfill is important to assess as the fine fraction may be difficult to revalorize and therefore, it will strongly impact the business model of the ELFM project.

5.6 Conclusions

The traditional landfill content characterisation is time consuming and expensive as it requires a large number of waste samples (boreholes, trenches, trial pits). The RAWFILL methodology coupling geophysical imaging and targeted waste sampling strategy can not only reduce survey costs but also provide useful information to stakeholders in order to draw up profitable business plans for landfill mining projects.

5.7 References

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6 Enhanced Landfill Inventory Framework (ELIF)

6.1 Introduction

A significant challenge for stakeholders involved in ELFM operations is to evaluate the project's profitability based on quantity and quality of dormant resources that can be excavated and recovered from a landfill site. Related reliable decision elements are missing in most of the reviewed landfill inventories covering the 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 resource potential. In most cases, even the volume of waste remains unknown and only very general information is given about type of deposited waste materials (which is often a mixture of domestic, industrial and construction waste deposits).

The purpose of this chapter is to supply ELFM stakeholders (public and private companies) with correct 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 must be fed with information, coming from existing sources and, in many cases, from site survey (see **Chapters 4 & 5** for more information).

6.2 What is ELIF ?

"Enhanced Landfill Inventory Framework" is a landfill inventory structure focused on information regarding resources that can be extracted from a landfill (materials, energy carriers and land). ELIF is used to describe landfills not only in terms of environmental and risk issues but also the quality and the quantity of dormant materials contained within, in order to supply relevant data for stakeholders interested in ELFM project. This approach is quite innovative, as no other landfill inventory among those analysed within the framework of the RAWFILL project, contains such ELFM-driven information.

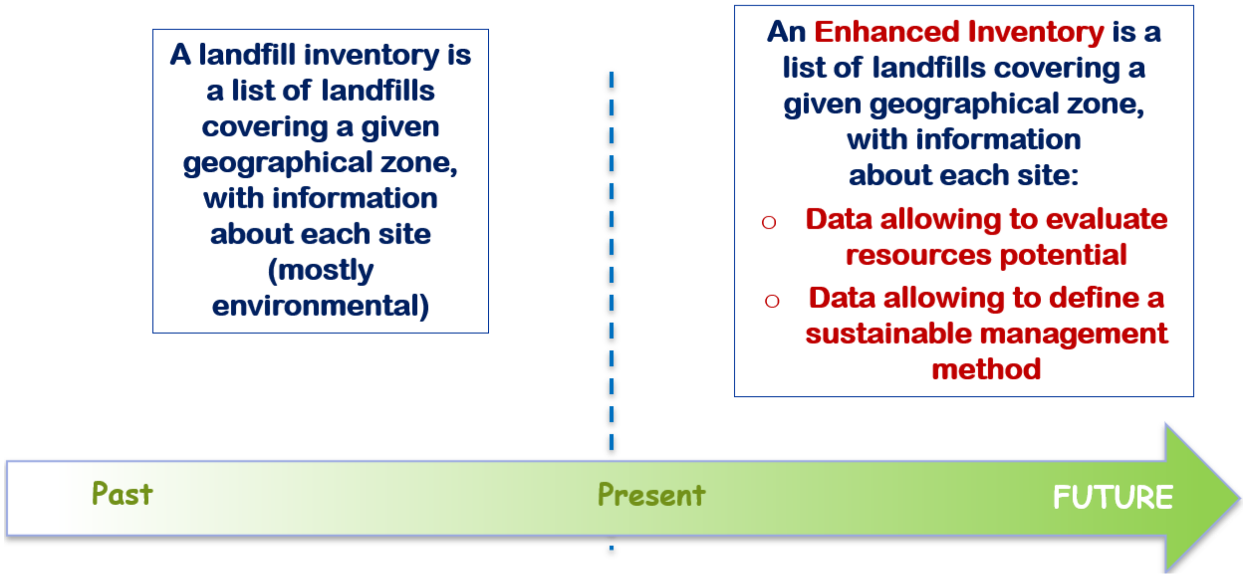

Figure 6-1 Enhanced Landfill Inventory Framework added value.

There are three main drivers related to a decision to launch an ELFM project:

1. An **economic driver** related to material valorisation and land reclaiming;
2. A **territorial strategy driver** related to the planned local/regional land development;
3. An **environmental driver** related to environmental and human health issues.

Additional drivers such as reducing the negative visual impact of the landfill on the landscape, nature conservation, etc. were also identified within the RAWFILL project.

The ELIF structure takes these drivers into account, although its structure is divided into five chapters: (1) generic information, (2) landfill ID Card, (3) surroundings, (4) landfill geometry, and (5) waste. These drivers are defined into various fields/indicators (gathered in environmental form, social form, technical form, economical form).

Data in ELIF forms the basis for the Decision Support Tools (DST) ranking tool and thus is a prerequisite to assess feasibility, business plan & business cases for launching profitable projects. DST 1 - Cedalion is a ranking tool that will allow ELFM projects prioritization based on suitable physical, environmental, technical and social information (See **Chapter 7** for more information). It integrates the multiple aspects involved in ELFM projects, i.e. economic, technical, environmental and social factors in order to compare and classify landfills regarding their ELFM interest. When the landfill presents no interest for ELFM, DST provides alternative interim use options to reclaim the land occupied by the landfill (e.g. installation of solar panels, energy crop, recreational use, nature redevelopment).

6.3 Structure and tool

ELIF comes in two forms:

1. An inventory structure that includes all the fields, possible responses and their definition: this structure can be deployed in an existing landfill database to allow encoding the necessary information for the evaluation of a ELFM project on the landfills.
2. An Excel tool ready to use: this tool offers a user-friendly interface for encoding information specific to each landfill. It then makes it possible to summarize all the information in the form of a single table which can be directly exported to a database or to the DST 1 - Cedalion (see **Chapter 7**).

6.3.1 ELIF Structure

Categories

The ELIF fields are divided in five categories:

Table 6-1 ELIF divisions and most representative fields.

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, depth, 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 Resource Distribution Model (see **Chapters 4 & 5** for more information)

Data accuracy

Regarding existing information, the level of accuracy of some data is sometimes difficult to estimate, for example the indicated surface of the landfill which can be mixed with the total surface of the site, the volume of waste deposits which can be just a rough estimation based on a mean height and a given surface, the type of waste materials which remain common in uncontrolled landfills, among others.

Data source

For some fields, it will be crucial to identify the origin of the information and specify if this information has been measured with some relative precision, simply estimated, or is known based on documents. Data measured by the responsible of the database will be considered as the most valid ones.

ELIF Fields

For the detailed description of the ELIF fields, we invite the reader to refer to the **Appendix A**.

6.3.2 ELIF Tool

The ELIF tool is explained in details the following sections. For further information about how to fill the ELIF tool, we recommend the reader to visit the RAWFILL e-learning platform dedicated to the ELIF: https://www.rawfill-elearning.eu/

Download and installation

The ELIF tool can be found and downloaded from the following links:

1. RAWFILL website: https://www.nweurope.eu/projects/project-search/supporting-a-new-circular-economy-for-raw-materials-recovered-from-landfills/#tab-5
2. SPAQUE website: https://spaque.be/project-type/rawfill/e-library
3. OVAM website : https://www.ovamenglish.be/rawfill-in-a-nutshell

The ELIF can be downloaded as a compressed file with a RAR extension. The compressed file can be extracted with a file compression software. Once extracted, a list of Excel files constitutes the ELIF tool. Those files can be opened with Excel® from Microsoft Office®.

6.3.3 Structure of the tool

ELIF is composed of two types of Excel files (**Table 6-2**):

1. The *RAWFILL LF#.xlsm* files, dedicated forms for each landfill: each file can be used to describe a landfill with the ELIF structure.
2. The *RAWFILL ELIF.xlsm* file summarizes the information of all *RAWFILL LF#.xlsm* files in a single table. This table can then be exported to an existing database or to the DST 1 - Cedalion (see **Chapter 7**).

Table 6-2 ELIF tool structure.

***RAWFILL LF#.xlsm* file**	Input	- LF description - Waste description - Environmental form - Social form - Technical form - Economical form - Additional Information - Resource Distribution Model
	Output	- Comment Report - ELIF RAW DATA - DST 1 INPUT
***RAWFILL ELIF.xlsm* file**	Summarize all the relevant information contained in the *RAWFILL LF#.xlsm* files in a single table. This table can be exported to an existing database or to the DST 1 – Cedalion.	

6.4 RAWFILL LF# files

Each *RAWFILL LF#.xlsm* files consists of 11 sheets. The first eight sheets are used to encode information about the landfill. The three last sheets are outputs summarizing the encoded information (**Table 6-2**). A representation of the different sheets can be found in **Appendix B**.

6.4.1 Structure of a sheet

The sheets of the RAWFILL_LF#.xlsm files have the following base structure. The left part contains the ELIF fields (in green in **Figure 6-2**). Depending on the indicator, fields have either a dropdown menu, numbers, or free text. If the user does not know some information requested in the form, the user can leave these fields empty. The tool is designed to allow different levels of completeness. Because the user may want to be more specific and provide more information than just what the scrolling menu allows, the right part (in blue in **Figure 6-2**) is provided to write free notes and comments. The section can also be used to write down remarks about the source or the quality of the data. An indicator of completeness of the form is present on top (in orange in **Figure 6-2**). It is possible to reset the form to a blank form using the two reset buttons (in red in **Figure 6-2**). Fields with the symbol * are used for the scoring of the DST1 - Cedalion.

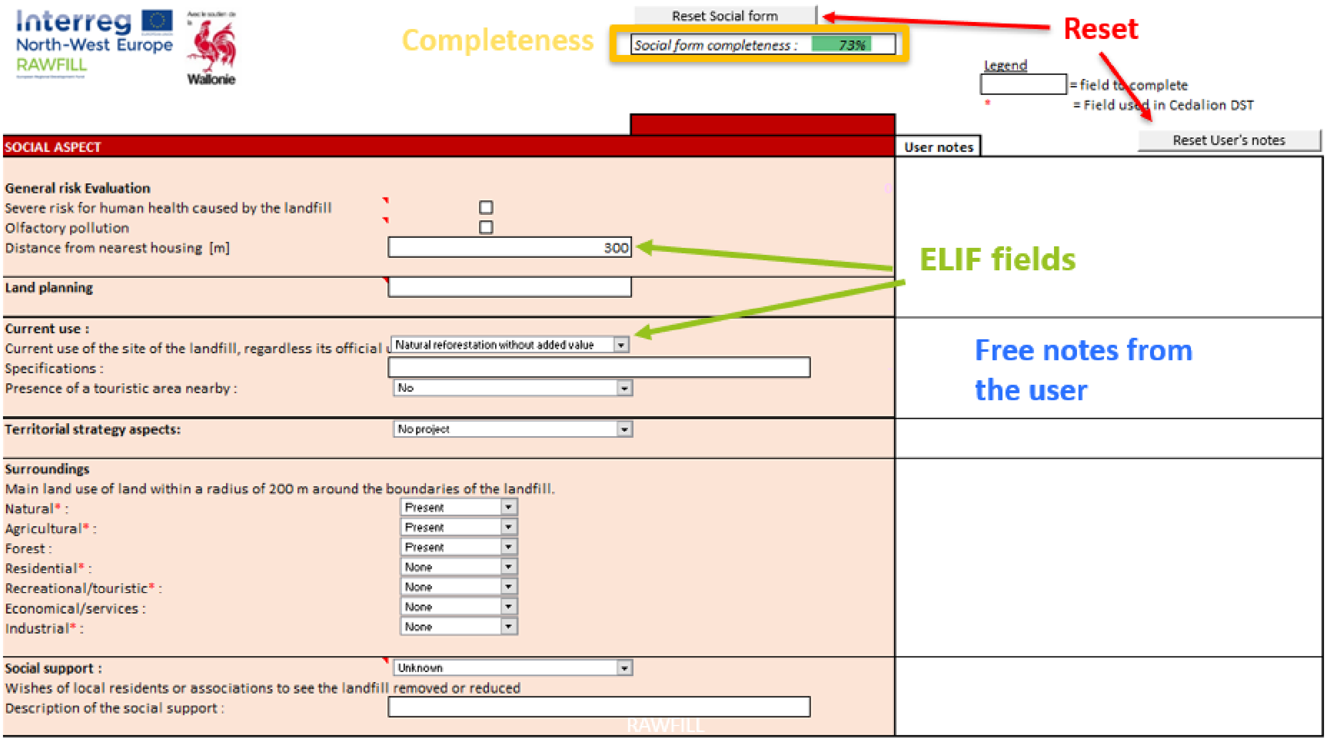

Figure 6-2 Structure of an ELIF sheet.

6.4.2 Landfill description

The sheet called LF description allows the user to encode general administrative information about the landfill.

6.4.3 Waste description

The waste description sheet is designed to encode information about the landfilled waste. Depending on the level of information, it is possible to use a simplified waste description tab, or a detailed waste description sheet. This sheet is also used to insert information about the main waste type, the specific waste stream, the hazardous waste, the main physical state, the daily cover and the waste homogeneity.

6.4.4 Environmental form

The environmental form describes the impact of the landfill and a potential landfill mining project on the environment. It includes indicators about general risk evaluation, specific environmental issues, surface and groundwater vulnerability, air emission, biodiversity, soil contamination and erosion.

6.4.5 Social form

The social form describes the landfill from a social point of view. It provides answers to the following questions: Is there a risk for the neighbourhood linked to the landfill? Is there some olfactory pollution? What is the land use of the landfill and its surroundings? Is there a land redevelopment planning that includes the landfill zone or a social support for removing the landfill?

6.4.6 Technical form

The technical form includes indicators that reflect the level of technical difficulty encountered to perform a landfill mining project. It contains indicators about status and dates, sampling, leachate treatment, biogas aerial collection system, landfill morphology, waste height/depth, stability of the waste mass, as well as the characteristics of top and bottom layers of the landfill.

6.4.7 Economical form

The economical form includes the indicators used to the profitability of a landfill mining project. It considers the regional policy, the current value in terms of remaining space or the cost (i.e. landfill mining operations costs, aftercare costs, remediation costs), the land value and the landfill content value. Some indicators completed in the waste description form and also used as economic indicators are automatically filled in the economical form to avoid completing the field twice.

6.4.8 Additional Information

The additional information sheet is used to encode additional information not directly related to the evaluation of the landfill mining potential but useful either for dynamic landfill management or to perform a landfill mining project. It includes a series of administrative information: data about who was responsible for the filling of the ELIF file, regulatory context, historic, permits, studies and analysis.

6.4.9 Resource Distribution Model

A dedicated sheet is used for the resource distribution model. The resource distribution module helps to describe the different waste layers identified by the RAWFILL characterization methodology (see **Chapters 4 & 5** for more information).

6.4.10 Comment Report

In the comment report sheet, the button *"Generate a User's note report"* creates a report containing all the user's notes of the 11 sheets.

6.4.11 ELIF RAW DATA

The ELIF RAW DATA tabs summarizes all the information of the *RAWFILL LF#.xlsm* file in a single table. This table can then be exported to an existing database which has been preliminary adapted to include the new fields defined in the ELIF. To export data about multiple landfills (i.e. more than one *RAWFILL LF#.xlsm* file*),* the user should instead use the ELIF RAWDATA sheet of the *RAWFILL ELIF.xlsm* file (see **section 6.5.1**).

6.4.12 Import DST 1 - Cedalion site visit

ELIF can automatically import the data collected during the site visit in the online tool DST 1 – Cedalion (for further information about the DST 1, see **Chapter 7**). In order to do that, the user can copy/past the result of the field visit in this sheet and click on the button *"Import data from Cedalion to ELIF"*. **Caution:** this process may overwrite previously encoded data. Therefore, we strongly recommend the user to preliminary check the data acquired on site with the data already encoded in the DST 1 – Cedalion. This can be done automatically in the DST 1 – Cedalion.

6.5 RAWFILL ELIF file

The *RAWFILL ELIF.xlsm* file consists of three sheets:

1. Manual: this page describes how to use the tool.
2. ELIF RAW DATA
3. DST1 INPUT

6.5.1 ELIF RAW DATA

The ELIF RAW DATA sheet contains a table that summarizes the information of all *RAWFILL LF#.xlsm* files. This table can then be exported to a suitable, existing database.

6.5.2 DST1 INPUT

The DST1 input sheet converts the RAWFILL ELIF table into a table that can be directly copy/past into DST 1 - Cedalion. The DST 1 - Cedalion is then used to rank and select the best way to valorise each landfill (i.e. Waste-to-Materials, Waste-to-Land, Waste-to-Energy and Interim Use options). More details about the DST 1 – Cedalion are provided in the following chapter (**Chapter 7**).

6.6 Conclusions

The ELIF structure offers the possibility to fully characterize a landfill from its environmental impact to its economic potential. This innovative inventory structure, developed based on an extensive benchmark of landfill inventories across Europe, also incorporates information regarding the waste composition of the landfill, its social impact as well as technical information for future landfill mining project. Filling the ELIF is a continuous process. Data could be included at each step of the landfill characterization. For instance, the exact landfill waste content can only be known based on site investigation (i.e. geophysics and targeted samples or traditional characterization methodology – see **Chapters 4 and 5**). Assessing the environmental impact requires, among others, water, air and soil analysis as well as monitoring. The identification of the social impact evolves door-to-door survey. All of this information can be progressively included into the ELIF.

In addition, the ELIF is a basis for the DSTs, in particular the DST 1 - Cedalion providing a quick response about the future landfill site valorization as well as a first ranking. The data encoded in the ELIF can be directly exported to the DST 1 – Cedalion, which is explained in detail in the following chapter.

7 Decision support tools (DSTs)

7.1 Introduction

After the characterization phase, an evaluation of the data is needed to get a classification of landfills and organize further site planning. The sheer quantity of former landfills requires a prioritization because of the limited resources available to act with (financial, technical, human). RAWFILL has chosen a two-step approach to address the large numbers of sites in a relatively short period. The DST 1 - Cedalion will primarily deliver a ranking of all landfills. This first level ranking allows the users to set up more comprehensive data-collection, undertake quick responses or develop interim uses. This feedback system improves the inventories and the data-feed of the next step. The DST 2 - Orion is a more dynamic model integrating the landfill in its physical, economic and social environment. This application delivers a selection of landfills with high feasibility degree for ELFM project.

7.2 Overview of current Decision Support Tools (DSTs)

Designing a decision support tool for landfill mining and/or waste management purposes is not new. However, the way of using them varies with each developed tool as well as the amount of output provided. Nevertheless, one tool can be linked to another via identical criteria that were used in the applied model e.g. volume, waste types, etc. The following sections will give an overview of some - but not all – researches conducted in the field of decision support within the landfill mining subject. We will shortly present the different research studies emphasizing the key criteria of the different models explained. This has been done to sort out the criteria that emerged often versus criteria that were used only once or a select number of times. We argued that these criteria must be keystones in a good decision support tool and had to be included in the DST 1 called Cedalion, but only if the criteria represented readily available information. Otherwise, DST 1 - Cedalion would risk being a tool too complex to users with little or no knowledge about landfills and waste management.

7.2.1 RECLAF model

RECLAF is based on the same evaluation approach as used by the Public Waste Agency of Flanders: mapping, surveying and mining (Behets *et al.,* 2013; Wille, 2016). The external factors involved in the project were subject of a one-scenario test using software from the Vienna University of Technology (Cencic & Rechberger, 2008). The approach was tested on a landfill close to the municipality of Bornem (Flanders, Belgium). Key findings were that the landfill was not economically profitable at this moment, but with a positive outlook in view of increasing ground prices and decreasing sorting prices (Winterstetter *et al.*, 2016).

7.2.2 The Smart Ground model

This tool, developed by the EU Smart Ground project[23], allows the user to have a first understanding of the feasibility of mining a landfill, by estimating the net income of the project, as well as the social and environmental impacts. The Smart Ground DST was made for municipal solid waste landfills and provides a cost benefit analysis for nine different mining scenarios differing in the level of technology and processing effort. All scenarios are solely focused on the different way to excavate the waste materials. The user can decide which criteria are used to determine the best scenario in their case. Moreover, the tool allows the estimation of the amount of rare earth elements present in the landfill, as well as its potential economic value. In this tool, the possibility of interim use was not taken into account.

7.2.3 Holistic Management of Brownfield Regeneration (HOMBRE)

The HOMBRE project, funded by EU, was active between 2010 and 2014. The project had four different objectives (Grotenhuis, 2010):

1. *A zero brown-fields strategy*: urban, industrial and mining sites are screened to get a better picture of them. The origination of brownfields in these settings is necessary to device a successful overall brownfield redevelopment program.
2. *Assessment of brownfield regeneration scenarios*: development of an improved sustainable spatial planning. Parallel to the latter also decision-making processes to enhance the uptake of brownfield regeneration projects. A holistic approach is used in these processes.
3. *Integrated Regeneration Technologies*: partners investigated so called technology trains. These are different methods, actions or strategies that are combined to have a reciprocal enhanced effect. The investigated combinations consisted of energy + water; building materials + soil; soil + water; urban greening + restoration; bio-energy + remediation.
4. *Intermediate Renewal*: targeting the improvement of vegetation, landscaping and facilities on brownfield sites to ensure social, economic and environmental cohesion with the surrounding land use.

Similar to the approach of creating a decision support model for landfill sites, one of the targets of HOMBRE was to create such a model for brownfield management including environmental, economic and social factors. The Brownfield Navigator integrated legislation with modelling and mapping (GIS) technology to deliver qualitative support to its users. The long-term outcome would be zero brownfields in the participating countries (Spain, France, Germany, The Netherlands, Poland, Italy and the United-Kingdom) and secondly in the whole EU.

[23] http://www.smart-ground.eu/

7.2.4 FLAMINCO

FLAMINCO is a decision support tool created by OVAM in 2013 to quickly analyze all the data about the Flemish historical and active landfill sites allowing a consistent policy for all the landfills located in Flanders. The tool helped policy makers to pick out the best suitable landfills for a profitable landfill mining project by ranking all available landfills. After some years of experience, the consensus on this tool was that FLAMINCO had a good although little complex framework, but the scoring did not display the actual reality.

7.3 DST 1 (Cedalion): fast screening & recommendations

Within the RAWFILL project, a dual decision support tool system (DST 1 - Cedalion and DST 2 - Orion) was developed. The DST 1 – Cedalion provides a fast screening of the landfill sites and general recommendations regarding the future management of landfill sites. Based on the recommendations given by the DST 1 – Cedalion, the DST 2 – Orion gives detailed advices and a tailored solution for a landfill site based on information gathered from the other existing tools.

DST 1 – Cedalion uses the same methodology and framework than FLAMINCO but was designed based on new insights, partner input, stakeholder feedback and practical experience. The output of the tool are proposals grouped into four categories (*see below*) for landfills in various time-related stages. It is possible to directly import the data encoded in the Enhanced Landfill Inventory Framework (ELIF - see **Chapter 6**) into the DST 1 – Cedalion. The final goal can be - but not necessarily is - a landfill mining project in the future.

7.3.1 Objectives and definitions

To determine the potential of a landfill, the following four objectives are taken into account:

1. Objective 1: Waste-to-Materials (WtM);
2. Objective 2: Waste-to-Energy (WtE);
3. Objective 3: Waste-to-Land (WtL);
4. Objective 4: Interim Use (IU).

Even though landfill mining is quite a recent concept, various studies have already been carried out for objectives 1 and 2 (WtM and WtE). These studies are mainly based on the concepts of life-cycle assessment, Circle to Circle and Lansink's Ladder. Unlike for WtE and WtM, little attention has been given to objectives 3 (WtL) and 4 (IU) from a landfill mining perspective.

The following definitions have been established for the various objectives:
Waste-to-Energy (WtE): the process of generating energy in the form of electricity or heat from the thermal breakdown of waste through any thermal conversion technology or combination of conversion technologies.
Waste-to-Land (WtL): the creation of space at the location of the landfill site and the assigning of a new land use to the landfill site.
Waste-to-Material (WtM): the valorization of the waste streams that are released from a landfill and the reuse of the waste streams as materials.

Interim Use (IU): the valorization of the waste stream is postponed until a certain point in the future. Until that moment, the landfill body will support one or more temporary functions targeting an added value for its surroundings or society and at least will keep the future conditions for the landfill mining project stable.

7.3.2 Criteria in the model

To determine the potential of ELFM, six criteria are used:

Criterion 1: Type

Focuses on the content of the landfill. This criterion includes the type of waste deposits, the harmfulness of the waste materials present on site as well as the internal structure of the landfill (i.e. heterogeneous, layered or monolandfill). The following eleven types can be distinguished: municipal solid waste (MSW), industrial waste, dredging materials, waste water treatment sludge, inert materials, fly ash, asbestos, metal slags, mining waste, military waste and other. The type “Other” can be used for certain monolandfills that have a content not abundantly found in other landfills across the EU. For instance, Flanders (Belgium) reports to have monolandfills containing gypsum, whereas the state of Brandenburg (Germany) possesses some kroon and steel deposits (COCOON, 2018).

Criterion 2: Main period of landfilling activities

To every type of deposited waste, a time span can be assigned which influences its content and potential. This time span is based on known or documented activity of the landfill site. To work properly, users must indicate the period in which the landfill was most active (i.e. period where most of the waste materials of the landfill were landfilled), in case the activity goes beyond a given timeframe. Within the RAWFILL project, four timeframes have been defined (**Table 7-1**).

Table 7-1 Timeframe defined in the framework of the RAWFILL project.

Timeframe	Explanations
<1955	MSW, industrial, mixed and some landfills classified as "others" with a peak activity before 1955. These landfills have a low economic value for ELFM projects. In addition, the potential for energy recuperation is low because of the high share of inert materials.
1955 – 1980	The massive consumption of plastics can be taken as a first game changer in the composition of the waste material. Large scale production of the most common plastics we know today began in the 1950s (Wallace, 2017). Most of these plastics end their product cycle the same year they were produced (Dengler, 2017). We took 1955 as reference year, halfway the plastic emerging decade.
1980-1999	At the end of the seventies, the recycling of plastics took off (Geyer *et al.*, 2017), but a new type of waste emerged: electronic waste. The "Khian Sea" waste disposal incident in 1986 (R3E, 2016), is still one of the best examples of the disposal attitude in that decade and led to the Basel Convention to restrict countries in exporting their e-waste abroad (CDR Global, 2015). Therefore, 1980 marks the start of the third time interval.
> 1999	The Council directive 1999/31/EC of the EU (European Commission, 1999) marks the transition from an undocumented landfill policy to a controlled, consequent managing of waste streams. However, we cannot avoid the fact that some regions like Germany, Flanders and the Netherlands already posed a well-developed waste policy by that time (COCOON, 2018).

Criterion 3: Volume

Using the Flemish landfill database as a reference, the definitions of a small, medium and large landfill were redefined. As the actual volume of many landfills still needs to be collected, the categorization (small, medium, large) was calculated by multiplying the surface area of land plots, known historical waste deposition and an assumed average waste depth of three meters (OVAM, 2013). The total number of records that was used was 3318 (**Figure 7-1**). These records were divided in intervals of 1,999 m³ (e.g. 0-1,999 m³; 2,000-3,999 m³ and so on). After this, the cumulative percentages of frequencies were used to determine the three categories of volume (small, medium, large):

1. All landfills with a volume less than or equal to 29,999 m³, corresponding to the lower 40% of the landfills present in the Flemish database, are defined as small;
2. All landfills between 30,000 m³ and 299,999 m³, corresponding to 50% of the total number of landfills present in the Flemish database, are considered to be average;
3. All landfills greater than 300,000 m³, corresponding to the upper 10% of the total number of landfills present in the Flemish database, are considered to be large.

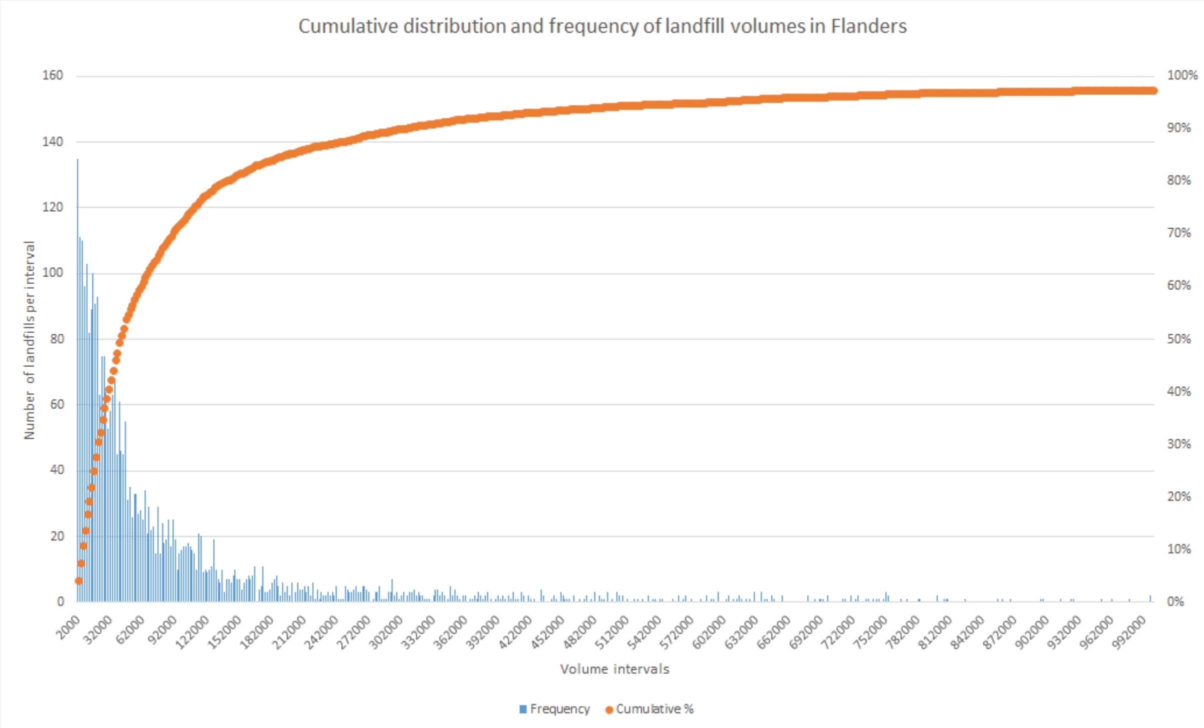

Figure 7-1 Cumulative distribution and frequency of landfill volumes in Flanders (Belgium).

The precise volume can be based on actual measuring data (e.g. geophysical imaging, topographic survey) or other forms of experimental determination. It is also possible to use default values in DST 1 - Cedalion. The volume, itself, is not used to decipher the priority of the ELFM investigations. It requires to be coupled with the landfill content. For instance, a small landfill with a lot of metal content can have a higher priority than a large landfill filled with plastics. Another example includes the difference in the surface area between landfills, that can be many times smaller/greater while containing the same volume of waste deposits, influencing the return on investment strongly because the value of the reclaimed land is proportionate to the surface area.

Criterion 4: Use

The criterion regroups the following parameters: the type of cover used on the top of the landfill, its surface state and the slope of the landfill. All the parameters are strongly related to the possibilities of redevelopment on site.

Criterion 5: Accessibility

The criterion is used to evaluate the accessibility of the landfill (distance to the road network, possibility for the road to support heavy truck, presence of paved roads on the landfill itself, waterways,…).

Criterion 6: Surroundings

The criterion surroundings contains the proximity of drinking water protection areas, presence of Natura 2000 areas or other conservation areas and general land use.

For **groundwater protection zones**, regional policies vary because other definitions are used but often consists out of up to three different zones (Vlaamse Milieumaatschappij, s.a.; Chelmi, 2015; InfoMil, s.a.). In Flanders, for instance, three zones are defined:

1. The 24 hours zone (i.e. "critical" in DST 1 - Cedalion) corresponding to a restricted area where contamination can reach the source of drinking water within 24 hours;
2. The bacteriological zone (i.e. "severe" in DST 1 - Cedalion) corresponding to the zone surrounding the 24 hours zone. Contaminations can reach the source within 60 days or is located within a 300 m radius;
3. The chemical zone ("acceptable" in DST 1 - Cedalion) corresponding to the largest zone: contaminations are present within a maximum radius of 2 km.

The **spatial development type** is strongly correlated with the value of the land and therefore can be vital to ensure a profitable landfill mining activity. However, in case the conditions are not favorable and interim use is necessary, it can also help to determine which form of interim use suits the best for the surrounding neighborhood.
There are eight types of land use (LUCAS, 2009) of which seven are relevant to the context of landfills in Europe. The seven types are:

1. Artificial land
    - Residential areas (e.g. houses, apartments)
    - Commercial areas(e.g. parking's, malls, hotels)
    - Industrial areas
    - Recreational land (e.g. resorts, golf courses, ball fields, camping)
2. Cropland (e.g. permanent crops, arable land)
3. Grassland: same function as pastureland, but with native vegetation;
4. Woodland: deciduous, coniferous and mixed forests;
5. Water (e.g. streams, canals, lakes, reservoirs) ;
6. Wetlands (e.g. marshes, coastal and tidal wetlands,) ;
7. Bareland including beaches, quarries, gravel, sand and clay pits.

In DST 1 - Cedalion, a distinction is made into present and potential land use, the first one being the current occupation of the landfill body, the second one the actual assigned land type based on land use planning.

7.3.3 DST 1 – Cedalion output

The result of the DST 1 – Cedalion is a score for each objective (WtM, WtE, WtL, IU) allowing to rank the landfills according to their ELFM potential. In addition, for each landfill site a quick response is given when it is possible. This quick response aims to orientate the user in his decision regarding the landfill management (e.g. potential for ELFM, Interim use - nature conservation, infrastructure development). For the landfill sites having a potential for ELFM either for material recovery or land value/pressure, the application of the DST 2 - Orion is strongly encouraged.

7.4 Interim use: developing sustainable use and gaining support

Landfills have a lot of potential, but a lot of them will not be mineable for their contents (low value of the waste materials, non-recyclable waste deposits, etc.) in the near future. However, preparing the sites for that moment of exploitation in the future will have benefits and might shorten the total time of the landfill mining project.
By default, the choice of interim use should have benefits for the surrounding inhabitants if present. If not, benefits for the environment should be considered. Moreover, the duration of the planned interim use is decisive for the choice the user can make. In DST1 - Cedalion, the RAWFILL project partners defined several, but certainly not all possibilities of interim use on a landfill, ranging from months (e.g. cultivation) to 30 years (e.g. solar power plant).

7.5 DST 2 - Orion: advise on existing tools and/or detailed analysis of the business case

Landfills selected by Cedalion as having a high potential for redevelopment are referred to the DST 2 – Orion, which combines various existing applications. The idea behind Orion is that each of these applications has its own strengths and weaknesses, but with a combined use of selected tools it will be possible to make the best decisions for the landfill management.

In addition to the existing tools, a new tool, called OnToL[24] (Online Tool for the Evaluation of Landfill Mining Projects) and developed by OVAM in collaboration with Technical University of Vienna, was included in the DST 2 – Orion. It was developed based on the Reclaf model (Winterstetter *et al*., 2016). The methodology of the United Nations Framework Classification for Resources (UNFC) assessment model is applied. This is a classification system used in the circular economy. It was introduced by the UN in 2018 to classify anthropogenic stocks according to their potential of exploitation. This UN classification system is based on TU Wien research. The brownfield opportunity matrix, developed by the HOMBRE project, was also adapted for landfill sites and included in the DST 2 - Orion.

[24] Available as a online application at https://landfill-mining.at/home

DST 2 - Orion comprises of a roadmap, helping the user to make a choice among the different existing decision support tools. These tools mostly are quite complex to use, so in this stage of the research it is advised to ask help from experienced landfill experts. Results of the geophysical survey and targeted waste samples (see **Chapters 4 & 5**) as well as the scoring of DST 1 - Cedalion, among other information are required as input.

If the DST 2 - Orion confirms the ELFM potential of the landfill site or if the ELFM project is economically viable and/or the social and environmental benefits are demonstrated, the ELFM project can start. Recommendations for landfill mining operations are presented in the following chapter (**Chapter 8**).

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8 Recommendations for landfill mining works on site

8.1 Introduction

This chapter summarizes some practical recommendations to realise landfill mining operations. It is addressed particularly to public and private landfills owners and manager operators, public, and consultancies/engineering firms who are interested in mining a landfill. The chapter is focused on on-site works, and includes the following steps:

- Preparation;
- Waste excavation (bulk or selective excavation);
- Organisation of the lorry movements inside and outside the landfill;
- Rainwater, biogas and leachates management;
- Waste sorting and/or pre-treatment;
- Containment of residual waste or waste to valorise in the future (optional);
- Backfilling with suitable materials (treated waste or exogenous materials as soil);
- Reshaping the site.

All questions regarding authorizations and permitting, dialogue with stakeholders and neighbours, business model/business plan, waste recycling off-site and monitoring are not considered here, as they are described in **Chapter 10** of the Landfill Miner Guide.
In this chapter, all civil work organisations and features that are common to all types of excavation works are not described.

8.2 Prior use of RAWFILL ELIF data sheet

When carefully filled, the Enhanced Landfill Inventory Framework developed by RAWFILL (ELIF - see **Chapter 6** for further information) may provide great benefits for works preparation as it contains a lot of suitable information necessary for the design of the project:

- Information about the landfill content and the spatial distribution of resources ("Waste description"). RAWFILL's Resource Distribution model also provides valuable information;
- Information about risks which may occur during works, as the main potential hazards identified prior to the beginning of the project will remain present during works. They will obviously influence works organisation and operations (for example flooding risk, landfill stability problems, biogas and leachates releasing, erosion, etc.);
- Site-specific environmental issues and biodiversity protection/development must be carefully considered;
- Analysis of surface water conditions, geological context and groundwater vulnerability will eventually lead to specific measures in order to protect water resources (e.g. management of rainwater and leachates, installation of a storm basin and/or a water treatment plant);
- Information about surroundings will indicate how far to go with mitigation measures as odour, dust and noise control, organisation of lorry movements, working hours;

- A first indication of possible social support or NIMBY[25] resistance can be found in "Social form";
- Possibility of reusing existing infrastructure (e.g. as a leachate treatment plant) can dramatically facilitate operations and reduce operation costs;
- Landfill geometry will define the best way to excavate and manage waste as well as the eventuality of filling the void with new materials and reshape the site;
- Descriptions of access roads and other transport facilities are of great interest to select the machines and equipment that can be used on the landfill and to define waste transportation conditions for recycling and valorisation plants.

8.3 Attention points specific to ELFM operations

The following checklist summarizes all important operations to be considered when organising the works. It constitutes a general guideline destined to help everyone who wants to start an ELFM project, but the reader must remember that any project is unique, and requires to be carefully planned, studied and analysed in terms of risk analysis, work organisation description, terms of reference, etc. The project and all the decisions related to it will always be the responsibility of the project developers and contractors.
The main focus is on specific landfill mining operations, but all classical civil engineering methods, lorry movements organisation, mapping, fences, environmental follow-up, risk and safety plans, waste management, traceability and usual procedures must be applied.

Authorizations, permitting and regulations

Before starting operations, it is important to check that all authorisations and permits have been issued regarding the landfill, waste transportation and waste valorisation for the specified period. As landfill mining is rather new, most of the NWE waste/landfills/soil/environmental regulations are not fully adapted for this kind of operation. Adaptation of the legislation or specific derogation can be discussed and arranged with the competent regional authorities (**Chapter 12**).
Regarding civil engineering aspects, quality assurance plan, health/safety plan, all expected works must follow suitable national, regional or local normative and regulatory frameworks.

General works organization

Temporal distribution of the works must be carefully planned as the possibility to work year-round, or in batch will depend on the usual time constraints (limited duration for permits, availability of equipment, mobilization and demobilization costs…), but also on specific points:

- Biodiversity protection measures (e.g. trees cannot be cut during nesting periods);
- Capacity of facilities to absorb waste flows that will be mined (some facilities may have limited capacity for mined waste as they are already used for other flows and as the quality of mined waste can sometimes stay beyond acceptance criteria);
- Capacity of pre-treatment unit(s) that will be placed on site in order to prepare the waste for the given purpose;

[25] Abbreviation for « Not In My BackYard ».

- Storage volumes on site;
- Lorry movements intensity acceptance by neighbours.

Social support

The involvement of local communities is vital to ensure the success of works that may last for some years, even if all permits and authorizations have been issued, and the project is fully compliant. To avoid blocking works for months or years, a very dynamic link with local communities must be established for trust to be created and maintained. A suitable communication plan must be set up, showing the benefits of removing waste and redeveloping biodiversity and ecosystem services. Regular meetings and work visits should be organised (For more information, please refer to **Chapter 11**).

Works description

A technical description of the works including the following items should be prepared:

- Preparation works;
- Identification of specific ELFM procedures (e.g. works with biogas and leachates, excavation of waste, transportation of hazardous waste);
- Organisation of the lorry movements inside the landfill where space and mobility for heavy trucks can be limited;
- Organisation of the lorry movements outside the landfill;
- Waste excavation;
- Rainwater, biogas and leachate management;
- Waste sorting and/or pre-treatment;
- Containment of residual waste or waste to relandfill for valorisation in the future (optional);
- Backfilling with suitable materials (treated waste or exogenous materials as soil);
- Reshaping the site;
- Cleaning;
- Redevelop biodiversity, ecosystem services and social added value.

Risk analysis and mitigation

It is crucial to evaluate all health (i.e. workers and neighbours), environment (i.e. fauna and flora), surrounding soil and water (groundwater and surface water) risks related to the landfill mining operations. It is important to remember that expected waste quality and associated hazards may vary due to new conditions (exposure to air and rainwater). Risk mitigation is applied to the on-site works and on the waste transportation in suitable conditions. Risk mitigation in waste valorisation facilities is under responsibility of these facilities. For each specific risk, preventive measures including workers information and worker training must be given. Adapted personal and collective protective equipment must be used (shoes, masks, gloves, disposal coveralls, among others).

Suitable specific risk mitigation equipment must be available on site. Some examples are listed below:

- Fans for gas dilution;
- Firefighting equipment adapted to the type of fire that may appear in waste mass;
- Suitable bags for asbestos collection;
- Active charcoal filters on fine materials outlet to remove volatile compounds;

- Pumps and storage tanks or ponds for liquid layers;
- Secured containers for hazardous drums, barrels or bulk chemicals that can be found.

Contingency plan

The realisation and regularly updating of a contingency plan adapted to the site and the waste must be performed. This measure is especially recommended when mining hazardous industrial waste, or waste where UXOs (e.g. unexploded ammunition) can be potentially found.

Identification and mitigation of nuisances

A description of preventive and mitigation measures that will be used must be listed for each identified nuisance such as gases and vapors, odors, dust, vibrations, noise, road cleaning, etc.

Working areas

It is essential to map the facilities and the dedicated areas on site (i.e. works quarters, machine park and maintenance area, sorting and pre-treatment installations, material storage). These areas may evolve during work progress and their potential evolution should be considered during the planning/mapping of the site. As space can be limited, a reorientation of these elements may be necessary multiple times, depending on the scale of the project.

Knowledge about waste distribution and waste description

The Resource Distribution Model (RDM) developed by RAWFILL provides a 3D map of the waste deposits (see **Chapter 4** for further information) and therefore, indicates the presence of homogeneous waste layers/areas. For each homogenous layer/area, the following information is provided:

- Geometry:
  - Surface
  - Average thickness
  - Maximal thickness
  - Volume.
- Average in-situ density (T/m³)
- Main physical state
  - Mainly solid
  - Mainly liquid
  - Powder
  - Sludge
  - …
- Waste size distribution (according to adapted meshes)
- Global waste composition and composition (for each range of sizes)
- Average water content (if analysis is available)
- Presence of gases
  - Generated by organic materials (biogas, mainly methane)
  - Generated by industrial products
- Gas composition (if analysis is available)

- Water table(s) within the waste mass (connected to the local water table or small perched water tables).

The opening of the waste mass will change conditions during the works (e.g. temperature, exposure to oxygen and rainwater…) and may reactivate sleeping processes (e.g. gas production, chemical and physical reactions, production of new leachates). It will also change important parameters such as water content and so may change recyclability conditions and influence valorisation processes (i.e. maximal water content allowed to burn waste in cement kilns).
The division of the landfill into homogeneous zones with a different waste composition can influence the sorting and pre-treatment equipment to install on-site. Better efficiency will be reached if specific equipment is used for each zone.

Hazardous waste and specific pollutants

The presence of hazardous waste and specific pollutants in the waste (i.e. asbestos or medical waste in domestic waste landfills) will lead to special safety and security measures during the works and during their evacuation if they must leave the site. As the waste composition is never 100 % known, the safety plan should wisely consider the worst-case scenario, but it must be balanced with the necessity to get the works done in reasonable conditions. The best way to keep the balance between safety and efficiency is to constantly monitor risks in order to give a quick and adapted response to any situation. A daily works inspection by safety manager or qualified people as well as regular training of operators is recommended.

Biogas and gases management

Should biogas or specific gases (from industrial waste streams) be produced during the works, specific measures must be taken in order to protect workers and neighbours, i.e.:

- Accelerated mineralisation (prior to the works, if technically possible);
- Dilution by powerful fans;
- Water curtains or sprinklers;
- Machines with pressurised cabins and filters;
- Temporary coverage (eventually coupled with gas collection and treatment system);
- etc.

Explosion risk is the main risk to manage before gas and dust inhalation. Explosimeter must be present and used on site all the time. Usual gases to monitor are commonly oxygen, methane and carbon dioxide, but it can be necessary to measure other specific gasses such as sulfate, carbon monoxyde, hydrogen sulfide, etc. Oxygen must be measured in open pits when workers must enter them. Several PID sensors to track volatile organic compounds can be installed around the working areas.

Figure 8-1 Small bubbles can be seen at the surface of the water attesting the presence of biogas (Credit photo: Atrasol).

Rainwater and leachate management

Leachate will in any cases be produced during the excavation works, so specific measures must be taken in order to collect and eventually treat it before discharging into a river, a sewage system or an infiltration system.

Leachate flow must be calculated considering the amount of water coming from the waste and the rainwater on the catchment area. A suitable return period for rainfall must be chosen, considering increasing intensity of precipitation and storms due to climate change. Works should be organised to minimize leachate formation, for instance, by opening only small cells and covering stand-by waste areas with temporary coverage. In any case, rainwater must be collected separately to avoid excessive leachate production. Dilution of leachate with rainwater is possible but not encouraged.

Leachate must be analysed in order to define the best treatment or the possibility to by-pass it. In this case, laboratory analysis should be done before discharge and the use of an impervious storage basin is recommended. It is important to remember that leachate composition may be different than expected due to possible reactivation of chemical, biological and physical processes occurring within the disturbed waste mass. Treatment processes are specific (e.g. aeration, MBR – membrane bioreactor, charcoal adsorption columns) and will not be described here, but please note that the use of a hydrocarbon separator with a coalescing filter before discharging point is always recommended.

Existing infrastructures on the landfill and immediate surroundings

The inventory and mapping of buildings, aerial and buried infrastructure should be performed. Within the landfill, it is necessary to pay attention to gas collection networks, flare, gas and/or leachate collection shafts or horizontal pipes, concrete structures, electric lines, etc. The opportunity to reuse existing infrastructure (rainwater and leachate collection systems or storm basins or impervious leachates lagoon) during the works as well as the necessity to protect some of them should be considered.

Stability of the landfill and the new slopes that will be created

General mass stability of the waste deposits must be assessed, as well as stability of the new slopes that will be created during mining. This keeping following, but not limited to, factors in mind:

- Risk of slope destabilization;
- Truck weight allowance;
- Vibrations;
- Removal of water tightness upper layer.

Geotechnical properties (as cohesion and friction angle) of waste, especially domestic waste, are difficult to evaluate and generally requires to be measured in the laboratory. Ranges of geotechnical parameter values for different types of waste can be usually found in the scientific literature. In that case, it is important to consider the worst and the best scenario. In addition, the geotechnical properties of the waste material may evolve through time. The slope angle and the maximal height of the working face should also be considered. The safety factor can be calculated to ensure the slope stability and anisotropy of the mass must be examined. When working nearby constructions, stability calculation with the right methods and parameters are necessary and stability measures should be applied. In addition, some monitoring of the waste stability is required.

Figure 8-2 Horizontal cracks at the top of a landfill attesting stability problem (Credit Photo: Atrasol).

Figure 8-3 Destabilization of the bottom ground due to landfill slide (Credit photo: Atrasol).

Excavation

Waste excavation is obviously the main step of a landfill mining project. Common civil engineering machines such as excavators, bulldozers and dumper trucks can be used. Buckets must be adapted to the type of waste to dig. The use of screened buckets can be helpful to directly remove leachates or fine materials. Stone crushers and breaking hammers may be necessary when large fragments of concrete, other construction waste or hardened materials (i.e. industrial waste as slags) can be found in large quantities. Equipment for cutting cables or long elements may be necessary as well.
Waste excavation can be bulk excavation as well as selective excavation (digging layer by layer or spot by spot to consider various waste compositions leading to various waste pre-treatment or treatment).

Regular measures of excavated volume and waste composition

Regular evaluation of volume, density and waste composition must be performed in order to ensure the conformity with forecasting. Please refer to **Chapter 5** to select suitable waste properties to measure. When distortions with forecasting appear, it may be necessary to realise a separate storage of the new waste and to treat them afterwards, after adaptation of treatment method. Quality control of the pre-treated waste must also be ensured.

Treatment

Treatment integrates all mechanical processing used to produce recycled materials (e.g. ferrous and non-ferrous metals, aggregates) and to generate as RDF [26] fraction concentrating components with high caloric value (wood, plastics, textiles, etc.).
Treatment on site will be rather simple or complex, depending on:

- Site situation: neighbours, surrounding biodiversity, available space for treatment and storage, etc.
- Type of waste to be mined and modalities of recycling and valorisation
- Distance to waste recycling and valorisation facilities
- Type of facilities: burning plants (incinerators or boilers), cement kilns, construction materials, etc.

Treatment is specific and will depend on the types of waste material, homogeneity, water content, grain size distribution.
A typical installation will contain the following machines:

- Weighbridge;
- Feeder;
- Scalper;
- Trommels / ballistic separators;
- Magnetic separator (overband magnet, drum magnet);
- Eddy currents;
- Air screens (cross-flow, zig-zag wind sifters…);
- Manual sorting line ;
- Containers/dumpsters;
- A generator that provides power to the machines.

[26] Refuse Derived Fuel

Shredders may be added to the sorting/pretreatment line, in order to reduce particle sizes and fit requirements of facilities (burning RDF for instance).

To ensure proper work conditions, all the machines can be installed on a concrete platform, or a platform of at least 30 cm thick compacted granulates above an impervious 1 mm HDPE or 1.5 mm geomembrane. Platform dimensions will depend on installation, please note that 2,500 to 4,000 m² are usually encountered surfaces.
A total traceability of all evacuated waste must be performed.

Biodiversity protection and development

Inventory of ecosystems should be realised prior to works in order to define species to protect or to eradicate (e.g. invasive species: animal pests, Buddleia, Japanese knotweed). Periods of works should be adapted to consider nesting and reproduction seasons following regional good practises. Environmental monitoring of the works may be necessary.

Energy and water supply

Electricity sources, fuel tanks and water supply on the landfill site must be defined before beginning the works, especially if sorting operations are performed. The carbon footprint of the works should be calculated and efforts to minimize it should be made, as well as other sustainability aspects.

Backfilling

Traceability of backfilling that will be used to eventually fill void space created by the mining (nature, origin, geotechnical properties and chemical analysis) must be ensured. Organisation of the lorry movements outside and inside the landfill must be defined.

"As built" plan

All ELFM works must be carefully documented and all documents related to traceability must be collected:

- Map of the working zones (excavation and pre-treatment/preparation) and storage areas;
- Materials/waste balances;
- Waste valorisation flows.

Validation

As usual, follow-up of the works by specialised consulting office and validation by independent third party is recommended.

8.4 Conclusions

This chapter summarizes some practical recommendations to start landfill mining operations under the best possible conditions. Please see it as a reminder checklist helping you to design a project with more suitable details and in safe conditions. Following steps have been shortly reviewed: preparation phase, waste excavation, organization of the lorry movements inside and outside the landfill, rainwater, biogas and leachates management, waste sorting and/or pre-treatment, backfilling with suitable materials and finally reshaping the site.

9 Waste valorisation

9.1 Introduction

Under the Enhanced landfill mining concept, three types of waste revalorization are mentioned: (1) Waste-to-Land (WtL); (2) Waste-to-Materials (WtM); (3) Waste-to-Energy (WtE). In this chapter, three ways to revalorize the landfill site are explained to increase the financial revenues related to waste revalorization or to decrease the cost of the landfill mining operations.

9.2 Glossary

Combustion/incineration: thermal breakdown of waste supplying an excess of air, producing a flue gas (carbon dioxide, oxygen, nitrogen, water steam) and heat. Temperature ranges from 800 to 1,450°C. This technology is well-known as the first incineration plant was built in 1865 (Gibraltar plant). The main advantages of the combustion/incineration are the following:

- Volume reduction (more than 90% of the municipal solid waste volume) ;
- Weight reduction (around 70% for municipal solid waste) ;
- Reduction of chemical hazards as hazardous molecules are often destructed by the heating :
- Production of heat ;
- Production of electricity (sometimes considered as "renewable energy").

Waste to Energy (WtE): process of generating energy in the form of electricity or heat from the thermal breakdown of waste through any thermal conversion technology or combination of conversion technologies.

Gasification: thermal breakdown of waste under oxygen starved conditions (oxygen content in the conversion gas stream is lower than needed for combustion), thus creating syngas and solid residues as char. Temperature ranges from 500 to 1,600°C.

Lower caloric value/Net caloric value: total energy released as heat when a substance undergoes complete combustion with oxygen under standard conditions.

Mechanical Biological Treatment plant (MBT): waste processing facility combining a sorting facility (mechanical process) and biological treatment (e.g. composting, anaerobic digestion).

Plasma gasification: treatment of waste through a very high intensity electron arc, leading to temperatures of more than 2,000°C. Within such a plasma, gasifying conditions break the waste down into a vitrified slag and syngas.

Pyrolysis: thermal breakdown of waste in the absence of air, to produce char, pyrolysis oil and syngas. Temperature varies from 250 to 700°C.

Refuse-Derived fuel (RDF): fuel generated from various types of waste such as municipal solid waste or industrial waste.

Waste-to-Materials: waste previously landfilled and valorised as resources.

9.3 Land recovery

Depending on the location, landfill characteristics, and market factors, land recovery may potentially be the best option to ensure the financial viability of the landfill mining project. It is particularly interesting to recover land, when the land value in the area is high, or when the site is already included in a land use planning. In these cases, the rehabilitation of old landfills is an opportunity to implement new redevelopment projects. The site can be redeveloped for several different purposes such as residential, commercial, industrial or mixed-used. Other uses like parks, recreational areas and municipal facilities might also be considered when the land has a low value or was heavily contaminated (for more information about site rehabilitation, see **Chapter 10**).

Private investors may be interested in land revalorization as the landfill site can be generally acquired at low costs. Sometimes, landfills are located in areas where infrastructure already exists. This is a good opportunity to save money as the sites are already accessible to rail lines, ports and public transportation. Similar to brownfield, the landfill site redevelopment offers benefits in comparison to greenfield development by preserving the greenspace and reducing urban sprawl. The landfill site redevelopment may be the linchpin generating a positive environment for new investment and leads to transformation of entire neighbourhoods. The selling of a rehabilitated landfill site with a redevelopment project guarantees substantial economic benefits for the investors. By redeveloping the landfill site, the economic value of the land surrounding the sites can also increase. Moreover, local stakeholders may be more likely to get involved due to concerns by the future development in the neighbourhood.

9.4 Material and Energy recovery

This section covers the most common waste streams and the possibility of either recovery of material or energy from the waste resource are discussed. Each waste stream is described in detail.

Waste-to-Materials parameters:
The important parameters to assess the potential of revalorization are summarized in **Figure 9-1**. The state and the type of materials are key. The waste content and its proportion in valuable materials helps to decipher the best way to revalorize them.

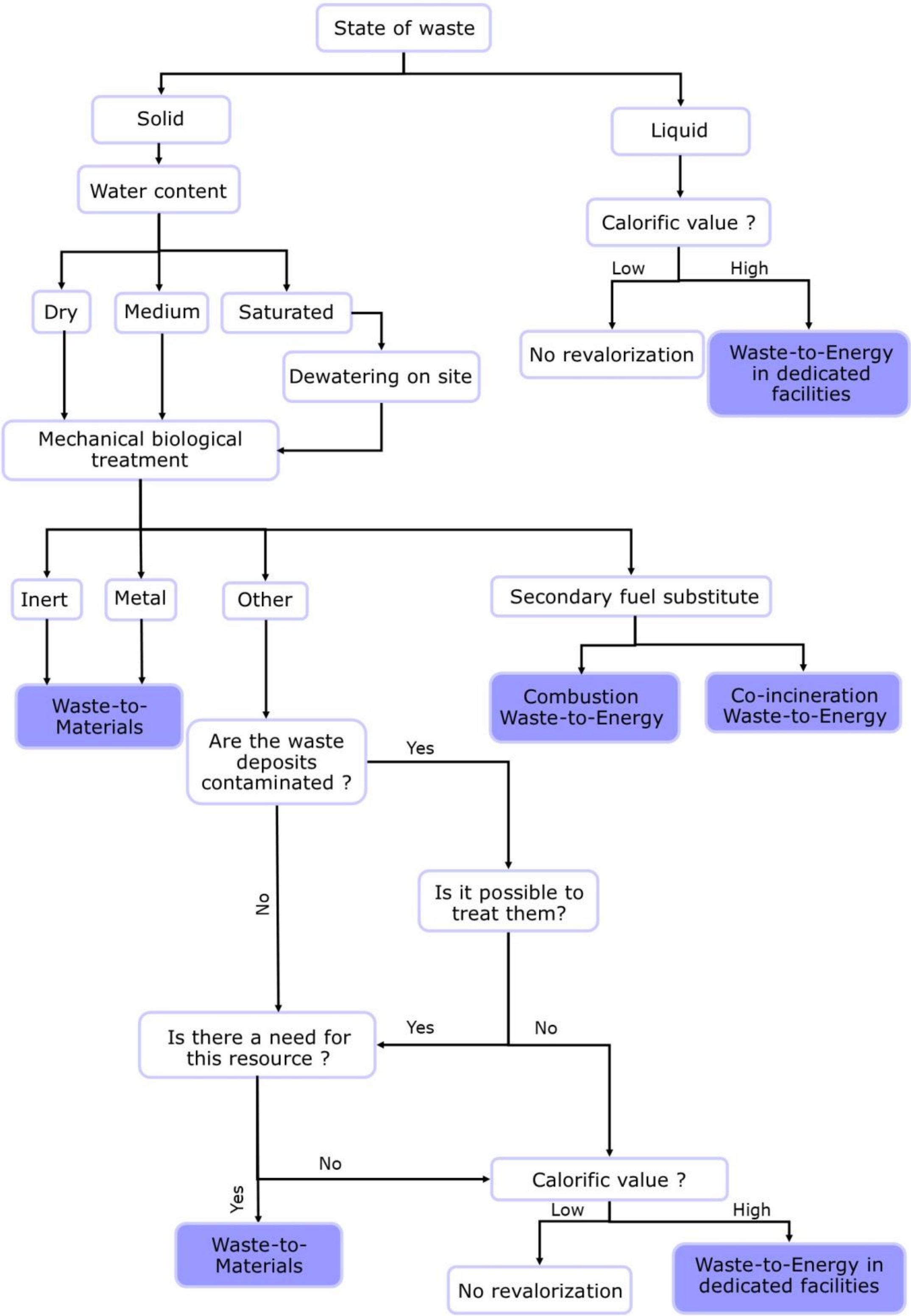

Figure 9-1 Decision tree helping to select the best way to revalorize the waste excavated from old landfills.

Preparation of waste for Waste-to-Materials recovery:

It is important to mention that most of the waste recovered from landfills is not suitable for material recovery as they are often polluted, dirty or do not correspond to the EU standard to be directly reused. Therefore, most of the time, WtE recovery is the most suitable option mainly depending on the caloric value of the waste material. The caloric value of the waste material is based on the carbon, ash and moisture content of the material (Hernández Parrodi *et al.*, 2018).

Main parameters involved in Waste-to-Energy processes

When excavated waste, especially household waste, is destined for incineration or any other thermal treatment, three important parameters to consider are (1) the waste composition and its lower heating value; (2) the water content and (3) the organic matter content. The water content depends on the type of waste deposits, the climate conditions during landfilling period, the age of the waste materials (as some degradation/biogas production occurs with time), the presence of an impervious capping and the presence of a water table within the waste mass. The organic matter content is related to the type of waste deposits and the age of the waste. The organic matter content is also responsible of degradation/mineralization processes. **Table 9-1** provides indicative lower heating value of some typical waste stream.

Table 9-1 Typical value of lower heating value for waste materials. [1]Almadius et al. (2015), [2]Quaghebeur et al. (2013), [3]Ramos et al. (2011), [4]Numes et al. (2017), [5]Saveyn et al. (2016), [6]Hogland et al. (2004), [7]Jani et al. (2016).

Type of waste	Description	Lower heating value (MJ/kg)
Mixed Municipal solid waste	Mixed household domestic waste	6.3 – 10.5[1]
Cardboard and paper	Cardboard and paper excavated from landfills	6.7 – 12[2]
Plastic	Plastic excavated from landfills	19 - 28
Tires	End-of-life tires	32[3]
Textile	Not landfilled	15[4]
Refuse-Derived Fuel (RDF)	Pellet or floc material produced from MSW and similar non-hazardous waste	11-26[1]
Fine Fraction		0.4-4.8[2,6,7]

Preparation of waste for Waste-to-Energy treatment

Preparation techniques may vary according to the expected results, considering that landfilled waste is difficult to separate without specific operations. Often, the preparation process will eliminate exogenous elements not suitable for treatment; recover ferrous and non-ferrous metals; reduce water content and increase the caloric value. For that purpose, a mechanical-biological treatment (MBT), using sorting techniques, magnets, Eddy currents, drying, crushing, etc can be used. For example, secondary refuse fuels can be used in cement kilns if they fulfil a specific size, a caloric value of more than 21 MJ/Kg and water content <15%. Standard lower heating value of secondary refuse fuels is between 13 and 23 MJ/kg (Aenergyes *et al*., 2015).

In the following sections, the revalorization potential of the most common waste deposits usually found in old landfills are presented.

9.4.1 Ferrous and non-ferrous metal

Waste-to-Materials

Recycling metals allows saving costs from exploration, mining, and primary refining. Moreover, the energy requirements to recover secondary metals are lower than for primary metals. The proportion of metal present in landfills depends on the type, the location, and the period during the waste was landfilled. Quaghebeur *et al.* (2013) showed that the metal content decreases over time in municipal solid waste. In Remo landfill (Belgium), the metal content varies between 3 and 6%. Similar contents have been found in other landfills (e.g. Särkkä *et al*., 2016). The ferrous and non-ferrous metals are presented separately. Ferrous metals usually constitute the largest part of the metal fraction present in old landfills.

Since the 1990s, ferrous metals have been recycled in Europe as they are easy to collect and separate from the non-ferrous metal by magnetic separation. To be revalorized, ferrous metals cannot contain too many impurities in the form of other metals (Cu, Sn, Pb, Ni, Cr, Mo…), S, P, nor be mixed with too much soil or other mineral materials. At present, more than 50% is recovered after incineration, separate collection, or from waste collection facilities. Steel is mainly reused in the electric furnace and represent a large part of the steel production (France: at least 40% of the steel production comes from recycling products, Damien, 2002). A study conducted in France estimated steel content in domestic waste at 9 Kg/capita per year, with packaging as the main source.

Most common non-ferrous metals are Al, Cu, Pb and Zn. These non-ferrous metals are particularly interesting to recover from landfill as they have a high value on the market. The value of metal is also correlated with its state and its degree of corrosion (for instance, Zn is easy to corrode but Al is not). Non-ferrous metal scraps are separated from ferrous metal using Eddy currents and then separated based on density. When they are present in leachates as cations, they can be collected by precipitation or electrolysis, but these operations are rarely profitable. Nowadays, due to separate collection, Al accounts for only 0.5% of the weight in typical NWE household waste (Atrasol, internal study on secondary Al streams).

9.4.2 Cardboard and paper

Paper and cardboard wastes are considered by EU as non-hazardous waste. Following the definition given by Eurostat (2013), this waste category includes fibre, filler and coating rejects from pulp, paper and cardboard production.

Waste-to-Materials

According to Saveyn *et al.* (2016), 99% of the current paper production are treated and recycled. However, old landfills often contain a large proportion of paper waste. Paper wastes recovered from landfills are usually mixed with other waste and thus potentially contaminated, making them unsuitable for revalorization. Therefore, paper wastes recovered from landfills are not easily recycled as materials and most of the time are valorised as energy.

Waste-to-Energy

Lower heating value of collected (dry) paper and cardboard is around 17 MJ/kg (Saveyn *et al*., 2016). However, paper and cardboard extracted from landfills have a lower caloric value depending on the age and the landfilling conditions. Quaghebeur *et al.* (2013) reports lower heating value for landfilled papers and cardboard between 6.7 and 12 MJ/kg, which is not ideal, considering a minimum value of 14 MJ/kg is required for material to burn without supporting fuel. Cardboard and paper recovered from landfills can be mixed with other waste streams prior to incineration.

9.4.3 Plastic

The term "plastic" covers a large range of polymers. Plastics are considered by the EU as non-hazardous waste. However, they can contain various proportions hazardous chemicals such as flame retardants and artificial colourings.

Waste-to-Materials

Plastics represent a very heterogeneous stream of waste as they exist in many different forms and applications. Plastic waste collected from landfills are usually not recovered as materials due to their composition, the difficulty to separate the plastics from other landfilled waste materials, pollution and degradation. Degradation of landfilled plastics is still poorly documented regarding processes, conditions and degradation rate. A low added-value application can be the compaction into blocks that can be used as backfill to fill up cavities in civil works. Relandfilling of plastics requires geotechnical studies at short, middle and long-term, as geotechnical properties will change with time. Most of the time, they can be mixed with soil or a soil-like fraction (*see below*) in order to produce poor quality backfilling and reduce elastic settlements when placed.

Waste-to-Energy

Landfills may contain high proportions of plastic material on average 5 to 25 wt% (e.g. Münnich *et al*., 2015; Quaghebeur *et al.*, 2013; Jones *et al*., 2013; Van Passel *et al*., 2013). These plastic waste materials have a potentially high caloric value (Kurian *et al*., 2003). The potential of using plastics to recover energy depends on several factors: the type of polymer (HDPE, PET, PP), the source of the plastic (e.g. packaging, agriculture, EEE, vehicles), the degree of pollution as well as the method used to separate the plastics from the other landfilled wastes (Saveyn *et al*., 2016). The caloric values range from 19 to 28 MJ/kg according to Quaghebeur *et al.* (2013). Studies have demonstrated that the caloric value is not affected by the years of storage (Quaghebeur *et al*., 2013; Zhou *et al*., 2014) but other experiments conducted in the industry show the opposite (Atrasol, pers. comm.). Plastics can be prepared as RDF, mixed with other streams as wood and textiles. The RDF can then be co-incinerated in incineration plants or cement kiln. As plastics recovered from landfills contain impurities (Zhou *et al*., 2014) and pollutants like hydrocarbon and heavy metals (Rotheut and Quicker, 2017), the use of excavated plastics as RDF may require pre-treatment before being converted into energy (Canopoli *et al*., 2018). An output of landfill mining operations will certainly be an RDF material with specific properties (size, water content, heating value, etc.) depending on the burning facilities.

9.4.4 Glass and Ceramic

Waste-to-Materials

Many waste ceramic materials such as glass, pottery, porcelain, and brick are usually landfilled. However, even if this waste type is less conducive to recycling, they can be revalorized in WtM if the leaching tests demonstrated that the waste materials are non-hazardous. Due to their low economic values, they are generally used as backfilling material. Innovative technologies have been recently developed to revalorize the ceramic and glass waste material. If not polluted by ceramics, glass waste can be recycled as cullet in glass production, as raw material for the production of abrasives, in sandblasting, as an aggregate substitute in concrete, in road beds, pavement and parking lots, as raw materials to produce glass pellets or beads used in reflective paint for highways, to produce fiberglass, and as fractionators for lighting matches and firing ammunition (Chen *et al*., 2002; Zainab & Al-Hashmi, 2009). Ceramic waste materials are mainly reused in the road foundation and in concrete as an aggregate substitute. Glass and ceramic cannot be revalorized for energy recovery due to their low caloric value.

9.4.5 Construction waste

Waste-to-Materials

Construction waste (bricks and concrete, aggregates, etc.) can easily be separated from other waste streams and prepared (crushed and sieved) for reuse as low-value backfilling. An important point will be the washing of the impurities and the proof that they will not release contaminants into the ground, so representative leachate tests must be performed. Another point will be the long-term behaviour of brittle materials as old, not enough fired bricks can crumble and seal drainage layers or be released into the environment. Stone and concrete cannot be revalorized into energy.

9.4.6 Household waste

Following Eurostat (2013), household waste materials are defined as "mixed municipal waste, bulky waste, street-cleaning waste such as packaging, kitchen waste, and household equipment". Household waste materials are considered non-hazardous. The composition of the household waste changes over time. These changes can be attributed to degradation of the waste as well as the evolution of society, waste management procedures and waste legislation (Quaghebeur *et al*., 2013).

Waste-to-Materials

Due to the heterogeneous character of household waste, it is difficult to directly revalorise. Household waste should preliminary be sorted and separated into different waste streams.

Waste-to-Energy

The caloric value of the household is directly related to its waste content (i.e. plastic, paper/cardboard, wood, textile, glass/ceramic, metal, stone and the fine fraction). Scientific literature reported caloric value between 6.2 to 11.8 MJ/kg (Kathirvale *et al*., 2004; Quaghebeur *et al*., 2013). Household waste can be used as RDF after separation of non-combustible fractions, sieving and sometimes water content reduction.

9.4.7 Rubber and tires

End-of-life tires generate most of the rubber waste materials. According to EU standards, it is considered non-hazardous waste. In this section, we are not discussing the rubber production waste like hoses, gloves, technical rubber goods. In the production of tires, five types of rubber are usually involved: natural rubber, styrene-butadiene rubber, polybutadiene rubber, isobutylene-isoprene rubber and isobutylene-isoprene halogenated rubber (Giannouli *et al*., 2007). Fibres and metals are additional components (Ramos *et al*., 2011). Regarding tires, the bigger they are, the more natural rubber they content. This feature is important since the possibility to receive green certificates is specific to combustion plants (Atrasol, internal study). Proven methods (ADTMD 6866 -08) are used to assess renewable and non-renewable fractions by measuring the ratio of ^{14}C and ^{12}C isotopes, with low $^{14}C/^{12}C$ ratios indicating older, non-renewable sources. A standard composition of tires is the following one:

- Light vehicles: 69% of C (which 18.3% comes from biomass) and 11.5% Fe
- Heavy vehicles: 61.1% of C (which 29.1% comes from biomass) and 26% Fe

Therefore, tire recycling will involve recovery of metals and recovery of elastomers for material or energy valorisation.

Waste-to-Materials

The first step to recycle end-of-life tire is shredding. This can be done using a mechanic shredder or a cryogenic shredder (Ramos *et al*., 2011). The latter technology uses liquid nitrogen to cool the tire to temperatures between - 50°C and -100°C. At these low temperatures, the rubber behaves as glass and can be easily breakable into pieces (Cano *et al*., 2006). Depending on the recovery purpose, the three components of tires (i.e. rubber, steel and fibres) should be separated. The shred material has numerous applications in civil engineering: foundation for roads and railways, drainage material (in replacement of sand and gravel), landfill (rarely used), construction, among others (ETRMA, 2019). Whole tires are used at small cases for coastal protection, erosion barriers, artificial reefs, avalanche shelters, slope stabilization, road embankments and landfill construction operations as protective/drainage layer for geomembrane on steep slopes, etc. Recycled rubber made from shredded tires associated with binder thermoplastic or polyurethane can produce a large range of objects from thermal insulating sheets to motorcycle helmets (ETRMA, 2019). Long-term degradation over time must be considered. As elastomer of old tires will not ensure proper recycling compared to recent produced tires collected properly from dedicated facilities.

Waste-to-Energy

The main advantage of tires (and other rubber sources) as a source of energy is their high caloric content (32 MJ/Kg, Ramos *et al*., 2011). Therefore, they can be used as fuel for co-processing (cement kilns), in district/industrial heating plants/boilers, thermal power stations and pulp and paper mills (ETRMA, 2019). In steel plants, end-of-life tires, which have been preliminary shredded, are used in electric arc furnaces as a substitute for anthracite (1.7 kg of end-of-life tire = 1 kg of anthracite). Moreover, the steel contained in the tires are recycled (Zaharia *et al*., 2009). Other tires combustion processes have been studied as pyrolysis or gasification, to produce char and various gases or solid matters

(Atrasol, internal study). Some useful information about WtE use of tires can be found on the ALIAPUR website[27].

9.4.8 Textiles

Waste-to-Materials

Studies and experiments have demonstrated that the quality and state of the textiles recovered from the landfill are incompatible with a direct reuse as textiles (e.g. Quaghebeur *et al.*, 2010). The landfilled textile materials constitute a degradable fraction. Therefore, the current technologies do not allow to efficiently recover the textile fraction as material. Moreover, their potential to generate biogas through degradation is not suitable to be reused on site. Consequently, textiles are often re-landfilled in sanitary, modern landfill facilities.

Waste-to-Energy

In most of the cases, textiles extracted from landfills can be recovered as a part of an RDF production mixed with plastics and wood pieces. The lower heating value of the textile is around 15.5 MJ/Kg[28] (Nunes *et al*., 2017).

9.4.9 Wood

According to the EU (Saveyn *et al*., 2016), wood material should be separated into two categories, non-hazardous and hazardous waste material. Wood waste material consists of wooden packaging, sawdust, shavings, cuttings, waste bark, cork and wood from the production of pulp and paper. Wood from the construction and demolition of buildings are also integrated into this waste category (Eurostat, 2013). Hazardous wood waste materials are defined by the presence of hazardous substances such as mercury or tar-based wood preservatives which can contain Cu, Cr and As.

Waste-to-Materials

Landfilled wood will not likely be recovered as material but prepared as RDF, mixed with other streams. However, some “clean” pieces of wood can be mulched and reused on site if chemical analysis does not show the presence of contaminants such as heavy metals (e.g. Pb, Zn) or organic pollutants.

Waste-to-Energy

Lower heating value of wood is around 15 MJ/kg. Hazardous wood waste containing impurities and pollutants are mainly not suitable for co-incineration plants. Moreover, it may require additional energy consumption for pre-treatment of waste and emission abatement systems (Saveyn *et al*., 2016).

[27] https://www.aliapur.fr/fr/
[28] Value for non-landfilled textiles

9.4.10 Fine fraction

Fine fraction (0 to 60 mm) of landfilled municipal solid waste is the result of not only of the degradation processes of waste material initially present in the landfill, but also of temporary cover of the waste by soil or sandy, silty materials or sludge. Fine fractions have been identified as 40-80 wt% of the total waste in several landfills where tests were performed (e.g. Hogland, 2002; Masi *et al*., 2014; Kaartinen *et al*., 2013; Kurian *et al.*, 2003; Hull *et al*., 2005; Mönkäre *et al*., 2016; Quaghebeur *et al*., 2013; Hernández Parrodi *et al*., 2018). The fine fraction is obviously critical to assess the feasibility of a landfill mining project. Composition and percentages in weight of the fine fraction may vary in a wide range. In landfill rich in municipal waste deposits, Quaghebeur *et al.* (2010) showed that the fine fraction consists mostly in degraded garden and food materials. The proportion of plastic, paper/cardboard and textile is also significant. Wood, metal, rubber may also be present. Fine fractions can also contain hazardous materials such as batteries, hospital waste, among others. Materials characterized by grainsize below <4.5 mm are assimilated to soil and is often called soil, soil-like or soil-type fraction in the scientific literature. Permeability is low, as the material is poorly graded, from 10^{-7} to 10^{-9} m/s.

Waste-to-Materials

Most of the time, the fine fraction cannot be reused or recycled, but some experiments are conducted in order to find some use for the materials. As the fine fraction constitutes a majority of the landfills content, the recovery of this fraction has a huge impact on the viability of any landfill mining project.

Three fractions are quite easy to recover and may justify a separation operation for recycling: metals, ground-like fraction (as soil substitute, neosoil, backfill) and inert materials (to produce aggregates for construction products) (Hernández Parrodi *et al*., 2019). To improve the quality of the fine fraction, removal of particles by washing followed by drying operations can be performed but costs remain high for a low added value of the material.

When chemical analysis of micro-pollutants shows no concentration of hazardous substances such as heavy metals or organic contaminants above regional/national accepted levels, they can be used in capping layers when no specific geotechnical requirements are needed, or no risk of erosion is present. In rare cases, the fine fraction, when characterized by high phosphorus, can be reused as soil fertilizers. Experiences using phytoremediation to decontaminate fine materials are currently conducted in France (for more information, see Landfill of Bordes case study in **Chapter 12**).

Waste-to-Energy

Due to their mineral content and soil-like materials, the fine fraction may have a low caloric value and will produce a large amount of ashes. Several studies (e.g. Hernández Parrodi *et al*., 2018; Rincón *et al*., 2018) show that SiO_2 and CaO are the most common chemicals which represent more than 50% of the <10 mm fraction. Regarding the geochemical content of the fine fractions, it mainly consists of SiO_2, CaO, Al_2O_3 and FeO (Spooren *et al*., 2012). Previous landfill mining studies mostly show low caloric values (between 0.4-4.8 MJ/kg) for fine fractions (Hogland *et al*., 2004; Jani *et al*., 2016; Quaghebeur *et al*., 2013). However, Wolfsberger *et al.* (2015) measured higher caloric values for the fine fraction <20 mm (between 4.4-9 MJ/kg) in two Austrian landfills. It has been reported that the caloric value of the fine fraction tends to decrease over time (Jani *et al*., 2016).

9.5 Conclusions

The excavated waste from landfills can be either revalorized into Energy or Material. To choose the best option for each material, the state of the waste as well as its market value need to be considered. In the future, we expect to have more waste materials recovered as the techniques of separation and revalorisation are being developed. The valorisation of land could also be an added-value to the landfill mining projects to generate profits.

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10 How to rehabilitate a landfill after mining?

10.1 Introduction

The rehabilitation of the landfill site after a mining operation is obviously necessary regarding environmental and human health protection. This is also a legal requirement as the site will be considered a non-rehabilitated controlled landfill or non-authorized dumpsite, for which EU regulations (transposed in regional/national rules) are applicable. The terms and conditions of the rehabilitation works are usually defined in the mining authorization permits and vary depending on the regional legislative framework. In addition, these terms and conditions strongly depend on the type of landfill, the presence of non-valuable materials as well as the quantity of remaining waste on site (which will be the most common situation). Legal authorization such as authorization to relandfill on site may change the methodology and viability of the procedure.

The aim of this chapter is to provide guidelines to help landfill owners and managers who want to start a landfill mining project to understand the peculiarities of the rehabilitation process. This chapter will not discuss here preventive measures to ensure the safety of the workers on site as they are similar to the ones taken during landfill mining operations (see **Chapter 8** for more details). This chapter provides general considerations, but it must be kept in mind that every rehabilitation project should be designed carefully considering all the specific aspects.

A successful rehabilitation plan and the implementation of a sustainable redevelopment project on site require good communication with residents in order to be accepted as an improvement of the current situation, following some nuisances that will occur during the landfill mining operations and the rehabilitation process. Residents, local authorities and media should be informed correctly throughout the different steps of the rehabilitation works, which should be organized to minimize all nuisances affecting residents (traffic, noise, dust, odors, etc.).

An important answer to the residents' concerns lies in the added value of the landfill mining and rehabilitation processes. The rehabilitation phase is a key process to reduce the ultimate (mostly hidden) environmental impacts of the former landfill and is also the key to increase the redevelopment of biodiversity or landscape, if the site is not destined for construction. Site rehabilitation must be designed to be, as beneficial as possible for the community.

10.2 Assessment of the environmental and social factors

10.2.1 How to select the most optimal redevelopment project?

It is recommended to carefully plan the redevelopment project of the site before starting the landfill mining project, because the decision-making and the final rehabilitation operations will be influenced by the future project. Depending on the type of waste remaining on site, additional protective measures must be taken to guarantee the future safety of the site. For example, redevelopment projects focusing on human activities (in particular, residential area, school and childcare) are not recommended for previously hazardous landfill sites if the rehabilitation solution of the landfill implies retaining waste deposits on site. Therefore, it is possible that the redevelopment project might be modified or aborted during the landfill mining operations or after the rehabilitation operations due to remaining pollutant concentration in enclosing soil/rocks, and/or groundwater exceeding the safety standards defined by the regional/national authorities. Construction of a capping layer of 1 m soil, clay, clay and geomembrane, and a drainage layer can be a sustainable solution to protect human health from remaining contaminants especially in case of volatile products[29]. In some cases, land-use restrictions may be imposed.

The type of redevelopment projects can be decided based on indicative flowchart (**Figure 10-1**) illustrating the decision-making process to define the future activities on site. The first question to address concerns the excavation of the waste deposits and the hazard level of the landfill's content. If some waste deposits will remain on site or if hazardous waste deposits have spread contamination in enclosing soil/rocks and/or groundwater, it can be better to dedicate the redevelop the project to industrial, commercial or recreative project. This should be decided based on the assessment of the risks of exposure to pollutants and expert judgement. In addition, protective measures such as the building of concrete slab might be required to reduce the risks.

Previous landfill mining experiences often show that the recovery of the secondary raw materials does not guarantee the financial balance of the landfill mining project. In some cases, the value of secondary raw materials is not even taken into account[30]. A solution to ensure an economic benefit of the landfill mining project is the recovery of the land and the implementation of profitable redevelopment projects such as residential, industrial or natural areas, especially when the land has a high value and the site is included in local strategic land use planning. For stakeholders, it is difficult to assess the economic value of park as they do not generate direct income. However, their presence generates positive externalities, increase the life quality of the neighborhood and show a positive impact on the property value (Anderson & Cordell, 1985; Morancho, 2003). Municipalities can adopt this option to improve the well-being of the residents. This recycling of the land contributes to limiting land take. Landfill mining also reduces the risks related to the landfill and therefore, the aftercare cost (when applicable). In addition to the financial balance of the project, environmental and social benefits need to be taken into account. Based on the type of redevelopment project (e.g. industrial, commercial, residential), a detailed analysis of the impact of redevelopment should be performed by experts.

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[29] The protective measurements should be adapted depending on the type of remaining waste.
[30] See RAWFILL deliverable WP T12.1. - LFM benchmark experiences.

Finally, the success of a redevelopment project strongly depends on stakeholder involvement (see **Chapter 11**). A redevelopment project should be in line with the socio-economic needs of the local community and profitability for the project developer/investor (Lang & McNeil, 2004). It can either provide environmental remediation, civil infrastructure renewal, economic development or neighborhood revitalization. Should stakeholders' satisfaction not be achieved, then those reasons have to be clearly identified and the redevelopment project redesigned until for more optimal stakeholder satisfaction.

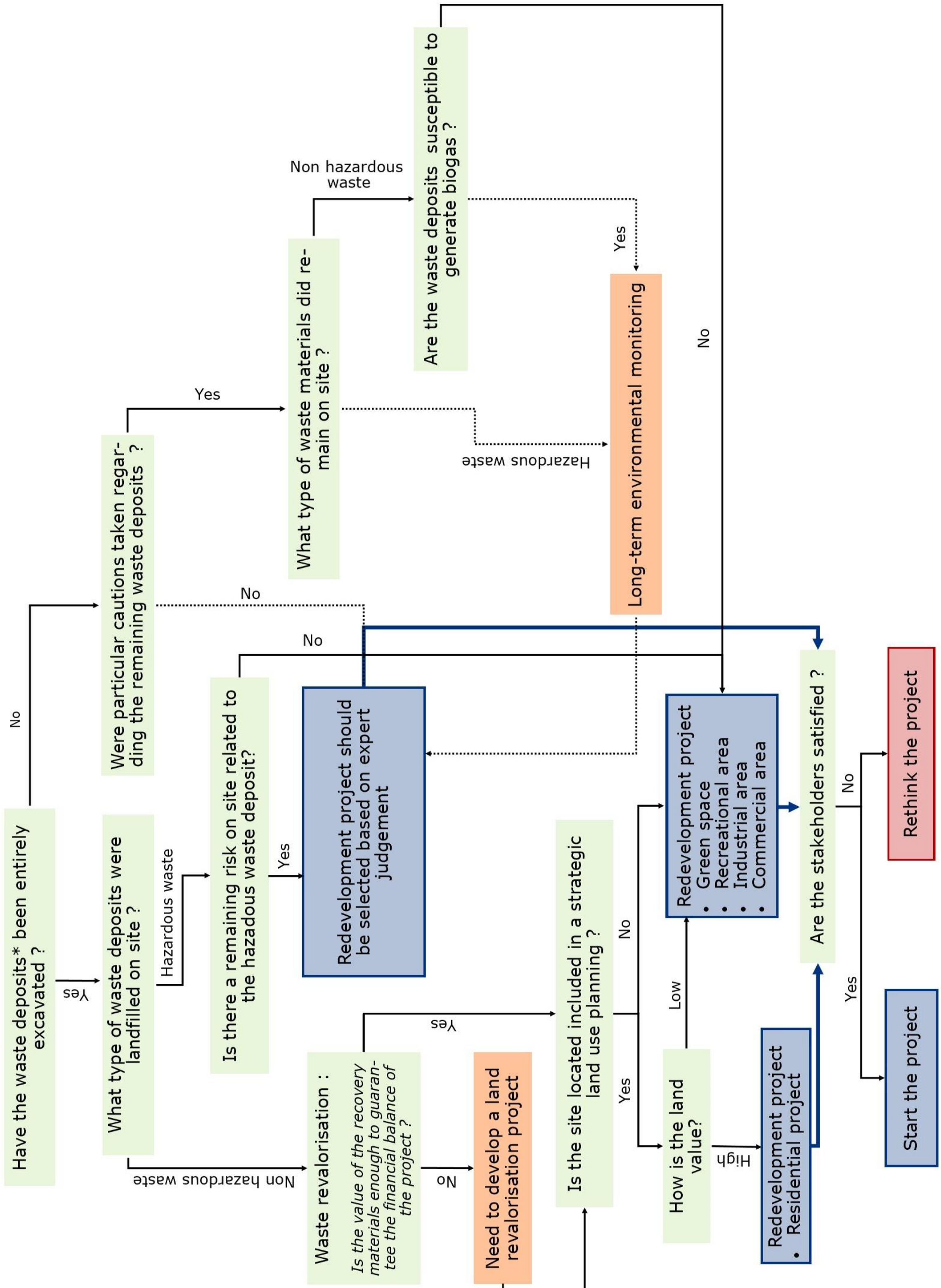

*Figure 10-1 Flowchart to decide the future redevelopment project. * Except for inert waste which can remain on site with adapted protective measurements and without affecting the type of redevelopment project. The dashed lines represent the situations that are better to avoid when possible.*

10.3 Waste management

Non-recyclable waste evacuation is often expensive and can negatively affect the economic viability of the landfill mining project. A solution to ensure a better financial outcome for the project is to re-landfill low or no value waste deposits on site. Note that in most of the northwestern European countries, relandfilling on site is strictly forbidden, or requires specific permits or additional taxation.
The authorization to relandfill on site varies depending on the European Country. For example, in Wallonia (Belgium) or Germany, permits can be delivered to relandfill, but the operator/investor are held to strict criteria. Once the authorization to relandfill is obtained, two options exist for the waste deposits remaining on site after the landfill mining operations: (1) reuse on site (as backfilling) or (2) waste containment.
Several parameters such as the type of waste deposits and the type of redevelopment should be considered to determine the most suitable option for the site rehabilitation. The most important parameter to assess is the hazard level of the waste deposits. Non-recyclable/reusable hazardous deposits (e.g. toxic, harmful, highly flammable, radioactive, etc. - e.g. hospital waste, military waste or industrial waste) cannot be used on site as upper backfilling above an impervious layer. Their relocation to dedicated facilities would generate prohibitive costs prevent the project being profitable. Hazardous waste containment is more expensive and require more stringent permits.

10.3.1 Waste deposits as backfilling

The decision to reuse waste on site should be decided before the beginning of the landfill mining operations as the different waste streams need to be evaluated, planned and managed in order to maximize the reuse of low-value materials on site. The reuse of non-hazardous and non-valuable waste deposits to fill the void space created during the landfill mining operation is a good way to reduce the cost of the landfill mining project. Waste deposits that fulfill a series of strict geochemical and geotechnical criteria can be used on site for the site rehabilitation (**Table 10-1**).

Table 10-1 Examples of waste requirements to fulfill to reuse waste on site.

Waste requirements to be reused on site	
1. Physico-chemical stabilization of the waste	• The waste cannot produce ecotoxic leachates. • No combustion or potential physical and chemical reactions with other waste products are allowed. • The waste is inert • The waste material should not contain a significant organic content and sulfate concentration.
2. Geotechnical requirements	• The compaction, consolidation and long-term stability of the waste pile should be carefully studied. • Requirements/criteria vary depending on each NWE region.

Waste deposits containing organic matter such as wood, non-degraded municipal solid waste, textiles, among others should be avoided for backfilling as they are susceptible to generate biogas during their degradation process. Moreover, their geotechnical properties will often be poor.
Plastic and construction waste that were preliminary crushed into small aggregate may also be reused on site after demonstrating their inert behavior. Laboratory measurements such as leachate tests are mandatory in order to establish that leachate and air emissions do not exceed the safety standards as defined by the authorities. Geotechnical properties of backfilling material should be carefully studied in long term, real-case conditions. Even if the leachate produced by the waste backfilling is not ecotoxic, it must be collected and treated depending on the type of pollution (e.g. specific chemical/physical treatment, oil separator, -aerated- lagoon systems, …) before being rejected into the environment.

10.3.2 Waste containment on site

The second option is to confine non-hazardous, non-valuable waste on site in a dedicated and limited area. It is important to mention that local authorities and residents are often opposed to on-site remaining waste even if it has been proven that the waste deposits are harmless to human health and environment. Due to financial constraints and to ensure the economic viability of the project, the non-hazardous, non-valuable waste can be contained on site.
In case of future technological development, the value of the current non-recycled, non-valuable waste may increase so that the option of a new phase of landfill mining could be considered. A good practice is to aim for minimizing the area of the site occupied by waste deposits, to sort the waste materials per type and to store them in different cells. The location of the cells as well as their lateral and vertical extension should be mapped and documented to facilitate possible future excavation. This solution – containing waste deposits on site – raises the question of the legal status of the site: "Is the rehabilitated site still, or partially, considered as a landfill due to the waste on site?". To perform this on-site option, permits should be delivered by the competent authorities. It must be stressed that the aim of the landfill mining operations is to provide a sustainable solution for, in most of the cases, old landfill management. Therefore, aftercare conditions should be optimized on site where possible.

10.4 Reshaping the topography of the site

As mentioned above, it is crucial to involve residents and local/regional authorities in each step of the rehabilitation process. The reshaping of the site topography should be decided in consultation with the residents. The decision to reshape the site after the landfill mining operations depends on several factors:

- the natural topography and the anthropogenic landform related to the former landfill;
- the financial balance of the project;
- the (potential) future redevelopment;
- the presence of valuable ecosystem/biodiversity (e.g. Natura 2000 area);
- Impacts on water management, both up- and downstream of the basin.

The reshaping of the site is not mandatory (except for water management purpose requiring at least 1 or 2% slope after settlement). However, in the case of former landfills preliminary occupying old quarries or pond lakes, leaving an open pit after the waste excavation can be potentially dangerous (e.g. accidents, stability of the steep slopes, mass movement, water erosion). Regarding the former landfill characterized by a landform rising above the surrounding area (e.g. mound, heap hill), it can be interesting to smooth the residual slope of the site in order to avoid potential mass movement and soil erosion triggered by surface water run-off. Moreover, depending on the type of landform related to the former landfill and the future use of the site, the flattening of the site surface might be beneficial.

3D geomorphological modeling is interesting as it provides valuable information on the topographical reconstruction of the site. It helps to restore the site architecture and contribute to the redevelopment of equilibrium slopes through the management and control of geomorphic dynamics. Reclamation should be planned and performed based on the geomorphic principles, and it necessitates local landform based topographic reconstruction, replacement of original surficial deposits and management of the long-term geomorphic processes (Martín-Duque *et al*., 2010).

Regarding the type of backfill material that can be used to reconstruct the site's topography, three solutions are identified:

- reuse of the soil-like materials on site;
- reuse of non-valuable, non-hazardous waste or inert construction waste collected in the vicinity;
- importation of ground/soil/material from another landfill site.

The soil-like materials obtained after sieving the excavated waste can be used as backfill material. If inert, crushed construction waste can also be reused on most sites. Once it has been prepared into suitable aggregates, it can be directly reused as backfill material if it fulfills the geotechnical requirements (e.g. bearing capacity, shearing properties) defined by the project's future development. Using excavated soil from other sites can be a good opportunity to generate financial incomes and to ensure the economic viability of the landfill mining project. Depending on the proximity with the surface water/groundwater source protection zone, extra caution should be taken to mitigate the risk of groundwater pollution. Regional legislation specifies what type of soil material can be deposited within the depression if the landfill is located within the surface water/groundwater protection area. In Wallonia, for instance, it is forbidden to import soil from another site in groundwater protection areas. However, exemptions can be obtained under certain conditions.

After backfilling and/or flattening of the site, it is recommended to cover the ground by a topsoil layer. The thickness of the topsoil layer varies depending on two factors: (1) the type of waste deposits contained in the former landfill; (2) the future activities on site Generally, a thickness of one meter of topsoil suffices to protect the ecosystem and human health. The final artificial landform should meet geotechnical requirements to ensure the long-term stability and to prevent potential natural hazards affecting the area such as floods, storms, erosion and earthquakes.

Additionally, the final landform should be revegetated to restore biodiversity. Compensation measures can also be implemented to promote the establishment of new ecological systems (for more information see **section 10.6**).

10.5 Environmental monitoring

This provides guidelines regarding the environmental monitoring of landfill sites after ELFM operations. In accordance with the local authorities and the regional legislation in force, the duration mentioned in this section might be adapted. Environmental monitoring is essential for the protection of human health, water reservoirs, soil and ecosystems. The monitoring strategy is based on the content of the former landfill and the presence of residual waste on site (reuse as backfilling material or waste containment). Even if all the waste deposits have been evacuated, short-term monitoring is recommended to assure the absence of residual risks on the potential receptors.

Environmental monitoring consists of monitoring and analyzing surface and groundwater. Water monitoring involves: (1) a good understanding of the local hydrogeology; and (2) monitoring pollutant concentrations following landfill mining operations. If the pollutant concentrations still exceed the standards and are not prone to natural attenuation, the implementation of a temporary water treatment station may be required.
Groundwater monitoring requires a minimum of three piezometers implemented down-, (1) and upstream (2); chemical analysis should be performed at least twice a year for contaminants such as heavy metals, hydrocarbons, chlorides, nitrates, sulfates, etc. If required according to the nature of remaining waste, air quality must also be monitored at suitable intervals using ambient air samplers. Residual biogas emissions can occur after the landfill mining operation of non-mineralized household waste. If necessary, biogas monitoring equipment can be installed on site, especially if the site is designed to be rehabilitated for residential purposes. Soil analyses should be performed after the site rehabilitation to guarantee that the soil is not contaminated by a remnant pollution.

- *No waste deposit remains on site*

Water, soil and air monitoring should be performed at the end of the rehabilitation to validate the environmental safety of the site and to start the implementation of a redevelopment project on site. If the environmental analysis shows the presence of pollution, a short-term environmental monitoring should be done (*see the section below*).

- *Recovered materials from the landfill reused as backfilling material or waste containment*

Water, soil and air monitoring should be performed on site for a sufficient timespan. The duration of the environmental monitoring is site specific and should be based on the environmental risk assessment. Regional legislation can sometimes dictate the duration of the environmental monitoring. In general, after a monitoring of several consecutive years[31] without safety issues, the site is no longer considered as a threat to the environment and the implementation of the redevelopment project can start.

[31] Defined at the begining of the ELFM project in consultation with the regional authorities.

If pollutant concentrations in the air, soil or water are still above the safety standards at the end of the environmental monitoring period, the duration of the monitoring should be extended. Several consecutive years without incidents[32] (i.e. no exceeding of the safety standards) is necessary to demonstrate the safety of the site and to start the redevelopment project on site. The monitoring of the site can be terminated earlier with the agreement of the competent authorities.

The costs related to the long-term environmental monitoring can be potentially important (higher than 10.000 €/year) and therefore, it should be taken into account in the decision of containing waste materials or reuse waste as backfilling material on site.

At the end of the environmental monitoring, an assessment of the residual risks is necessary to confirm the compatibility of the site with its future use.

10.6 Specific situation: Site located in a Natura 2000 area/ Protected area

If the former landfill site is located in a protected area or at its border, additional remediation measures may be required. In this section, the case of landfill sites located entirely or partially in a Natura 2000 area/protected areas is discussed. These protective measures could also be applied to the landfill sites where endangered or threatened species have been identified.

Old landfills are often revegetated and therefore frequently shelter rare/endangered species. The natural reforestation of sites allows the rare and threatened species to use the old landfill for breeding and resting purpose. That is why, some old landfills have been integrated in the Natura 2000 network (in Wallonia, 17 % of the old landfill sites are entirely or partially included in the Natura 2000 network). Mining the landfills located in the Natura 2000 area is possible but it requires some preventative actions throughout the landfill mining operations and rehabilitation work as well as compensation measures. Similar preventative actions could be applied to the landfill sites located at the border of a Natura 2000 area. In such cases, discussions with regional authorities are necessary in order to define the protective measurements to take during the site rehabilitation. The Natura 2000 network is compatible with human activities as soon as the sites are being managed in a sustainable manner (European Commission – Environment, 2020).

The presence of landfill can sometimes create suitable conditions for the development of a new ecosystem. The geochemical content of the site can be modified by the presence of waste deposits allowing the thriving of specific fauna and flora. For instance, the presence of metalliferous grasslands is linked to the soil enrichment in heavy metals related to the industrial aerial pollution deposits and/or the industrial waste deposits. The calcareous grasslands are growing on lime deposits are also a good example of rare ecosystems developing on landfills.

[32] Defined by the regional legislation.

Even if the excavation and the reshaping operation disturbs the fauna and the flora present on site, the rehabilitation of the site will improve their long-term living conditions by removing the waste pollution and recreating natural habitat[33], comparing to the previous existing situation. In the case of modification of the soil's geochemical content by waste deposits, soils having similar geochemical content can be added to artificially restore the natural conditions for the development of specific fauna and flora. Overall, an improvement of the initial situation should be demonstrated to get the authorization from the competent authorities to start the landfill mining project in a Natura 2000 area.

Restoration or recreation of natural habitats should be planned and include in the reshaping of the site (*see* **section 10.4**).
In order to protect the flora, it is recommended to collect seeds and saplings before the beginning of the landfill investigation and sow them on site during the rehabilitation work to restore the pre-existent ecosystem. Landfill mining operations and site rehabilitation are also a good way to eradicate invasive plants such as the Japanese knotweed and the giant hogweed. All these actions and initiatives aiming the promotion of wildlife and biodiversity are an added value to the landfill mining project.

10.7 Conclusions

Site rehabilitation is regulated by regional legal framework and differs regionally in Northwest European regions. Site rehabilitation should be planned before starting a landfill mining operation and residents should ideally be involved in each step of the rehabilitation process and site redesign. In order to minimize the cost and ensure an economic balance of the project, non-valuable, non-hazardous waste materials can be either directly reused on site or can be contained on site. When waste deposits remain present on site, environmental monitoring (air, soil, water) may be required to ensure the long-term safety of the site and allow the implementation of redevelopment project. The success of the landfill mining redevelopment project can be measured based on environmental remediation, civil infrastructure renewal, economic development and neighborhood revitalization.

10.8 References

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11 Stakeholder involvement

11.1 Introduction

The success of landfill mining projects is dependent on numerous aspects, ranging from economic viability, environmental/ecological impacts, to stakeholder engagement.
Identifying the different stakeholders and their needs is a necessary step in any project, but particularly important to enable a sensible Enhanced Landfill Mining (ELFM) implementation due to the impact stakeholders can have on the execution of a ELFM project. Some of the major stakeholders involved in ELFM projects include landfill owners, governmental institutions, technology providers, local communities as well as energy and production companies. The stimulating or hindering influence of a stakeholder is mostly determined by how their needs are addressed. These needs are the expectations and requirements the stakeholder has towards the project's implementation. This chapter highlights how to identify, plan and manage stakeholders and their project specific needs. At the end of the chapter, two case studies are presented to illustrate the stakeholder engagement in ELFM projects and different approaches in stakeholder engagement.

11.2 Identify stakeholders

The first step of the process is to identify the stakeholders.
Initial identification can be based on the different parties (stakeholders) mentioned in project documents, such as (but not limited to) the project charter, contracts, permits, and legislation.

It is however important to consider which parties are indirectly affected by the project. Indirect stakeholders are not as straight forward to identify. While there is no standardized approach, the quadruple helix approach provides a good framework to consider indirect stakeholders spread across public institutions (at a local, regional, national and European level), academia (universities, research organizations), private organizations (corporations, SMEs, enterprises, start-ups) and citizens of local communities who may be affected.

Landfill mining projects are particularly prone to being affected by stakeholders without direct involvement. Stakeholder must therefore be carefully considered, making sure all foreseeable parties are identified in due time. The aspect of mapping the relationships between project and stakeholders when using the quadruple helix method is therefore strongly recommended and will be further discussed under the development of a Stakeholder Management Plan.

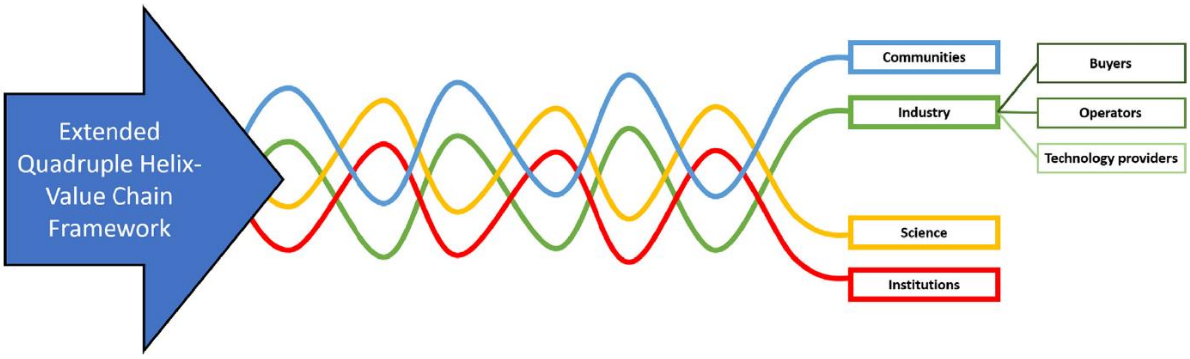

Figure 11-1 Schematic of the Quadruple Helix stakeholder identification approach (Einhäupl et al., 2019).

Whilst most intense at the start, stakeholder identification is a continuous process which should be periodically performed throughout the lifetime of the project. Unidentified stakeholders may appear at later stages, existing stakeholders may become irrelevant, and both power and interest may vary over time.

11.3 Stakeholder Management Plan

In order to manage the ELFM project, it is important to understand the dynamics of the involved stakeholders. With the stakeholders identified, a strategy should be developed on how to manage each individual stakeholder. To define which method of management is most suited for a particular stakeholder, it is imperative that their needs and expectations of the project are fully understood. Consequently, it is considered prudent to engage with the identified stakeholders at the earliest moment possible to ascertain their motives (Ackerman *et al*., 2011).
Generally speaking, the initial contact with a stakeholder is aimed at discovering or validating their expectations, their interest, their influence and their needs from the project.

Due to the specific nature of landfill (mining) projects, there are potentially important items to raise during first contact. Einhäupl *et al.* (2019) generated a questionnaire during their work on eliciting stakeholder needs within ELFM projects. Whilst not exhaustive, the questionnaire (see in **Appendix C**) at the end of the Landfill miner guide) is a good foundation to guide the initial contact with a new stakeholder.

Having gathered information on the identified stakeholders, a stakeholder register is strongly recommended to keep track of this information.

A stakeholder register can be as simple as a table containing (at minimum) basic information such as:

- Name
- Relation to the project
- Expectations from the project
- Level of interest

- Level of influence/power

Free templates are easily found online. Useful links are provided at the end of the chapter. When affiliated with a project management organisation, be sure to check the tools offered to their members online.

The name, relation and expectations are information to be collected and verified in discussion with the stakeholders. Their level of interest and influence are subjective ratings. Commonly these two indicators are judged on a scale of 5, with 1 being low and 5 being high.

With a completed stakeholder register, a strategy can be defined and refined for effective management (Eskerod & Jepsen, 2009). A basis to select management approaches to different stakeholders is taking their influence and interest to the project as defining attributes. To visualize this, stakeholders may be plotted on a simple two-dimensional orthogonal grid (**Figure 11-2**).

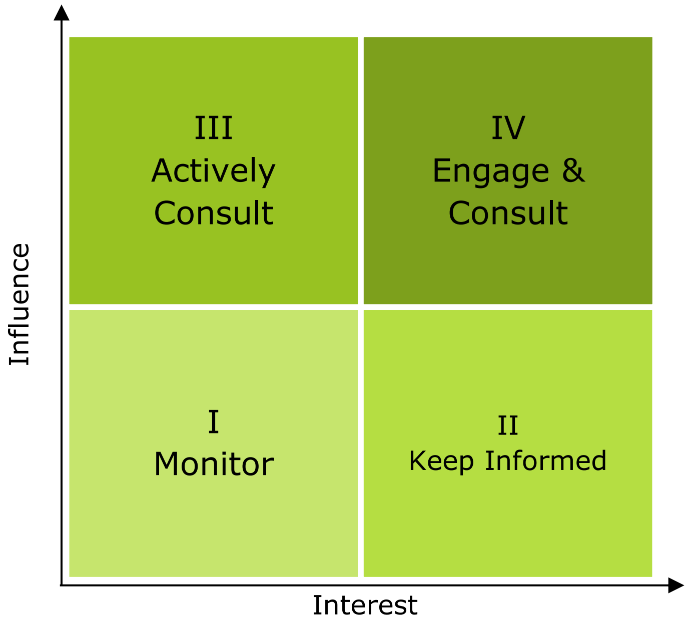

Figure 11-2 Influence/interest matrix.

This leads to the formation of four quadrants, which can be used to define suitable four management strategies (Project Management Institute, 2017).

The first group, consisting of parties with both little interest and little say in the project, are subject to a "monitoring" approach. Those falling into this category should be reassessed periodically to check if they have not migrated into one of the other categories. They require no further special attention beyond this.

The second group contains those parties with little or no influence on the project's progress or results, but who carry a high level of interest. As a result, this group of stakeholders should be involved when exchanging information. Ideally, the group can become a contributing factor by providing a two-way stream of information and insights. If so, their positive influence could grow. Reassessment of this group happens more naturally than the first group.

Stakeholders with significant influence on the project's results and/or progress, but with little interest in the project, are part of the third group. Due to their influence, these stakeholders should be consulted throughout the lifecycle of the project. Their influence can create powerful solutions, or obstacles, along the way. Their low level of interest, however, implies that the project management team has to take the initiative. This category is difficult to manage as their "absence" makes them more likely to be accidentally omitted at crucial times by the project management team. Care should be taken to actively involve them in an unobtrusive manner.

The final group of stakeholders have both great influence and interest in the project's progression. Their interest makes them easy to include throughout the project. While engagement is easier to acquire with this group, it is still a worthwhile effort to show initiative in order to foster a good relationship. Similar to the third group, their influence should be properly harnessed and considered as either a significant asset or liability to the project.

The project's communication plan should be updated in order for communication channels, frequency and messaging to be adjusted to the individual stakeholders and their associated management strategy.

11.4 Manage and control stakeholder engagement

The effective management of stakeholders is rooted in creating and fostering beneficial relationships. Having a tailored approach and an adjusted communication plan are vital tools in successful stakeholder management (Bosse *et al*., 2009). However, to truly engage with stakeholders and have them contribute constructively to the project, it is important to emphasize the social aspect in project management. A beneficial relationship will only be created over time, through repeated interaction, mutual thrust and understanding.

The communication plan lays the foundation for repeated interactions. While the word "repeated" is key, it should be emphasized that quality is significantly more important than frequency. Long discussions are often more fruitful in obtaining an understanding than a flurry of short interval interactions. And, specifically for the stakeholders with low interest in the project, an excessive frequency can be experienced as a hindrance, creating resistance. What is excessive and normal are, of course, entirely subjective and should be judged based on the initial interactions. Fine tuning should occur upon further interactions (Al-tabtabai *et al*., 2001).

As described in the planning section, the goal of the first interaction is to gauge the interest, influence and expectations from a stakeholder. The goal of the other encounters is to create a mutual understanding of each other's needs. If a particular stakeholder is a proponent of the project, then their expectations are commonly fairly well aligned with the project's goal. Where there is misalignment between the project's ambitions and their expectations is where potential opportunities for improved results can be found. If a stakeholder is

opposed to the project, a mutual understanding may alleviate their concerns, or be altogether convinced of the merits of the project.
Likewise, mutual understanding implies that a compromise between the original project goals and the prevailing expectations may have to be made.
The creation of a mutual understanding of each other's expectations requires empathy on both sides, and is therefore often the most difficult step in stakeholder management. The creation of thrust is a derivation of this understanding, compounded by a transparent communication intrinsic to all stakeholder management.
In the case of landfill mining projects, the alignment of expectations between project owners and the local population are often seen as being diametrically opposed. Despite this strong misalignment, case studies have proven that a converging of expectations can be reached by means of active engagement and suitable stakeholder management approaches.

11.5 Pro-active approach in the :metabolon project on Leppe landfill in Lindlar (Germany)

The Leppe landfill used to be a municipal solid waste landfill with a disposal area of 39 hectares and a waste volume of 9 million m^3. Due to the uncertainty of localized waste composition and the novelty of "Landfill Mining" as a concept, landfill mining was not considered as an option for this landfill. Since 2006, the :metabolon project converted the Leppe landfill into a modern waste management centre, focusing on innovation, research and education. It is accessible to the public, accompanied by a viewing platform on top of the landfill and a multitude of information options and recreational activities for junior as well as senior visitors. Guided tours are organized for the public, researchers, scholars, as well as other landfill owners. During these tours, different aspects of the project are highlighted, such as photovoltaic systems on landfills and the biowaste treatment technology. The :metabolon project evolves continuously, leading to many interdisciplinary co-operations between experts and research institutions. In this evolution, :metabolon aims to create innovation in waste and resource management and to educate the current and next generation on sustainable circular economy. It is a good example of interim use of the landfill when ELFM is not feasible.

Figure 11-3 View of the Leppe landfill (source: www.bavweb.de).

The project was funded by the European Regional Development Fund (ERDF) and by the German Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia (MULNV). Other stakeholders are Bergischer Abfallwirtschaftsverband (BAV), the municipalities of Lindlar and Engelskirchen, local authorities (OBK, RBK), the Technical University of Cologne (TH Köln) and local residents.

The :metabolon project was initiated by BAV in 2004 in conjunction with the legislative change of waste disposal and the ban of depositing untreated municipal solid waste. Many landfills were closed, prompting landfill operators to start thinking about other concepts to profit from a closed landfill. At the time, landfill mining was not an economically viable option in Germany, and at the time there was no real concept of interim use. With the initiation of project :metabolon, the possibilities on how to use a landfill accompanied by research and education had to be displayed to landfill owners, public authorities and private companies.

BAV is a German Waste Management Association involved in several national and international projects, among which RAWFILL and NEW-MINE. Both RAWFILL and NEW-MINE projects are related to landfills and landfill mining. BAV believes that there is a need for interdisciplinary collaboration and education in the field of circular economy. They concluded the core business of :metabolon should be (1) education and knowledge transfer, (2) economic development and value creation, (3) tourism and local recreation and will further evolve according to the initial idea of an open and transparent landfill.

A petition for a referendum by local residents was expected in the planning phase of the :metabolon project. However, through early involvement and continuous effort via information sessions and workshops, the public opinion changed into a positive view on the project. Some of the initial opponents have even been converted to strong supporters of the project.

Since the :metabolon project is an interdisciplinary project, it was difficult to unite relevant stakeholders with different views, opinions and backgrounds. It was consequently difficult to align their ideas and actions. Since interim use was a new concept for policy makers, a lot of effort was needed to inform stakeholders, especially on the political level.

BAV pro-actively started with ten different project proposals which were judged by all stakeholders. Through close engagement and consulting, they were able to streamline all stakeholder needs into the current realisation of :metabolon.
Since the beginning of :metabolon, BAV and TH Köln meet regularly to coordinate the actions and work packages of this multidisciplinary project. When there are global adaptations to the overall project, BAV takes the initiative to organise a meeting with all stakeholders.

With more than 50,000 visitors and 5,000 visiting students per year, it demonstrates the wide acceptance of the public for the project :metabolon on the Leppe landfill.

11.6 The Locals: How a group of residents united as an engaged stakeholder in the Remo project in Houthalen-Helchteren

Group Machiels initiated plans for a landfill mining project for the Remo landfill, called Closing the Circle. In this project, they aim to rehabilitate an operational landfill, in the municipality of Houthalen-Helchteren, using ELFM methodology. This means all landfill waste materials will be mined and treated for reuse as new raw materials, while non-reusable materials will be used for optimal energy production. At first, there was resistance from local residents. The resistance was rooted in part due to past experiences, lack of information and the fear for environmental nuisance or even damage.

In 2009, a number of local residents formed a dedicated group called "the Locals", at their own initiative, to participate as a stakeholder in the Closing the Circle project. Within the context of sustainability and advances in cleantech, they were open to the concept of landfill mining, provided that the necessary safety requirements are respected.

Figure 11-4 The Locals organizing meetings and supporting workshops (Source: the Locals).

The Locals realized that a large part of their concerns were based on a lack of information. To combat this, the group informed themselves by organizing regular meetings with knowledge institutes, universities, industry experts and technicians of Group Machiels. These meetings were organized in view of gathering independent information and performing research on new developments in enhanced landfill mining and the feasibility. The Locals follow local and international developments, for example by joining RAWFILL, NEW-MINE, COCOON meetings and symposia on Enhanced Landfill Mining. Their intention is to share all knowledge they have gathered with other local organizations and local citizens. The Locals is a good example of a citizen science project that can be replicated in other projects to create social acceptance.

They were also in close contact with Group Machiels to discuss the plans, the progress and complications of the project. This provision of early and first-hand information to the Locals, allows participating members to seek out expert advice to form correct judgement, and prevents misinterpretations from second-hand sources (i.e. news articles, hear-say, …). Meetings held between the Locals and Group Machiels were arranged at the initiative of the Locals. Everyone is allowed to attend these meetings, a measure taken to reduce the threshold for other citizens willing to participate and get informed. However, an ethics code is imposed to those attending to prevent dispersion of (mis)information to media.

There is a close collaboration between the Locals and Group Machiels. As a direct result of their involvement, the Locals have pressed for the implementation of testable metrics to be used for both a monitoring and an early warning system. The early warning system is there to notify the responsible team as early as possible (preferably before they experience any effects) so accurate action can be taken. The warning system consists of several sensors and a monitoring system allowing to detect gas emissions. These sensors are used to have concrete data on emissions from the landfill. They not only warn nearby residents of landfill gases but can also prove some smells do not originate from the landfill. The system is already installed, before the project starts. These first measurements will serve as a reference point for the mining project, as well as identifying current emissions from closed parts of the landfill. Further, the system will remain active throughout the entire landfill mining project, with the collected information to be freely available. Due to the complexity of environmental and climatological conditions, the monitoring system serves to confirm that the source of any perceived nuisance indeed originates from the mined landfill.

In summary, stakeholders involved in this project are ”the Locals”, the city councils of Houthalen-Helchteren, several independent knowledge institutes and Group Machiels. These stakeholders meet on a regular basis, with a frequency dependent on current developments.

11.7 Conclusions

Stakeholder management is based on a systematic approach of identifying, managing, controlling and communicating with different parties who may affect or be affected by a project. Despite the presence of many blueprints on how to conduct stakeholder management, it is at its root a social endeavour and thus will require tailoring to the unique situations faced by an individual project.
Fundamental tenets can be summarized as:

1. Think broadly when identifying your stakeholders ;
2. Initiate contact at the earliest opportunity ;
3. Understand the concerns or expectations of each stakeholder ;
4. Maintain the stakeholder management plan as a living document. Update regularly and when the project enters a new phase.

11.8 Useful Links

Stakeholder register templates:
Free: https://www.smartsheet.com/free-stakeholder-analysis-templates
Paid: https://pm-templates.com/npm13.12-stakeholders-register.html

11.9 References

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Bosse, D.A., Phillips, R.A., Harrison, J.S. (2009). Stakeholders, Reciprocity, and Firm Performance. *Strategic Management Journal,* 30 (4), pp. 447–456.

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12 Inspiring examples of landfill mining project

This chapter is dedicated to successful landfill mining projects across Europe. In total, six landfill mining projects are presented. The drivers of each landfill mining project are unique to its circumstances: waste material recovery, environmental disaster, land redevelopment, scientific study. The aim of the chapter is to provide the reader examples of what can be achieved in a landfill mining project. Please note that some of the landfill mining projects presented here are still ongoing at the moment of writing.

12.1 Case study: The landfill of Onoz (Wallonia)

12.1.1 Description of the site

The landfill site (50°29’23’’ N, 4°40’12’’ E) is located in Onoz, province of Namur, Walloon Region, Belgium. The landfill of Onoz has a surface area of 58,000 m^2. Based on its topography, the landfill is divided into two separate areas: a lower western part and an upper eastern part, separated by a steep slope (**Figure 12-1**). The landfill of Onoz has been revegetated, providing an important ecological added-value to the site. On the top of the landfill is a calcareous grassland with its related fauna and flora growth. The rock walls surrounding the site constitute a natural habitat for rare and threatened species such as Eagle owls. European badgers are also present on site, living in burrows on the steep slopes created by waste deposits.

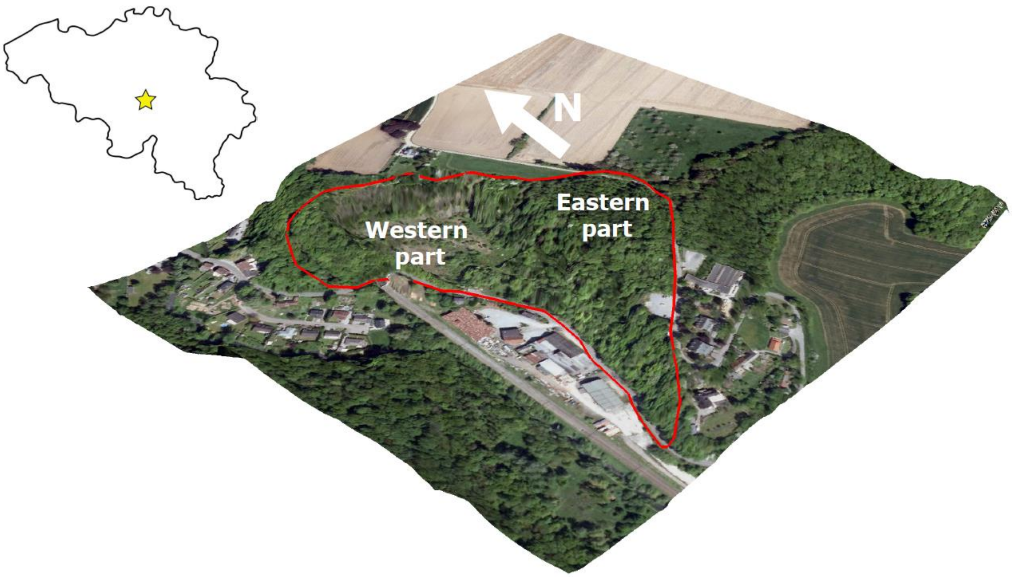

Figure 12-1 Location of the landfill site and its topography.

The geology of the site consists of massive carboniferous limestone and dolomite, intercalated with argillaceous limestone belonging to the Onoz Formation (Delcambre & Pinot, 2003). In the area, a large aquifer in the carboniferous limestone is present and is exploited by a public water company. The landfill site is located in an extended groundwater source protection zone as a pumping station is situated at approximatively 500 m downstream from the site. In the lower part of the site, the groundwater table is located around four meters below the subsurface and is in contact with the waste deposits.

From an administrative point of view (i.e. Walloon sector plan), most of the site (65% of the site) is located in green space and belongs to the Natura 2000 area network. The western border of the site is allocated for mixed economic activities. In this area, two lime kilns from the beginning of the twentieth century are still present. These structures are testimonies to the industrial past of the area.

12.1.2 History of the site

The site is a former limestone quarry and lime oven. The excavation of limestone and its related activities started in 1902 and ended in 1966. From 1967 to 1976, the quarry was used as landfill where industrial waste (lime and fly ash) were illegally dumped, filling the pit. The satellite images of the period showed that large quantities of fly ash were deposited on the upper part of the site. During the eighties, heterogeneous waste materials such as household, inert, tires, plastics were illegally deposited on the lower part of the site. Based on historical documents, the total volume of the landfill was estimated around 185,000 m^3. Since 1995, the site is studied and monitored by SPAQuE. In 2004, SPAQuE removed 750 tonnes of tire deposits that were present at the surface. Except for some occasional wild dumping, there is no more landfill activities on site.

12.1.3 Drivers for the landfill mining project

Land value/pressure is relatively low and therefore, cannot guarantee the financial balance of the project. The main driver to start this landfill mining project is the recovery of resources. The large quantities of fly ash and slaked lime will be revalorized (*see section 12.1.7*). The reshaping of the site after the landfill mining operations will ensure additional revenues as the project initiator works in the construction sector and need to find an outlet for excavated soils.

12.1.4 Stakeholder involvement

In order to launch the first landfill mining project, a Green Deal, based on the model developed in the Netherlands was signed between the Walloon region, the owner of the site (Immobilière Jean Nonet), SPAQuE and the municipality of Jemeppe Sur Sambre (the municipality where the landfill is located). A group was created to work on the implementation of the landfill mining project of Onoz site and to adapt the legal framework of landfill mining in Wallonia. The working group, which meets every month, gathered the signatories of the Green Deal. By signing the Green Deal, the Walloon region commits (1) to identifying the potential adjustments in the legislation to reuse materials recovered from the landfill; (2) to follow the landfill mining projects from a legislative point of view and provide, if and where needed, legislative adjustments; and (3) to disseminate the concept of landfill mining in Wallonia. The Immobiliere Jean Nonet engages (1) to make the site available for the landfill mining project; (2) to provide financial and technical support to the project; and, (3) to decontaminate the site according to the current legislation and rehabilitate the site at the end of the project. SPAQuE coordinates the project on technical and scientific aspects and provides administrative and legal support for the feasibility study, landfill mining operations, waste revalorization and site rehabilitation. Geophysical investigations and waste sampling were performed by the RAWFILL project partners. The municipality of Jemeppe Sur Sambre provides a local support. Meetings with the local residents were organized to present the project and to answer their questions. In addition, the project initiator went door-to-door to meet the local residents, to explain the landfill mining concept and to present the landfill mining project of Onoz site.

12.1.5 Characterization of the landfill content

A multi-geophysical approach was applied to the landfill of Onoz with the aim of obtaining a three-dimensional representation of the waste body and reduce the ambiguities inherent to each individual method. A series of geophysical investigations, involving electromagnetic induction (EMI), electrical resistivity tomography (ERT), induced polarization (IP), magnetometry (MAG) and different seismic methods (multi-channel analysis of surface waves, seismic refraction tomography, HVSRN – horizontal to vertical spectral ratio of noise) were conducted by the RAWFILL partners – the University of Liège and the British Geological Survey - during fieldwork campaigns in 2018 and 2019 (**Figure 12-2 & Figure 12-3**).

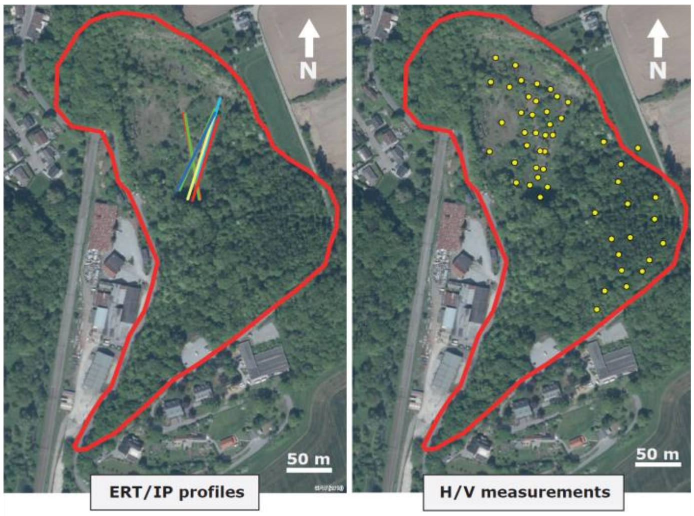

Figure 12-2 Geophysical surveys on Onoz site performed by the University of Liège and the British Geological Survey. Left: ERT/IP profiles. Right: Spatial distribution of the HVSRN measurements.

Geophysical mapping tools (EMI and MAG) were used to provide information about the lateral extent of the anthropogenic deposits and identify different waste facies. Once completed, profiling methods (ERT/IP and seismic methods) were applied to zones of interest revealed by mapping to obtain further vertical information about the waste extent and composition. Seismic methods were mainly used to study the geometry of the landfill and its internal structure. Electrical resistivity tomography and induced polarization were used to indicate the bedrock condition and the type of waste deposits.
After data analysis, a sampling plan was proposed with the aim to provide ground truth data to validate the interpretation made and reduce uncertainties. The sampling phase consisted of five boreholes and nine trenches (see **Figure 12-3**). Borehole and trench data generally agreed well with the geophysical interpretation. Samples collected revealed soil contamination in both parts of the landfill. The contaminants found in the waste include heavy metals, mineral oils, PAHs, VOCs and PCB. In the slaked lime layer, heavy metals (Aluminum and Mercury), PAHs, BTEX, VOCs, mineral oils and other chlorinated

compounds were found. In the fly ash layer, Aluminum, mineral oils, PAHs and VOCs contamination were detected.

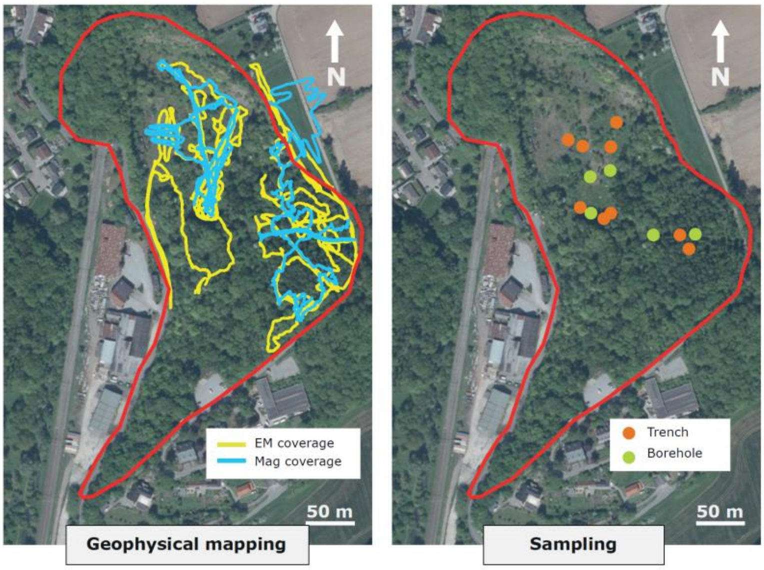

Figure 12-3 Investigations on Onoz site. Left: Geophysical mapping performed by the University of Liège and the British Geological Survey (EMI = Electromagnetic Induction; Mag = Magnetometry). Right: Spatial distribution of the waste samples (trenches and boreholes).

In the upper eastern part of the landfill, the geophysical mapping, and particularly the EMI results clearly delineated the lateral extension of the slaked lime and fly ash deposits which were characterized by very high electrical conductivity (> 40 mS/m) and very low electrical resistivity (<25 Ω.m) respectively. The distribution of the fly ash and slaked lime is very well constrained due to high contrast with the surrounding limestone bedrock characterized by much higher electrical resistivity. Unfortunately, the configuration of the site and the dense vegetation in the upper part of the landfill did not allow the deployment of geophysical methods to estimate the thickness of these deposits. The latter was determined afterwards by drilling boreholes, revealing up to 25 m of fly ash and slaked lime in place. The volumes of fly ash and slaked lime are estimated at approximatively 160,000 m^3 and 48,000 m^3, respectively (Caterina *et al*., 2019).

In the lower part of the landfill, ERT/IP results allowed the detection of the slaked lime and the fly ash deposits below a layer of ~3 to 6 m of heterogeneous waste deposits (industrial waste, wastes from the construction sector, car parts, rubber, among others) representing a volume of approximately 3,400 m^3. They also allowed the detection of the bedrock, even though in the lower southern part of the landfill, uncertainties remain concerning its depth due to the heterogeneous waste infill and inherent loss of resolution of the methods with depth (Caterina *et al*., 2019).

12.1.6 Description of the landfill mining operations

At the time of writing this chapter, the landfill mining operations have not yet started. The authorization for starting the landfill mining project is expected to be delivered by the beginning of 2021. Therefore, we will here explain the different phases of the landfill mining operations from a theoretical point of view (IRCO, pers. comm.).

The slaked lime and fly ash deposits will be entirely excavated. Regarding the heterogeneous waste deposits, the hazardous waste will be excavated and treated off site in dedicated facilities. All the waste deposits that can be recycled and reintegrated in the circular economy will be excavated and transported to dedicated facilities. Only the non-hazardous and non-recyclable waste will remain on site.

The duration of the excavation is estimated between two and five years depending on the quantity of fly ash that can be revalorized each year. After the waste excavation, one meter of arable soil will be deposited on the top of the bedrock and a thick layer of clay will then add on the top of the arable soil to guarantee the water balance of the site. Additionally, it will ensure the protection of the bedrock and its groundwater table. A storm basin will be created to collect the meteoric water from the site.

During the landfill mining operations and the reshaping of the site, environmental measures will be taken to protect the valuable biodiversity of the site. For instance, the forest clearing will be avoided during the nesting period of the Eagle owls. Additionally, the rock walls occupied by the Eagle owls will not be affected by the landfill mining operations. Natural habitats will be recreated on site, in a part of the site that will be untouched by waste excavations. For example, burrows in the sand hills will be recreated for the European badgers (IRCO, pers. comm.).

12.1.7 Waste revalorization

The most valuable secondary resource recovered from the landfill of Onoz will be the slaked lime and the fly ash. The geochemical analysis performed on slaked lime showed that the properties of the slaked lime were not altered by its landfilling. Therefore, the non-contaminated slaked lime will be directly reused without pretreatment or, if necessary, transformed into quicklime. The slaked lime will be used for mortar, plaster, and cement in buildings and other structures. The slaked lime will also be used for soil stabilization to make the soil suitable for load-bearing applications such as road construction. The quicklime will be used in iron and steel manufacturing. Concerning the large volume of fly ash, a part of the waste materials will be used in biomass combustion plants where fly ash is used to clean the filters. The rest will be recycled in the cement production as well as in structural fills and embankments.

12.1.8 Site rehabilitation

The local residents were concerned that the landscape might be affected by the landfill mining operations. After discussion with the local authorities, it was decided that the topography of the site will be recreated as initially using soils from other construction sites. The reshaping operations are expected to be done in a timespan of five years maximum. The site rehabilitation is also an opportunity to manage invasive species on site, such as the Japanese knotweed. On the upper part of the site, a natural forest, comprising of native species such as nerprun, crab-apple tree, fusain will be planted (IRCO, pers. comm.). There are currently no redevelopment projects on the western border of the site dedicated to mixed economic purpose. The two lime kilns will be preserved as they represent the industrial past of the region and of the site. The area legally designated as green space will be used as meadows for horses, and will protect local threatened species (Eagle owls, badgers).

12.1.9 Final results and landfill mining benefits

The final results of the landfill mining project are expected in ten years. Therefore, it is difficult to estimate the final outcome of the project and the long-term effects of the landfill mining of the Onoz site. Overall, we can expect that the removing of the waste will be beneficial for the site, the environment and the people living nearby.

12.1.10 Laws and regulations applied

As mentioned earlier, there is no legal framework for landfill mining in Wallonia. To implement the project from a legislative point of view, the Walloon region would provide authorization to start the landfill mining project in 2021 based on the current waste legislation and the soil-contaminated legislation. Special exemptions would also be delivered as the site is subject to a series of complex regulations due to its location in an extended groundwater source protection zone and its high biological interest (Natura 2000 area).

12.1.11 Budget

The owner does not want to communicate the projected cost of the landfill mining project and its potential economic benefit. They communicated that the recovery of resources will not be sufficient to guarantee the viability of the project. However, the financial balance of the project is ensured by the reshaping of the site, which serves as an outlet for the soil excavated from other construction sites.

12.1.12 Conclusion

The landfill mining of Onoz will be the first mining project in Wallonia. By signing the Green Deal, the Walloon region clears the way to the landfill mining in Wallonia. In total, more than 210,000 m^3 of industrial waste will be recovered and reused. The expected duration of the project is at least ten years.

12.1.13 References:

Caterina, D., Manrique I. I., Inauen, C., Watlet, A., Dashwood, B., De Rijdt, R., Dumont, G., Chambers, J., Nguyen, F. (2019). Contribution of geophysical methods to the study of old landfills: a case study in Onoz (Belgium). 17th International waste management and landfill symposium, Sardinia, Italy.

Delcambre, B., Pinot, J.-L. (2003). Carte géologique 47/1-2 Fleurus-Spy, notice explicative. Service Public de Wallonie, DGARNE, Namur. 96 pp.

12.2 Case study : The Samaritaine Landfill (France) and coastal hazards

12.2.1 Description of the site

The site (48°56'22.8"N, 1°32'49.3"W) is an old landfill located in the haven of la Vanlée in Lingreville (Department of Manche, Normandy, France). The landfill site, called the Samaritaine, is situated in a sand dune complex and has a surface area of approximately 4,320 m^2. It belongs to the French Coastal Conservatory and is part of the Natura 2000 network. Due to its location in a coastal area, the landfill site is regularly flooded during storm events. Over the years coastal erosion has progressively eroded the edge of the landfill resulting in waste pollution in the estuary.
In addition to the environmental hazard related to the Samaritaine landfill, the presence of waste deposits along the shores provided a negative impact on the tourism, which is essential to the economic activities of the Normandy region.

12.2.2 History of the site

The site was exploited as a landfill for municipal solid waste from 1965 until the 80s. At the beginning of the 1990s, the waste deposits were covered by sand and topsoil as a protective measure. Additionally, the south-west edge of the landfill, which is directly affected by the tides, was protected by rip-rap. Since the beginning of the 2010s, limited quantities of waste materials were observed along the shore and carried away by the tides into the estuary. In November 2016, a heavy storm caused significant erosion of the landfill, exposing the majority of the waste deposits (**Figure 12-4**). This event strongly impacted the haven of la Vanlée.

Figure 12-4 Waste deposits along the Normandy coast. The edge of the Samaritaine landfill was eroded during a heavy storm in 2016 resulting of the pollution of the estuary (Credit photo: Ouest-France newspaper).

Following the storm, emergency works were realized in December 2016 to protect the estuary from the pollution generated by landfill waste materials. The emergency works consisted of the following actions:

1. Collecting the waste deposits which were no longer protected by the sand and topsoil cover. In total, 450 tonnes of waste materials were evacuated to non-hazardous waste landfills.
2. Protecting the south and south-east edges of the landfill, which were also affected by coastal erosion, using geomembrane and rip-rap (800 tonnes of rocks were deposited).

12.2.3 Drivers for the landfill mining project

In this case, the driver was the environment. The environmental disaster of November 2016 clearly accelerated the landfill mining operations and the site remediation. The landfill mining operations started in November 2017 and ended in March 2018.

12.2.4 Stakeholder involvement

EPF Normandy was responsible for the waste excavation, waste sorting and the landfill rehabilitation. The company BURGEAP Ginger coordinated as project manager. The company LTP Loisel was in charge of the waste excavation, waste sorting and the landfill rehabilitation. SAS Les Champs Jouault was in control of the treatment of waste materials and more specifically for the waste materials class II. The quarries LMC were responsible for the waste class III.
The stakeholders were represented by the French Coastal Conservatory and the Prefecture. They established the legal environmental constraints during the landfill mining operations. The company BURGEAP Ginger ensured compliance with the environmental regulation.

12.2.5 Characterization of the landfill content

Site investigations were realized in 2011, prior to the environmental emergency of 2016. The site investigations were performed by SERAPI and consisted of ten trenches of 3 to 4 m depth using mechanical shovel in order to estimate the thickness of the waste deposits. Waste deposits and the sandy matrix were analysed. The results of the investigations indicated that most of the waste deposits should be treated as class II waste. It revealed soil contamination by heavy metals and hydrocarbons. The presence of leachate was also identified in the groundwater.
In the framework of the RAWFILL Project, geophysical measurements were performed before the excavation operations by the University of Liège and the British Geological Survey in order to delimit the geometry of the landfill and quantify the landfill mining content.

12.2.6 Description of the landfill mining operations

The first step of the landfill mining operations was to remove the topsoil and the vegetation cover. The topsoil was directly reused on site to physically separate the site from the neighbouring plots and to create a platform for the screening machine.

As the soil and the soil-like materials (mostly sand) were relatively soft, the waste excavation was realized using mechanical shovels. The waste materials were then transferred to the sorting platform located at proximity (**Figure 12-5**). To be reused on site, sand materials were stored on site and their pollutant content were regularly analysed. Sand material below the threshold of pollutant concentration defined by BURGEAP were stored in a dedicated space to be reused on site during the remediation process. The geochemical analyses showed that the first layers of waste deposits that were excavated were less contaminated.

At the beginning of the landfill mining operations, the screening machine was working well due to the favourable weather conditions. Approximately 450 to 550 m^3 were screened each day. The waste excavation was delayed due to the waiting time for geochemical analyses of the landfill material and the limited storage platform. In the following weeks, the weather started to turn bad, reducing the performance of the screening equipment down to 100-150m^3 per day.

The sorting platform allowed to separate the waste materials into three fractions (>100 mm, between 6 and 100 mm, <6 mm). The fine fraction was directly deposited on site whereas the coarser grainsize fraction were collected in waterproof skips of 30 m^3. An overband magnet was installed to recover the metals. Woods and asbestos were collected separately. In total, two mechanical shovels were necessary to feed the sorting platform and to put the resulting fractions in the appropriate waterproof skips.

People were forbidden on site during the landfill mining operations. To protect the site, security fences were installed around the site. In order to detect potential trace of asbestos on workers, sampling on the working staff was regularly performed.

Figure 12-5 Landfill mining operations on la Samaritaine landfill. On the back, the sorting platform which is located next to the site. The asphalted area was used to store the fine fractions while waiting for the results of the geochemical analyses.

12.2.7 Waste revalorization

Due to the emergency of the waste excavation, only three types of waste material were revalorized:

- 10.5 tonnes of wood ;
- 87.2 tonnes of metals ;
- 7,200 tonnes of sand directly reused on site after demonstrating that the sand was not polluted.

The rest of the waste deposits (i.e. 13,757 tonnes) were relandfilled in Class II and Class III landfill facilities.

12.2.8 Rehabilitation of the site

The goal of the rehabilitation was to revegetate the sand dune complex (**Figure 12-6**). During the remediation works of the landfill, the sand fraction which was preliminary screened and tested was reused to reshape the site.

Figure 12-6 Site after the rehabilitation operations (Credit Photo: Géraldine Lebourgeois).

12.2.9 Final results and benefits of the landfill mining project

The benefit of the landfill mining operations is mainly environmental. The rehabilitation contributed to reducing the erosion of the site and eliminate the potential pollution of the Estuary by the landfill. The site was restored into a sand dune complex. There is currently no redevelopment project planned on the site. The site, which still belongs to the French Coastal Conservatory, is dedicated to a nature area**.**

12.2.10 Laws and regulations applied

The legal constrains were dictated by the Prefecture. The technical specifications of the *BURGEAP Ginger* company and its supervision were designed to correspond to prefecture regulations.

12.2.11 Budget

The budget of the project was estimated at around 1.5 million euros. The list of expenses is summarized in **Table 12-1**. The project was funded for 33% by the Normandy region, 29% by the EPFN (Public Financial Establishment of Normandy), 18% by the Seine maritime water agency, 16% by the coastal conservatory (site owner), 3.6% by the department of Manche and 0.4 % by the Community of Coutance Mer and Bocage municipalities.

Table 12-1 Detailed budget of the landfill mining project at La Samaritaine landfill (France).

Nature of the Expenses	**Costs (-)**	**Benefits (+)**
Waste treatment (Class II)	490,000 €	
Waste treatment (Class III)	130,000 €	
Waste transport	90,000 €	
Metal valorization		11 500 €
Waste excavation and screening	155,000 €	
Wood		315 €
Site remediation	30,000 €	
Asbestos (treatment)	1,000 €	
Waste analysis	30,000 €	
Taxes	410,000 €	
Staff costs and external control *(estimation)*	~200,000 €	
TOTAL	**- 1,344,185** €	

For more information about this project, you can directly contact SAS les Champs Jouault at champsjouault@gmail.com.

12.3 Case study : The Landfill of Bordes (France)

Christian Paille-Barrere (Conseil départemental des Pyrénées-Atlantiques)

12.3.1 Description of the site

The landfill site is located in the village of Bordes (43°13'45.7"N, 0°17'34.5"W) in the south of France, near the Pyrenees. It is the former landfill of the Bordes municipality, occupying a surface area of ~47,000 m². According to local resident testimonies, the site was only exploited on a surface area of ~30,000 m^2. The landfill was implemented on the right riverbank of the Gave[34] de Pau River. The geology of the consists of sand and pebbles. On the south-western part of the site, the riverbank of the Gave de Pau River is still visible. The site is delimited by agricultural parcels in the north and south-east. The site is currently occupied by wasteland with a wooded park.
Fauna-flora study revealed that there was no protected species on site, except the presence of dragonflies.

12.3.2 History of the site

Before the landfilling activities, the site was characterized by a depression in morphology. According to historical documents, the landfill was authorized by the DREAL and its exploitation began at the end of the 1960s. The depression was progressively filled with waste materials until 1995, when the site was closed. The waste materials were deposited in layers of 30 to 40 centimeters and covered by clayey soils originated from the surrounding areas. In total, between 80,000 and 100,000 m^3 of waste (mainly municipal solid waste, construction waste and industrial waste) were deposited. This estimation is based on the records.

12.3.3 Drivers for the landfill mining project

The main driver to start this landfill mining project was the obligation of the municipality to perform site remediation. In 2002, the DREAL ordered by formal notice the municipality to rehabilitate the landfill site. Moreover, the location of the site on the floodplain of the Gave de Pau River was also problematic. In the past, it was common to install landfills on floodplains due to the low value of the land. Therefore, many landfills across NW Europe are currently facing the same issues. Since 2012, the site has been severely impacted by three major floods. In October 2012 and in June 2013, 5,000 m^3 of waste deposits were eroded and carried away by the Gave de Pau river. In June 2018, severe floods eroded the edge of the landfill (10,000 m^3 of waste materials were eroded and transported by the river). Emergency excavation works were performed between August and October 2018 to soften the slope of the riverbank. In total, 9,300 m^3 of waste deposits were excavated and provisionary stored under plastic film, waiting to be sorted, treated and recycled.

[34] The terminology “Gave” designates turbulent rivers located in the Pyrenees (France).

12.3.4 Stakeholder involvement

Following the flooding of the site, the local authorities (municipality of Bordes, Community of the Pays de Nay municipalities) decided to proceed at the remediation of the site. Out of all the remediation scenarios, landfill mining was the best option. In March 2017, it was decided by votes to launch a landfill mining project on the site. The project gathered people from the State Department of classified installation, the water policy service, the Gave managers, the local water agency, environmental and energy agency (ADEME), the community of Pays de Nay municipalities, the engineering department and the municipality of Bordes.

12.3.5 Characterization of the landfill content

The landfill extension was delimited based on the historical documents such as aerial photographs. In total, 44 trenches (max. 6-7 m depth) were performed on site to validate the landfill extension, to characterize the landfill content and to locate the aquifer at depth. The location of the trenches was selected to have one trench per 100 m^2. XRF in-situ measurements were performed on site to qualitatively analyze the geochemical composition of the soil and waste deposits.

The total amount of waste materials to excavate and treat was estimated at 64,000 tonnes. The waste deposits were classified into four categories based on their nature content:

1. Type 1: Subsurface heterogeneous waste (mostly inert, non-degradable waste with a few municipal solid waste deposit) mixed with soil, gravels and pebbles;
2. Type 2: Municipal solid waste;
3. Type 3: Construction waste;
4. Type 4: Industrial waste mixed with municipal solid waste.

The waste material as well as sand from the Gave de Pau River were analyzed for a panel of pollutants. The results showed that the site was contaminated with cadmium, molybdenum, hydrocarbons, polyaromatic hydrocarbons, polychlorinated biphenyl. Pilot holes were performed to analyze the water quality of the aquifer showing that the pollution in the aquifer was very diluted.

12.3.6 Description of the landfill mining operations

The landfill mining operation began in August 2019 and will end in April 2020. Due to the proximity of the Gave de Pau River, the landfill operations should be done in a short time span (initially between August and the end of November 2019). The waste excavations started downstream to upstream to avoid breaches and the flooding of the landfill by the Gave de Pau River. A dike was created to artificially redirect the river. Before starting the mechanical sorting phase, the waste deposits were stored in two storage areas. The storage areas consist of waterproof membranes connected to a retention basin collecting the surface water run-off. The waters were regularly analyzed. Uncontaminated waters were directly rejected to the river whereas contaminated waters were treated. On the storage area, several skips were present to collect the sorted waste. There, the waste deposits were divided into different skips. The non-hazardous waste classified as class II (e.g. plastic, textiles) were stored in a dedicated skip. Due to their size, the macro waste such as barrels and washing machines were stored without going on the sorting platform. The tires were stocked in a specific container. The metallic waste materials were sorted between ferrous and non-ferrous metal, and stored on two separated skips. Green waste remained on site. The non-inert macro waste deposits such as plastic, textile, tires were sorted. The concrete (>400 mm) was also sorted and separated.

The set-up of the sorting platform is summarized in **Figure 12-7**. The sorting platform (**Figure 12-8**) had a daily throughput of 650 tonnes. First, the waste deposits were screened using a drum device. The residual waste fractions were separated into three categories based on their grainsize using a scalper : (1) Fine fraction (0-20 mm); (2) Medium fraction (20-100 mm); (3) Coarse fraction (100 – 400 mm). The residual fraction (fine, medium and coarse) was provisionally stored in the secondary storage area before being reused on site. The second step consists in the screening of the residual (medium and heavy fraction). The residual fraction was separated based on its density using aeraulic screening systems. The low-density fraction consisted mainly of plastics and polystyrenes whereas the high-density fraction was composed of glass shards and pebbles, waste construction, among others. The next step was to put the high-density fraction on a non-ferrous metal separator consisting of an overband with Eddy current separators to isolate the coarse particle containing metals. The final step was to sort the high-density fraction manually to remove the waste that could not be separated with the equipment. The final waste materials were sorted based on their nature (e.g. plastic, metal, concrete).

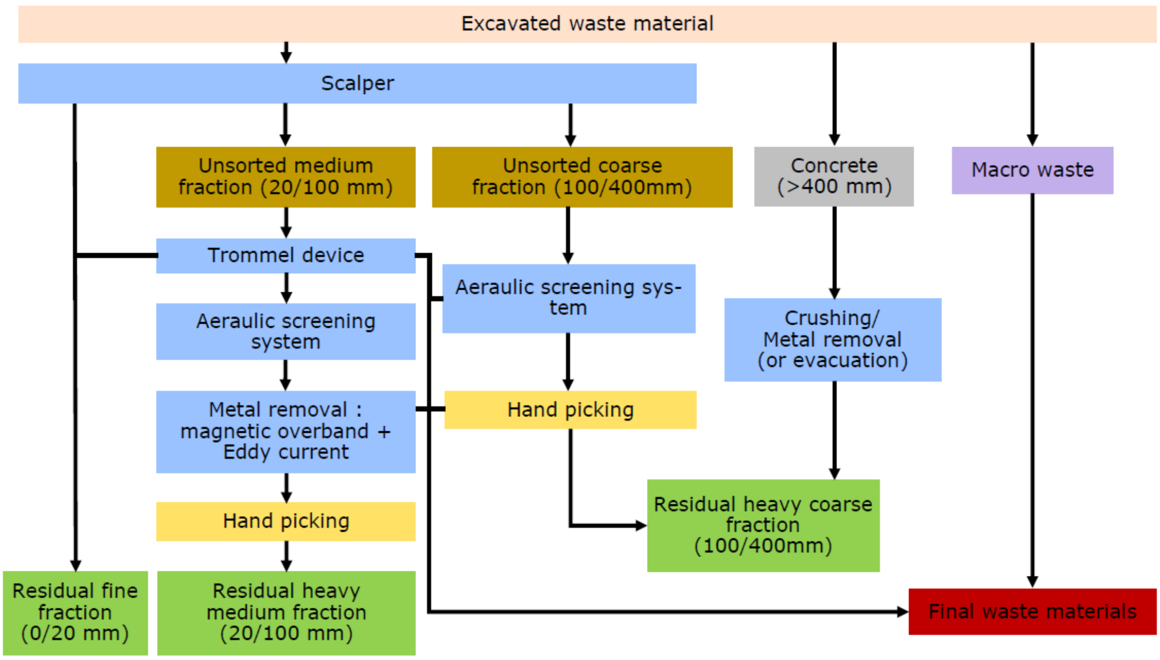

Figure 12-7 Scheme of the set-up of the sorting platform used during the landfill mining operations at the landfill of Bordes.

The different waste deposits were evacuated off-site to dedicated facilities. The class II waste was evacuated to the site of Précilhon (40km far from the landfill site). The waste materials were transported by truck using an agricultural road that was specially redesigned for the trucks. A UAV flew over the site on a weekly basis to quantify the excavated waste. In total, at the end of the project, around 64,000 tonnes of waste deposits shall be excavated. **Table 12-2** lists the different types of material retrieved from the landfill between August 2019 and January 2020.

Table 12-2 Resource materials recovered from the landfill of Bordes between August 2019 and January 2020. At the time of writing the guide, the waste excavation is not finished yet.

Type	Quantity	Valorization
Mixed waste	41,620 T	38,000 T reused on site (20,000 T of fine fraction + 18,000 T of 20 – 400 mm fraction)
Concrete (>400 mm)	1,910 T	1,910 T recycled in dedicated facilities
Ferrous metal	200 T	200 T recycled
Nonferrous metal	10 T	10 T recycled

Figure 12-8 UAV view of the sorting platform (Credit photo: Conseil Départemental des Pyrénées-Atlantiques).

Environmental monitoring

During the excavation of the riverbank the turbidity, the suspended solids, the dissolved oxygen concentration and the temperature of the water were checked every 2 hours to guarantee the water quality and to rapidly react when the authorized thresholds are exceeded. In case of threshold exceedance, the procedure was to stop the landfill mining operations immediately and wait for the stabilization of the parameters. Until now (January 2020), thresholds have been reached three times.

Environmental protection

Several measures were taken to protect the environment during the landfill mining operations. In order to avoid the contamination of the river with fuel from, all equipment used on site ran on biodegradable oil.

In France, there is a legal obligation to protect the reptiles living on site from the landfill mining operations. Therefore, their natural habitats will be recreated in eight locations with a minimum surface of 4 m², near the river and exposed directly to the sun. Their recreated natural habitat will consist in a pile of gabions and coarse materials. Gabions will also be partially buried at a depth of 10-15 cm below ground to protect the animals during their hibernation. Moreover, the tree stumps resulting from the tree cutting will be left on site for the xylophagous insects.

The long-term effects of the landfill operations on the biodiversity will be monitored for a duration of six years.

12.3.7 Waste revalorization

Most of the waste materials will be revalorized. The fine fraction will be directly reused on site. As this fraction is polluted, the fine fraction (0-20 mm) will be preliminary treated by phytoremediation (*see phytoremediation, under **section 12.3.8***). The medium fraction (20-100 mm) will be used on site as backfilling material and will be put between the natural ground and the fine fraction. The coarse fraction characterized by low density (plastic, polystyrenes, etc.) will be evacuated to a dedicated facility (ISDND de Précilhon) where they are to be relandfilled. The heavy density coarse fraction will also be reused directly on site at the bottom of the cells. This permeable material will optimize the underground water flow below the site and will act as a natural barrier to protect the water from the pollutant contained in the fine fraction.
Macro waste such as barrels, washing machines, etcetera will be evacuated to a dedicated facility center.
The concrete fraction (larger than 400mm) which could not be sorted automatically, will be entirely valorized in recycling facilities dedicated to the recycling of construction materials. The concrete aggregates smaller than 400mmwill be reused on site and the surplus will be evacuated off site by truck to a construction material recycled center. At the end of the excavation, 4,500 tonnes of concrete would be excavated, treated and revalorized.

12.3.8 Site remediation

At the time of writing the landfill miner guide, the site remediation has just started. The residual fractions (0/20 mm, 20/100 mm and >100 mm/400 mm) as well as the concrete aggregate will be used as backfilling material. The medium and coarse fraction will be combined (20/400 mm) to create draining boxes. On the top of this fraction, the fine fraction (0-20 mm) will be deposited. The site will be designed to allow the run-off of meteoric water. A part of the site will be dedicated to the phytoremediation system. For that purpose, the site will be revegetated using indigenous species. The revegetation of the site will be done by persons in need as a part of a social rehabilitation program. The landfill mining of Bordes landfill is not only an environmental project but it is also helping people to be socially rehabilitated by working there.

Phytoremediation

As the fine fraction (0-20 mm) usually contains micropollutants, it needs to be treated. The option of phytoremediation to treat this fraction was chosen. The type of plants were selected based on the types of pollutant present on site. The microbial activity within the fine fraction was also investigated in laboratories. The fine fraction will be sowed by hydromulching. This technique consists of projecting seeds, wood chips, fertilizers and biodegradable glue using water cannon. As the sowing will be done in spring, the spring seeding cultivation will be selected. The wood chips and haystacks will ensure the organic matter input for the fine fraction. The growing plants will provide nitrogen to the fine fraction stimulating the microbial activity.

12.3.9 Final results and landfill mining benefits

The results of the project are expected in 2021. Landfill mining has contributed to the rehabilitation of the site. Moreover, the reshaping of the site will modify the slope angles of the riverbank. By softening the ancient steep slope of the landfill, it will reduce the erosion potential of the Gave de Pau River and therefore decrease the impact of future flooding. It will also reduce the environmental impact of the site by halting the leachate and greenhouse gases production**.**

12.3.10 Laws and regulations applied

In France, there is no legal framework for landfill mining. The removal of the waste deposits removes the legal responsibility of the municipality. However, implementing a landfill mining project in Bordes was not easy. The decision to launch the landfill mining project was supported by the fact that the landfill of Beaucens[35], located in the Haute Pyrenees Department, was rehabilitated using landfill mining.

12.3.11 Budget

The project was funded by the region of Nouvelle Aquitaine (ERDEF funding), the water agency, and the municipality of Bordes. In total, the project costs 2,049,580€ (+ 450,000€ of Emergency works). The detailed of the expenses is summarized in **Table 12-3**.

[35] In total, 150,000 tonnes of waste materials (mainly municipal solid waste) were excavated.

Table 12-3 Detailed budget for the landfill mining operations at the landfill of Bordes.

Tasks	**Costs**
Earthwork *(waste excavation, concrete sorting, etc.)*	518,000 € (*excluding VAT*)
Mechanical sorting (fine, medium and coarse fraction) and skip installation	1,330,000 € (*excluding VAT*)
Concrete evacuation off-site (estimation for 5,000 tonnes)	20,350 € (*excluding VAT*)
Ultimate waste evacuation off –site, transport and relandfill.	64,230 € (*excluding VAT*)
Phytoremediation (remediation on site + laboratory analyses)	56,000 € (*excluding VAT*)
Environmental monitoring	42,000 € (*excluding VAT*)
Social rehabilitation project	19,000 € (*excluding VAT*)
+ Emergency works (August – November 2018)	450,000 € (*excluding VAT*)

12.3.12 Conclusion

The Bordes landfill site needed rehabilitation due to the proximity of the River Gave de Pau. The landfill mining operations help to reducing the environmental risks related to the presence of waste deposits. In total, 64,000 tonnes of waste materials will be excavated and most of them will be revalorized on site. The site of Bordes is also a pilot site for the remediation of fine fractions using phytoremediation techniques. Depending on the success of this trial, using phytoremediation technique on site following a landfill mining operation could be adopted by other landfill mining project across NW Europe.

If you want to know more about the landfill mining project of the Bordes landfill, you can contact the Conseil départemental des Pyrenées-Atlantiques (Pau): Christian Paille-Barrere - project manager (christian.paille-barrere@le64.fr).

12.4 Case study: The landfill of Sandford Farm (United Kingdom)

Duncan Scott (Vertase FLI Ltd)

12.4.1 Description of the site

Sandford Farm (51°27'30.7"N, 0°52'37.2"W) is located close to Reading, United Kingdom. The area subjected to landfilling was approximately 20 hectares. The landfill site was bounded closely with residential properties to the west and south. In total, three landfills were present on site. The deepest landfill located in the south of the site was approximately 11m depth. The two other landfills were shallower, not exceeding 8m depth.
The superficial geology at the site originally comprised River Terrace gravels. In the north of the site, the River Terrace gravels were underlain by Woolwich and Reading Beds of the Lambeth Group (clay, sand, sandstone) and London Clay in the South.
The site was located adjacent to the Old River and the River Loddon (tributaries to the River Thames). Groundwater was also present within permeable lenses within the Woolwich and Reading Beds of the Lambeth Group. Whilst the landfills on the site were not engineered with impermeable lining to prevent migration of contaminants into the water environment, significant pollution of groundwater and surface water as a result of the landfilled waste was not occurring. Groundwater present within the landfill waste did, however, have elevated concentrations of some metals, petroleum hydrocarbons and ammoniacal nitrogen.

12.4.2 History of the site

The site was formerly occupied by a farmland, which gave its name to the site. In the 1950s, the River Terrace gravels were extracted for use as aggregate in construction. The cavity was progressively filled with commercial and industrial waste deposits from the 1960s to 1990s. Even if the site was a licensed commercial / industrial landfill, there was no lining or environmental controls. In 2005, the landfill site was restored with subsoil and topsoil. The remediation plans to make the former landfill suitable for residential development was controversial and was blocked for many years. In 2012, planning permission for residential development was finally granted.

12.4.3 Drivers for the landfill mining project

The driver of the project was land redevelopment. The aim of the landfill mining project was to reclaim the land for development and to make it suitable for a residential end use. Due to its proximity to London, the land value is relatively high.

12.4.4 Stakeholder involvement

The site was purchased for redevelopment by a national house builder in the United Kingdom (Taylor Wimpey West London) who was the client. RSK Environment Ltd were employed by the client as the environmental consultant during the works. Vertase FLI Ltd were employed as remediation contractor to design and build a development platform across the site to enable the redevelopment of the site for residential use with public open spaces. This involved excavation of all the waste, processing of the waste to recover and reuse suitable materials in construction of the development platform, and demonstration to all stakeholders (the client and consultant, local planning authority, Environment Agency and National House Building Council) that the materials used did not pose unacceptable risks to human health, the environment and property.

12.4.5 Characterization of the landfill content

The landfill site investigation was undertaken prior to involvement by Vertase FLI Ltd by RSK Environment Ltd. In order to characterize the landfill content, geophysical measurements (Electromagnetic Ground Conductivity Mapping and Ground Penetrating Radar) were performed. The results showed that the lateral extension of the three landfills. Additionally, trial pits and boreholes were undertaken. The exact number of trial pits and boreholes has not been quantified for the purpose of this case study, however the numbers are estimated to be in the region of up to 100 of each.

The waste descriptions were correlated with the results of the geophysics. Based on the coupling of geophysics and boreholes, the volume of the waste deposits present in the landfill was estimated to be in the region of 340,000 m^3 (including the landfill capping soils). The investigation also helped to map the lateral and vertical extent (max. 11 m depth) of the waste deposits. Use of the trial pits to inform waste composition was also important. Based on visual observation, the waste deposits mainly consisted of soil, stone, bricks, concrete, plastic, glass, metal, paper and cardboard, wood, textiles, rubber and asbestos.

12.4.6 Description of the landfill mining operations

The landfill waste excavation started in March 2013 and the reclamation works ended in 2016. The reclamation works were operated by Vertase FLI Ltd. The strategy involved excavation of all the landfill waste. Several separation methodologies were employed to separate the waste materials into different streams. First, selective excavation was undertaken as pre-processing technique to separate large materials (e.g. boulders, rolls of carpet). The light plastics were separated from the raw waste using an air knife. For this particular site, three-way vibratory screeners were used to separate the excavated waste by size. The produced material size fractions that did not pass through 100mm spaced fingers (>100mm fraction), did pass through 40mm aperture steel mesh (<40mm fraction), and the middle fraction (40-100mm). The small fraction (<40mm) was suitable for immediate reuse. The larger fractions required additional processing to make them suitable. Ferrous metals were also recovered using magnets. Additional processing comprised manual hand picking of the waste to remove unsuitable materials.

12.4.7 Waste revalorization

As mentioned above, the waste materials were separated into different streams. Two of the objectives of the project were to maximize reuse of materials and to minimize off-site disposal in order to reduce the cost and the haulage vehicle movements. The soil-like fraction and small aggregate were directly reused on site without further processing. Large aggregate were crushed to form recycled secondary aggregate suitable for reuse. The plastic materials were reused at depth on site in the areas dedicated to public open space areas. Wood and timber could not be reused on site due to their potential to generate biogas during their degradation process. Therefore, they were shredded into smaller fragments and exported from site to a nearby country park for reuse. Like wood, textiles have a potential to generate gas making them unsuitable to be reused on site. The textiles underwent off-site disposal. The metal fractions (approximately 370 tonnes of scrap metal) recovered from the landfill waste were exported from site to metal recycling facilities. The tires were exported from site to landfill or recycling facilities. In total, around 95% (by mass) of the waste deposits were reused on site.

12.4.8 Site rehabilitation

The redevelopment project consists in the building of more than 460 residential properties. Piled foundations were used to construct the buildings. Gas protection measures were included in buildings to protect the future inhabitants from ground gas (e.g. subfloor ventilation, membrane recovering the entirety of the building footprints with penetration and joints sealed). Inside the residential area, public open space areas, play areas as well as sustainable drainage system (pond and swales) were designed.

The site reclamation works were designed by Vertase FLI Ltd to minimize the potential for future ground settlement; minimize future ground gas production; manage risks to human health of future site users; manage risks to the environment (e.g. pollution of the water environment); and maximize the reuse on site. Processed waste materials were reused to backfill the landfill voids after demonstrating the that materials were capable of meeting a series of geotechnical criteria (95% Maximum Dry Density, 50 kN/m^2 undrained shear strength, and <10% air voids) and that compliance with these criteria was demonstrable in the field.

12.4.9 Final results and landfill mining benefits

The landfill reclamation works ended in 2016. In total, it took four years to complete the landfill mining operations and the site rehabilitation. However, the construction of residential houses is still ongoing at the time of writing (January 2020). The greatest challenge of this project was to separate landfill waste to maximise the re-useable materials on site and to re-instate these materials to meet geotechnical criteria.

12.4.10 Laws and regulations applied

The site was being dealt with under the UK Town & Country Planning system to change its land use from that of capped historical landfills to residential land use. The primary goal of this legislation with respect to waste buried in the land is to ensure that upon completion of the land use change, the land (and materials buried in the land) are suitable for use and do not pose unacceptable risks of harm (to human health, property, the environment) and pollution (of surface water and groundwater).

The remediation works themselves (i.e. the excavation of the waste and processing of the waste materials) were regulated under the Environmental Permitting Regulations, whereby a permit is granted by the Environment Agency to conduct the works in accordance with strict environmental controls.

On this occasion, it was agreed by the Environment Agency that the re-use of the recovered materials (recovered from the landfill waste) to construct the development platform was exempt from the waste legislative regime adopted in the United Kingdom (taken from the Waste Framework Directive) provided that the reuse adhered to the requirements of the CL:AIRE Definition of Waste: Development Industry Code of Practice. By adhering to this framework provided by CL:AIRE, it could be demonstrated that the recovered materials were suitable for proposed reuse and were therefore not "waste".

12.4.11 Budget

The off-site disposal of all the landfill waste to another landfill facility was estimated to cost ~£51,000,000. Additional costs such as importation of inert material to fill the void would have further increased the project cost. Due to the maximization of the reuse of waste materials on site, the landfill mining costs were significantly reduced. In total, the project cost around £12,000,000.

There were very little saleable materials recovered from landfill waste. Approximately £26,000 was recovered from scrap metal (~370 tonnes) after haulage. However, the recovery of saleable materials from landfill waste was not the economic driver for the project.

The costs to the develop for purchasing the land and for the construction phase are not known. However, due to elevated property prices in the area (by virtue of the site location in relation to London and the south of England), the project is anticipated to generate an acceptable profit margin for the developer.

12.4.12 Conclusion

The reclamation of the Sandford farm landfills for a residential end use demonstrates that landfill mining (for the recovery of saleable materials from the waste) may not be a viable economic driver for some landfills in isolation. Instead it is also important to consider the value of the reclaimed land upon completion of the landfill mining works, which can generate substantial benefits to society and the environment.

For more information about the landfill reclamation works undertaken by Vertase FLI Ltd, you can directly contact Duncan Scott (Technical Director at Vertase FLI Ltd) by email (dscott@vertasefli.co.uk).

12.5 Case study: Gerringe Landfill (Denmark)

René M. Rosendal (Danish Waste Solutions ApS & AV Miljø)

12.5.1 Description of the site

Gerringe Landfill (54°42'26.9"N, 11°19'16.9"E) is located in the southern part of Seeland, Denmark close to the coast. The landfill is designed on a natural clay lining with a vertical clay liner around the site. In addition, a drainage system on the inside of the vertical clay liner system has been installed. The total surface area of the landfill is 12 hectares. The top of the landfill is located at a height of 19 meters above the surface.

12.5.2 History of the site

The site was established in 1973 and it is still in operation today. Since the beginning more than 800,000 tonnes of waste has been landfilled at the site. The remain capacity is estimated around 900.000 m^3. Since 1987, no organic and biodegradable material has been landfilled.

12.5.3 Drivers for the landfill mining project

In this case, the driver was to excavate waste suitable for incineration with energy recovery due to lack of waste available for incineration.

12.5.4 Stakeholder involvement

The municipal waste company I/S REFA was responsible for the project and the private waste company Denova was in charge of excavation, waste sorting and the landfill rehabilitation. Transportation of the waste was done by Marius Pedersen A/S. I/S REFA and Danish Waste Association ensured compliance with the environmental rules, and made the final report to the authorities.

12.5.5 Characterization of the landfill content

An excavation test was done at another landfill site owned and operated by I/S REFA, but due to asbestos present, it was decided to change to the Gerringe site. Tests performed on the Gerringe waste deposits showed no sign of asbestos contamination for the fine fraction. Therefore, the landfill mining operations could start at Gerringe landfill.

Figure 12-9 Landfill mining operations at Gerringe Landfill.

12.5.6 Description of the landfill mining operations

In February 2011, the final environmental permit was given to start "*Project Waste Minimization*" which was the first landfill mining project in Denmark. The landfill mining operations started in March 2011 and ended in September 2011.

Due to an ongoing landfill gas production, the intention was to excavate in the maximum depth of six meters. Thus, it was of the utmost importance not to excavate in biodegradable waste materials landfilled before 1987[36].

The total surface area chosen for excavation was approximately 6,000 m^2. It did not consist of any biodegradable waste but instead of waste suitable for combustion and recycling. The intention was to excavate an amount of 200 m^3 per day. Excavated waste was transported and screened on site in a coarse rotating trommel screen (Neuson TS7020) with a 25 mm screen for separation. A scheme regarding the excavation pit and organization of the overall work process is provided in **Figure 12-10**.

In relation to the excavation, the following elements were employed: (1) Excavator; (2) Moving floor and elevator conveyor belts; (3) A coarse rotating trommel screen; (4) A magnet; (5) Front end loader.

[36] The incineration plant was built in 1983.

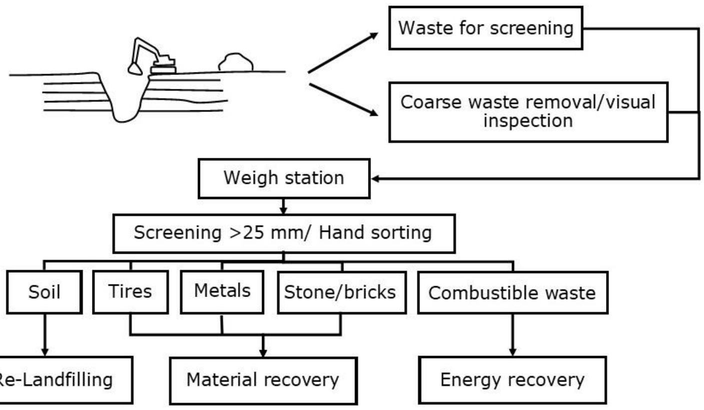

Figure 12-10 Excavation scheme.

12.5.7 Waste revalorization

A total of 2,860 tonnes of waste was excavated. Results of the excavation gave the following waste composition:

- 50.9% Combustible waste ;
- 41.9% Residual waste ;
- 4.1% Tires ;
- 2.3% Bedrocks/C&D waste ;
- 0.8% Iron and metals.

Combustible was incinerated at the local Waste-to-Energy plant. Tires, bedrock/C&D waste and iron and metals were sold for reuse and the residual waste (soil with mixed plastics, rubber, and glass) was relandfilled.

12.5.8 Laws and regulations applied

The legal constraints were dictated by the Danish EPA and an environmental permit was given to perform the project.

12.5.9 Budget

The project was funded by I/S REFA and cost approximately 111,000 €. As shown in **Table 12-4**, this implementation of the landfill mining project entailed more costs than revenues. The cost was rated at 67 € per tonne of waste excavated. The potential of waste for reuse was lower than expected (< 1%), the quality was poor and hard to sell with a profit, and the excavation, i.e. hauling and labor costs, was the most expensive part of the project.

Table 12-4 Cost-Benefit calculation for Gerringe Landfill.

Activity	**€/tonne**	**Costs/Revenues (€)**
Costs		
Entrepreneur (combustible waste)	14	20,160
Excavation	18	52,000
Sorting and screening	14	40,000
Transportation	10	16,533
Incineration costs	65	94,000
Re-landfilling costs	1.5	1,600
Administration	3	8,000
Revenues		
Iron and metals Bedrock/C&D waste Tires (bad quality)	200 0 0	4,234 0 0
Value of new landfill capacity	4	11,436
Tax refusion	63	105,066

12.5.10 Conclusion

Landfill mining at Gerringe Landfill showed that it is possible to excavate and sort municipal solid waste with a high potential - equivalent to 50%. In contrast, the potential of waste for reuse was lower than expected (< 1%) and the quality has been poor and hard to sell with a profit.

The results of the test excavations indicated that problems for the workers could occur when excavating pre-landfilled material, e.g. asbestos and other hazardous waste. Even though, it was not the case for this project, excavating the organic fraction should lead to extra precautions to secure the workers' health from landfill gas, odor nuisance, etc.

For more information about this project, you can directly contact: René M. Rosendal (+4522516664; rmr@danws.dk).

12.6 Case study: Skårup Landfill (Denmark)

René M. Rosendal (Danish Waste Solutions ApS & AV Miljø)

12.6.1 Description of the site

Skårup Landfill site (56°01'38.5"N, 9°58'24.8"E) is located in Skanderborg, close to Aarhus, which is the second biggest city in Denmark. The landfill was composed of several cells, but the landfill mining project only focused on Cell 1. Cell 1 of Skårup Landfill contained approximately 45,000 m^3 of waste consisting of household waste, slags, construction and demolition waste and domestic waste from both the private and public sectors.

12.6.2 History of the site

The site began operating in 1979 and it is still in operation today. Cell 1 of Skårup Landfill has been filled with waste between 1979 and 1981. The site should be closed before 2023 due to its location which does not comply anymore with Danish planning rules.

12.6.3 Drivers for the landfill mining project

The aim of the project was to provide insights about the technological and economic benefits and environmental aspects of excavation and sorting of pre-landfilled waste from Skårup Landfill. The target was to develop an application-oriented assessment tool/procedure to plan, select and perform future landfill mining projects at different landfills in Denmark and abroad.

12.6.4 Stakeholder involvement

The project was co-funded by the Environmental Technology Development and Demonstration Program (MUDP) and was initialized by the public waste company Renosyd in cooperation with different partners: Kingo Karlsen A/S, Danish Waste Solutions ApS, Biorem ApS and DGE Miljø- og Ingeniørfirma A/S and the Danish Environmental Protection Agency.

12.6.5 Characterization of the landfill content

Prior to the physical excavation and management of waste, a detailed pre-characterization of the actual landfill unit was carried out. Both registrations of waste and other historical material about the area and the landfill were collected by means of e.g. interviews with "old" employees, environmental status and former investigations. Furthermore, a non-invasive screening of the landfill stage was initiated to get a three-dimensional description of the material conditions in the waste. Geophysical measurements were performed before the excavation operations in order to delimit the geometry of the landfill and quantify the landfill mining content. Finally, an excavation test (3m depth) was done to get more information about the composition of the waste, the conditions for excavation and to confirm or deny the general assumptions about the composition of the waste. This pre-characterization of waste was important and provides a correct planning of the main landfill mining project.

12.6.6 Description of the landfill mining operations

Prior to the start of the project, the project partners applied for an environmental approval which was approved on May 23, 2016. The environmental approval was subject to compliance with a number of conditions that must be met and documented before, during and after the project. The excavation and sorting was done between August and October 2016. Excavation and sorting of the coarse waste fraction were carried out using an excavator with a sorting grapple. This pre-sorting could separate bulky items from the rest of the waste: e.g. tree roots, tires, lumber, furniture, major foundation bricks, carpets and large, heavy pieces of plastic film.

Figure 12-11 Landfill mining operations at Skårup Landfill.

After pre-sorting, the waste materials were passed through a vibrating sorting plant where it was separated into three particle size fractions:

- A fine fraction (<40 mm) - *this fraction consisted of soils and small pieces of waste*;
- A mid-size fraction (40-51 mm);
- A coarse fraction (>51 mm).

Magnets were mounted at the outlet of the coarse- and mid-size fractions in order to separate magnetic metal, and a plastic foil suction module was mounted, which blew the light plastic fractions into a separate closed container.
The waste deposits consisted for the most part of household waste with minor amounts of bulky waste. This meant that the sorting processes had to be adjusted, and there was performed re-sorting of some of the mid-size and coarse fractions to achieve a better fractionation of the waste.

12.6.7 Waste revalorization

In total, 2,049 tonnes of waste materials were excavated and sorted. The weight of the different fractions recovered are presented in **Table 12-5**. The inventory of the combustible fraction was carried out based on the results of the hand picking. Ferrous and non-ferrous metal scraps as well as bricks and stones were recycled in dedicated facilities. The rest of the excavated waste materials were either incinerated or re-landfilled.

Table 12-5 Final sorting results of the excavated waste materials from Skårup Landfill.

Sorted Fractions Skårup Landfill		
	Tonnes	**%**
Top soil	3,000	-
Recycling		
Bricks and stones	14.35	0.69
Iron and metal	28.09	1.35
Incineration		
Combustion residue	105.33	5.05
Re-landfill		
Fine fraction/clean soil	1,414.46	67.9
Residual waste	491.68	23.59
Special treatment		
Hazardous waste	0.037	0.002
Heavy contaminated soil	30	1.44
Total	2,083.95	100

12.6.8 Rehabilitation of the site

The goal of the landfill mining project was to do small-scale demonstration project – not a full-scale project. The soil fraction, rich in organic matter, was preliminary screened, tested and reused to reshape the site.

Figure 12-12 Site during the rehabilitation operations.

12.6.9 Laws and regulations applied

The legal constraints were dictated by the Danish EPA. An environmental permit was delivered before the starting of the project.

12.6.10 Budget

The practical implementation and recorded project costs were done based on the implementation of landfill mining projects using the specific methods of excavation and sorting from this project (**Table 12-6**).

Table 12-5 Generic costs and revenues for landfill mining operations in Denmark.

Costs	**Cost level**
Design and planning	25,000 – 37,500 €/site
Pre-investigation	6,250 – 18,750 €/site
Establishment of work area and facilities	6,250 – 12,500 €/site
Excavation of topsoil/cover	1.9 – 3.1 €/m^2
Excavation and sorting (pre-, coarse and after sorting)	50 – 62.5 €/T
Recovering and final cover	7.5 – 12.5 €/m^2
Clean up after project activities	3,125 – 8,750 €/site
Re-landfilling	0 €/tonne re-landfilling. 25 - 75 €/tonne at another landfill. No landfill tax.
Incineration of Waste	63.75 €/T
Crushing	2.5 - 5 €/T
Light contaminated soil	12.5 – 18.75 €/T
Heavy contaminated soil	43.75 – 75 €/T
Hazardous Waste	625 - 750 €/T
Transportation	3.1 – 12.5 €/T
Income and savings	**Revenues**
Income from the sale of (recyclable) materials	Iron/metal (112.5 €/T). Crushed concrete (2.6 €/T). Mix of crushed asphalt/concrete for road construction 0/32 mm (12.5 €/T).
Saving on treatment and management of leachate	50 €/m^2
Reversal of final provision	15 €/m^2
Reversal of landfill taks	59.4 €/T

12.6.11 Conclusions

The results of the project have shown that several factors influence the economics of a landfill mining project. It was difficult to describe all the costs and revenues that have influence on a project before excavating, even though you make good historic descriptions and take other measure precautions such as test excavations and use non-invasive methods. The situation often changes, and unexpected things happens which might affect the economy in a negative way.

Sales of excavated materials such as metals was a very important factor and considered as one of the most significant factors that contribute positively to the economics of a project. The quality of materials is often poor, contaminated or degraded, and hard to sell. A lot of externalities influence on the economy. Mining a landfill just for the material recovery is at this point not sufficient to generate profitable landfill mining projects. It is important to the landfill mining in a broader perspective by integrating the land recovery, void space recovery, the social and environmental benefits related to the removal of the waste deposits.

For more information about this project, you can directly contact: René M. Rosendal (+4522516664; rmr@danws.dk).

13 Summary

Several challenges still prevent the popular implementation of ELFM projects in North-West Europe, despite the transition from a linear to a circular economy being one of the EU priorities, and directly connected to four UN Sustainable Development Goals.
Guidelines to develop a landfill mining project from A to Z are provided in this book. However, the development of a landfill mining project is strongly dependent on the regional legislation and therefore local legislation should be consulted.

To encourage the implementation of ELFM project in Europe, RAWFILL project partners have developed tools and methods which aim at reducing the expense prior to ELFM operations. This guide book summarizes the RAWFILL methodology and provides key information for starting an ELFM project. The first step is to characterize the landfill by collecting data about the landfill content and therefore the economic potential of the landfill site. For that purpose, RAWFILL project partners developed an innovative landfill characterization approach based on multi-method geophysical techniques, coupled with targeted waste samples. This methodology is typically cheaper and faster than the traditional on-site investigation methods. As geophysical methods are non-invasive, it reduces the risk of damaging structure and the exposing to potential hazardous material during the investigation phase. A Resource Distribution Model (RDM), can then be developed based on the RAWFILL characterization information showing the spatial distribution of the resources in the landfill site.

With the investigation and the landfill content characterization phases completed, the ELIF (Enhanced Landfill Inventory Framework) and the DSTs (Decision Support Tools) can be applied in order to identify the ELFM potential of the landfill. The ELIF, created based on an extensive benchmark of landfill inventories across Europe, will help to fully describe and characterize the landfill from environmental, social, technical and economic aspects. It focuses on the quality and the quantity of dormant materials contained within.
Using on the data entered in the ELIF, DST 1 – Cedalion will provide a fast screening of the landfill site valorisation potential. A ranking of the landfill sites based on their ELFM potential is given. For the promising landfill sites, DST 2 – Orion will perform a more detailed analysis of the financial viability of the ELFM project. When the financial viability of the project cannot be demonstrated, environmental or social benefits may be the key drivers to conduct an ELFM project. Other landfill dynamic management alternatives, such as interim use is also provided. The interim use consists of finding a suitable land use alternative for the landfill site with suitable value. The duration of the interim use strongly depends on two key parameters: (1) the time needed for the landfill to reach appropriate mining conditions (e.g. no more biogas production, waste pile stability) ; and (2) the price market evolution for the landfilled waste resource.

If the business case shows a positive economic outcome or if social and/or environmental benefits are demonstrated, the landfill mining procedure can start.
A landfill mining project requires a series of operations which should be carefully planned prior to the beginning of the project: preparation phase, waste excavation, organisation of

the lorry movements inside and outside the landfill, rainwater, biogas & leachates management, waste sorting and/or pre-treatment, and site remediation.

Excavated landfill waste materials can be revalorized into waste-to-materials and/or waste-to-energy. To choose the best option for each material, the state of the waste, as well as its market value needs to be considered. The market value is one of the key parameters and should be regularly updated to ensure a coherent business model. As sorting techniques and revalorisation streams will evolve in the future, it is expected that more waste materials will be recovered and reused in the future.

Site rehabilitation is regulated by regional legal frameworks and therefore varies throughout the different Northwest European regions. Site rehabilitation should be planned before starting a landfill mining operation with the involvement of all stakeholders (including nearby or affected residents). The land redevelopment project and the land value can be the driver of the ELFM project. Its success can be measured based on environmental remediation, civil infrastructure renewal, economic development and/or neighborhood revitalization.

14 Contact persons

Feel free to contact one of the project partners below or check out the project website of RAWFILL.

Lead partner:

BELGIUM	Claudia Neculau (SPAQuE) Boulevard M. Destenay 13 4000 Liège	c.neculau@spaque.be

Contact details of the project partners:

BELGIUM	Renaud De Rijdt (Atrasol) Alain Ducheyne (VITO) Eddy Wille (OVAM) Frédéric Nguyen (Université de Liège)	renaud.derijdt@atrasol.eu alain.ducheyne@vito.be ewille@ovam.be f.nguyen@ulg.ac.be
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Appendix A: ELIF Indicators

This section describes and defines the ELIF indicators. The indicators are divided into subcategories : Generic information, Regulatory information, Landfill ID Card, Surroundings, Landfill morphology, Landfill waste materials.

Generic information

ELIF datasheet responsible: name and position of the person responsible for the validation of the datasheet.

- Name - *Text*
- Position – *Text*

Creation date: date of the datasheet creation.

- *Date (dd/mm/year)*

Date of updating: date of last updating of the data sheet. "Updating" means either completion of the data sheet with missing information or modification of existing data. We assume that regular backups ensure that all previous versions of the data sheets still exist somewhere. This way allows to avoid to keep log files.

- *Date (dd/mm/year)*

Regulatory information

This section gathers all local/regional/national regulatory information applicable for the landfill described in the data sheet, when it has an impact of a potential ELFM project. The goal is not to be very detailed, but to mention the existence of relevant information that the stakeholder can consult.

Regional policy encouraging ELFM: list of public policies applicable in the region covered by the database, having an impact on a potential ELFM project. Here are some examples: green policies, circular economy and specific recycling policies, end-of-waste, declassification of buried waste that are not more seen as production residue, geolocation of the trucks, waste traceability…

- *Text*

Regional incentives encouraging ELFM: list of public incentives for ELFM projects. Example: tax exemption or tax reduction for approved ELFM projects.

- *Text*

Dates of landfill ban: dates of regional landfill restriction for some specific waste streams. A restriction can be a limitation (examples: increasing taxes or beginning a selective collection with sufficient coverage) or a total ban (no more organic waste in domestic landfills from a given time).

- Name of the stream (metals, organics, hazardous waste, EOL vehicles…):
    - *Text*
- Regional code of the restricted stream:

- *Text*
- Date of applicability of the restriction:
  - *Date (dd/mm/year)*
- Type of restriction:
  - *Multiple choice: Restriction/Ban*

Site specific ELFM facilitation procedures: name and reference of legislative systems that can encourage ELFM operational projects on this particular landfill site, with their expiration date. Examples: a brownfield covenant signed with local government (Flanders), a soil management covenant (Wallonia).

- Reference :
  - *Text*
- Signature date :
  - *Date (dd/mm/year)*
- Expiration date :
  - *Date (dd/mm/year)*
- Summary :
  - *Text*

Regional authorization for in-situ relandfilling: reference of legislative text authorizing/forbidding relandfilling of ultimate waste in the same landfill.

- *Text*

Regional authorization for relandfilling at another landfill: reference of legislative text authorizing/forbidding landfilling of ultimate waste coming from this landfill in other landfills. Conditions (nature of waste, tax level, tax exemption) must be specified.

- *Text*

Landfill ID card

This section gathers all administrative information related to the landfill described in the data sheet.

Landfill name: usual name of the landfill or the place where it is located. As the landfill may appear under various names in various documents, all known denominations must be described in order to facilitate historical searches.

- Main denomination - *Text*
- Other name 1- *Text*
- Other name 2- *Text*
- Other name 3- *Text*

Landfill reference: identification of the landfill in its original database or file.

- *Text*

Landfill coordinates: geographical coordinates taken at the center of the landfill (WGS 84).

- X - *Text*

- Y - *Text*

Administration in charge: identification of the public administrative unit in charge of the follow-up of this landfill (permitting, control, monitoring, post-management/aftercare period). Example in Wallonia: if the landfill is still under operation, SPW - DGO3 is in charge. Otherwise, if the landfill is abandoned, SPAQuE is in charge.

- *Text*

Ownership: name of the current owner(s) of the landfill and his (their) legal status. This information is important to evaluate the complexity of developing an ELFM project. Details of the ownership are not described in this field, only the name of the owners.

- Name of owner 1
    - *Text*
- Status 1:
    - *List (Public, Private, Both, Unknown)*
- Name of owner 2
    - *Text*
- Status 2:
    - *List (Public, Private, Both, Unknown)*
- Name of owner 3
    - *Text*
- Status 3:
    - *List (Public, Private, Both, Unknown)*
- Name of owner 4
    - *Text*
- Status 4:
    - *List (Public, Private, Both, Unknown)*
- Name of owner 5
    - *Text*
- Status 5:
    - *List (Public, Private, Both, Unknown)*

Landfill operator(s): name of the operator(s) of the landfill with the date of his (their) intervention. Up to 5 operators are allowed. Operators may operate successively or simultaneously.

- Name of operator 1 - *Text*
    - Date of beginning – *Date (dd/mm/year)*
    - Date of end – *Date (dd/mm/year)*
- Name of operator 2 - *Text*
    - Date of beginning – *Date (dd/mm/year))*
    - Date of end – *Date (dd/mm/year)*
- Name of operator 3 - *Text*
    - Date of beginning – *Date (dd/mm/year)*
    - Date of end – *Date (dd/mm/year)*
- Name of operator 4 - *Text*
    - Date of beginning – *Date (dd/mm/year)*
    - Date of end – *Date (dd/mm/year)*
- Name of operator 5 - *Text*

- Date of beginning – *Date (dd/mm/year)*
- Date of end – *Date (dd/mm/year)*

Legal status of the landfill: legal status, for which we propose the following classification: legal covered by a permit, legal but without any permit, illegal, unknown or specific (in case of special status).

- *List (Legal covered by a permit/Legal but without any permit/Illegal/Unknown/ Specific)*

Permits: list of permits and authorisations with their dates and references. No more detail regarding permits are given here.

- Reference - *Text*
- Date of authorisation - *Date (dd/mm/year)*
- Expiration date - *Date (dd/mm/year)*
- Nature of permit - *Text*

Landfill type: landfill classification according to EU Directive (Hazardous, Non-hazardous, Inert) when it is applicable. Please note that the main types of waste that will be encountered in the landfill are described below in more details.

- *List (Hazardous/Non Hazardous/Inert/Not applicable)*

Landfill status and dates: current status of the landfill, with dates of begin and end. Several answers are possible, i.e. a landfill can be controlled (construction respecting legal requirements: watertightness, drainage, etc.) and still in operation or closed.

- Main period of landfilling activities - *List (<1955/1955-1980/1980-1999/>1999)*
- Legal status - *List (Controlled/Wild dump)*
- Usage status - *List (Abandoned/Still in operation at data sheet date)*
- Rehabilitation status - *List (Rehabilitated/Necessary to rehabilitate/Not rehabilitated)*
- Begin of landfill operation - *Date (dd/mm/year)*
- End of landfill operation - *Date (dd/mm/year)*
- Begin of rehabilitation - *Date (dd/mm/year)*
- End of rehabilitation - *Date (dd/mm/year)*
- Begin of aftercare period - *Date (dd/mm/year)*
- End of aftercare period - *Date (dd/mm/year)*

Landfill monitoring: information about the monitoring of the landfill by a public or private body. When monitored, the landfill can be either under operation or closed.

- Monitored at the data sheet date - *List (Monitored/Not monitored at data sheet date)*
- Company in charge of the monitoring - *Text*
- Date: begin of monitoring - *Date (dd/mm/year)*
- Date: end of monitoring - *Date (dd/mm/year)*

Fence/site protection: information about the access of the landfill, in order to identify risks from exposure to waste, biogas or leachate or risk of wild dumping by people who can access the site for various reasons.

- *List (Already protected/Not protected)*

Buried Volume: evaluation of the waste volume buried in the landfill at the date of the ELIF completion. Specify how the volume, which is a very important information, was measured or simply estimated.

- Total volume of the waste deposits (m^3) - *Number*
- Volume (m^3) - *List (Less than 100 000 m^3 of waste deposits/100 000 m^3 to 500 000 m^3 of waste deposits/More than 500 000 m^3 of waste deposits)*
- Measured/estimated - *List (Measured/Estimated/Unknown)*
- Method used for obtaining the volume - *Text*

Remaining Volume: estimation of volume available to receive new waste (i.e. ultimate waste from another ELFM project) or materials (i.e . soil for shaping the final landfill after ELFM operations).

- Volume (m^3) - *Number*
- Measured/estimated - *List (Measured/Estimated/Unknown)*
- Method used for obtaining the volume - *Text*

LFM costs (waste excavation and remediation costs): estimation of rehabilitation costs in € at the date of the ELIF completion. Rehabilitation can be temporary or final, so the given estimation must cover both of them.

- *Number (€ excluding taxes, VAT, etc.) : – if unknown: 1*

Annual aftercare costs: estimation of annual post-management costs in € at the date of the ELIF completion.

- *Number (€ excluding taxes, VAT, etc.) - if unknown: 1*

Warranties given: warranties given for rehabilitation and aftercare costs in € at the date of the ELIF completion. Note that this data can be usually found in the permits.

- *Number (€ excluding taxes, VAT, etc.) – if unknown: 1*

Studies: list of available studies related to the landfill, with references, date of completion and author. Specify if the study is public or confidential. Specify where the studies can be consulted. Studies can include press articles, pictures, maps, advice of official bodies, environmental documents, among others.

- Reference - *Text*
- Title - *Text*
- Date *(dd/mm/year)*
- Main author(s) - *Text*
- Confidentiality - *List (Public/Confidential)*

Sampling: list of waste samples extracted from the landfill, with references, date of completion and author. Specify the origin of the samples (from surface, small or large boreholes, trenches, pits) and describe the type of analysis performed (chemical, physical, material-recovery oriented).

- Reference - *Text*
- Date (*dd/mm/year*)
- Author - *Text*
- Sampling method - *Text*
- Analysis - *List (Chemical/Physical/Material-recovery oriented)*

Surroundings

This section is related to the surroundings of the landfill, mainly its physical environment and sustainability aspects. It also gathers some relevant information for launching an ELFM project.

Land planning: official land use of the landfill and the immediate surroundings (1 km away from the site borders) regarding the national/regional legislation (industrial, agricultural, residential).

- *Text*

Current use: current use of the site of the landfill, regardless its official use.

- Current use - *List (Residential use/Commercial use/Recreational use/Natural reforestation with added value/Natural reforestation without added value/Cultivation (crop, biomass)/Use for renewable energies/LF in operation/zone included in LF in operation/Others)*
- Specifications - *Text*

Tourism: presence of a touristic area nearby.

- Presence of a touristic area nearby - *List (Yes/No*)

Territorial strategy aspects: interest of the landfill site for the territorial development (i.e. located in an area affected by a territorial tool implemented or planned). In addition to the regional tools, each city or town can develop its own tools for redevelopment of the territory. Specify the references of the tools, if a redevelopment project of the area is planned and when it is expected to be realized. Example: urban redevelopment plan around the landfill from 2025.

- *List (Existence of a redevelopment project nearby/No project)*

Surroundings: list the various types of land use of land within a radius of 50 m around the landfill center.
Natural – *Check box (Present/Potential)*
Agricultural – *Check box (Present/Potential)*
Forest – *Check box (Present/Potential)*
Residential – *Check box (Present/Potential)*
Recreational/touristic – *Check box (Present/Potential)*
Economic/services – *Check box (Present/Potential)*
Industrial – *Check box (Present/Potential)*

Land pressure: estimation of the development potential of the landfill area. Local estimated land price if possible. Criteria: Price of housing, prices of the land, average income per capita, population density, unemployment rates, demographic predictions… Land pressure may be high, even if no specific territorial strategy exist.

- Land pressure text: *List (High land pressure/Medium land pressure/Low land pressure)*

General Risk evaluation: assessment of the main specific potential hazard presented by the landfill. Please note that flooding may be evaluated regarding climate changes aspects. Risk related to groundwater are described hereunder in a specific field "Groundwater vulnerability".

- Flood: Is the landfill located in flooding area? Did flooding already occurred at the landfill site? – *Check box.*
- Flooding Risk Level: Low risk: low risk or 50-year return event, Medium: medium risk or 20-year return event, High: high risk or <10-year return event - *List (Low/Medium/High).*
- Risk of landfill's collapse: Is there a risk of collapse related to the instability of the waste pile? – *Check box.*
- Person accident: Related to the risk of people being injury due to the lack of site protection (e.g. fence), the configuration of the site or the presence of dangerous/injuring waste deposits. – *Check box.*
- Direct exposition to waste, (bio)gas and/or leachate: Is there a risk of exposition to waste, (bio)gas or leachate for the neighborhood or other receptors? - *Check box.*
- Other: - *Check box.*
- Unknown: - *Check box.*

Environmental issues: known environmental issues associated with the existence of the landfill.

- Specific environmental issue (not related to water and geology)
  - Description of the Specific Environmental Issue - *Text*
  - Impact of the ELFM project - *List (Yes(positive)/Yes(negative)/No)*
- Surface water contamination
  - Surface Water - *List (Contaminated (estimated)/Contaminated (measured)/High risk of contamination/Medium risk of contamination/Low risk of contamination/No risk of contamination/Unknown)*
  - Analysis availability - *List (Available/Not available)*
  - Description - *Text*
- Geological context
  - Permeability - *List (Highly permeable soil or rocks/Medium/Low)*
- Groundwater vulnerability
  - Average level of upper groundwater table - *Text*
  - Groundwater type - *List (Exploited/Not exploited)*
  - Contamination or risks - *List (Contaminated groundwater (estimated)/Contaminated groundwater (measured/High risk of contamination/Medium risk of contamination/Low risk of contamination/No risk of contamination/Contaminated/Not contaminated groundwater)*
  - Description - *Text*
  - Include in a catchment protection zone - *List (Yes -close protection zone/Yes - extended protection zone/No)*

Erosion: Is there a proven erosion problem or a risk of landfill erosion?

- Erosion - *List (None/Weak/Severe/Potential)*

Social support: identification of wishes of local residents or associations to see the landfill removed or reduced. Information can be found through press releases, blogs, publications, etc.

- Social support - *List (Yes/No)*
- Description - *Text*

Biodiversity: is there a specific biodiversity to protect on the landfill site?

- Valuable biodiversity on site - *List (Yes/No)*
- Description - *Text*
- Site in Natura 2000 zone - *List (Yes/No)*

Access for landfill mining operations: evaluation of the accessibility conditions (for trucks and equipment) to the landfill. Distances are real distances (by road) and not as the crow flies.

- Paved road - *List (Yes/No)*
- Heavy trucks - *List (Yes/No/An access can be arranged)*
- Distance to main road (m) - *List (<5000 m/>=5000 m)*
- Distance to nearest harbour (m) - *List (<20000 m/>=20000 m)*
- Distance to waterways (m) - *Number*
- Distance to rail station (m) - *Number*

Facilities for landfill mining operations: distance to a waste treatment unit or another operational landfill that can receive ultimate waste from an ELFM project.

- Incineration plant - *List (No facilities identified/On site/<30 km/30 to 50 km/50 to 100 km/>100 km)*
- Cement factories - *List (No facilities identified/On site/<30 km/30 to 50 km/50 to 100 km/>100 km)*
- Waste treatment plant (in general*) - List (No facilities identified/On site/<30 km/30 to 50 km/50 to 100 km/>100 km)*
- Landfill for hazardous waste - *List (No facilities identified/On site/<30 km/30 to 50 km/50 to 100 km/>100 km)*
- Landfill for non-hazardous waste - *List (No facilities identified/On site/<30 km/30 to 50 km/50 to 100 km/>100 km)*
- MBT plant - *List (No facilities identified/On site/<30 km/30 to 50 km/50 to 100 km/>100 km)*

Leachates treatment plant on site: description of the leachate treatment plant related to the landfill.

- *List (Exists and operational/Exists and not operational (to be rehabilitated)/Does not exist/Unknown)*

Leachates treatment plant nearby: distance of the nearest operational treatment plant that could receive leachates from the landfill.

- *List (<10 km/10 to 20 km/20 to 50 km/>=50 km)*

Landfill producing leachates: Is the landfill generated leachates?

- *List (Yes/No/Unknown)*

Landfill geometry

Regardless the nature of waste, this section describes the geometry of the landfill and the associated construction elements that can be found on it.

Landfill Morphology: shape of the landfill and its integration in the surrounding area.

- *List :*
    - *Mound/heap/hill*
    - *Depression/quarry*
    - *Open dump*
    - *50% aboveground/50 underground*
    - *Slope/along a valley*
    - *Lagoon/pond*

Surface state: Description of the landfill surface.
List:

- *Grass*
- *Rough*
- *Shrubs*
- *Trees*
- *Other*

Surface: we distinguished here the area occupied by waste deposits and the parcels of the landfill site that can be quite different. Origin of the data and the way it has been evaluated are important for further analysis.

- Total surface of the site (m²) - *Number*
- Origin of the data - *Text*
- Total surface occupied by waste (m²) - *Number*
- Origin of the data - *Text*

Waste heights/depth: evaluation of the depth/height of the landfill from surface to natural ground. The number is positive (+) if above ground (height) and negative (-) if under the ground level (depth). Origin of the data and the way it has been evaluated is important for further analysis.

- Maximal (m) - *Number*
- Minimal (m) - *Number*
- Average thickness of the waste pile (m) - *Number*

Fragmentation: this field is related to the waste fragmentation: are they located in one single place or spread in several locations?

- *List (In one place/Spread in several locations)*

Stability of the waste mass: this information is related to the probability to encounter any issue related to the stability of the whole mass of waste. "Slope" and "water table" can be measured physically while "risk" will be an appreciation hanging on the nature and age of waste, their thickness, their slope, the presence of water, field observations and experience of similar cases

- Slopes - *List (Steep slopes (more than 15° from horizontal)/Gentle slopes (less than 15° from horizontal)/No slope)*
- Water table - *List (Water table within the landfill (<5 m depth)/Water table within the landfill (<10 m depth)/No water table within the landfill/No information about the water table)*
- Risk appreciation for future excavation works - *List (High risk/Medium risk/Low risk)*

Top layer: type and composition of the top layer of the landfill:

- Watertightness - *List (Presence of a watertightness layer/No specific watertightness layer)*
- Rainwater drainage - *List (Presence of a rainwater drainage/No specific rainwater drainage layer)*
- Gas drainage - *List (Presence of a gas drainage/No specific gas drainage layer)*
- Type of cover – *List (Geomembrane, soil, waste, mineral cover)*

Bottom layer: type and composition of the bottom layer of the landfill:

- Watertightness - *List (Presence of watertightness (clay/geomembrane)/No specific watertightness layer)*
- Leachate drainage - *List (Presence of leachate drainage layer/No specific leachate drainage layer)*

Air Emission: existence of (bio)gas and/or dust emissions.

- *List (Yes/No/Unknown)*

Biogas aerial collection system: information related to gas collection system placed in the landfill, especially if aerial system can hinder geophysics works.

- Presence - *List (Yes/No)*
- Description - *Text*
- Pipes - *List (running in surface/Pipe buried/No pipes)*
- Status - *List (To be decommissioned/In operation/In stanby)*
- Start date - *Date (dd/mm/yy)*
- End date - *Date (dd/mm/yy)*
- Valorisation system - *List (Flare/engine/No valorisation system)*

Landfill Waste materials

This section gathers all suitable information about the waste materials buried in the landfill.

Dates: begin/end of landfill operations/rehabilitation.

- Beginning of landfilling - *Date (dd/mm/yy)*
- End of landfilling - *Date (dd/mm/yy)*
- Beginning of rehabilitation operations - *Date (dd/mm/yy)*
- End of rehabilitation operations - *Date (dd/mm/yy)*
- Beginning of gas collection - *Date (dd/mm/yy)*
- End of gas collection - *Date (dd/mm/yy)*

Main waste type: main known waste stream according to common definitions.

- *List :*
  - *Municipal - household - domestic waste*
  - *Inert waste (construction waste)*
  - *Inert waste (industrial waste)*
  - *Industrial Waste*
  - *Military waste/UXOs*
  - *Mixed waste*

Monolandfill: is the landfill a monolanfill (only one homogeneous waste stream)?

- *List (Yes/No)*

Specific waste stream: specific waste streams as Dredging sludges/ Water purification sludges / Gypsum/ Fly ash / Asbestos / Slags/ Mining waste/ Lime/ Contaminated soils/ Others (free field). Specify the EWC (European waste code) if applicable and the percentage of the total volume of the landfill occupied by this specific stream. Specify how this percentage has been fixed (measured/estimated).

- Dredging sludges
  - Name: Name of the waste stream -Text
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*
- Construction waste
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) – *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*
- Water purification sludges
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*
- Gypsum
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*

- Fly ash
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*
- Asbestos
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*
- Slags
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*
- Mining waste
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*
- Lime
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*
- Contaminated soils
  - Name: Name of the waste stream -*Text*
  - EWC : (European waste code) - *Text*
  - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
  - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*

- Others
    - Name: Name of the waste stream -*Text*
    - EWC : (European waste code) - *Text*
    - Percentage : percentage of the total volume of the landfill occupied by this specific stream - *Number*
    - Specification : Specify how this percentage has been assessed – *List (Measured/Estimated)*

Hazardous waste: this field describes the probability to encounter hazardous waste materials in the landfill.

- *List (Assessed/Possible/None/Unknown)*

Radioactive waste: this field describes the probability to encounter radioactive waste[37] in the landfill.

- *List (Assessed/Possible/None/Unknown)*

Hazardous hospital waste: this field describes the probability to encounter hazardous hospital or medical waste in the landfill.

- *List (Assessed/Possible/None/Unknown)*

Hazardous military waste: this field describes the probability to encounter hazardous military waste deposits in the landfil. The presence of UXO (unexploded ordnance) presenting a tremendous risk must also be precised. UXO (grenades, bombs, etc.) comes from warfare, military exercises and dumping of ammunitions. The risk is always at least possible for the landfill older than 1945.

- *List (Assessed/Possible/None/Unknown)*

Asbestos: this field describes the probability to encounter free asbestos in the landfill.

- *List (Assessed/Possible/None/Unknown)*

Main physical state: this field specifies main physical state of the waste.

- *List (Solid waste/Powdered waste/Sludge/Liquid)*

Leachates: indicates presence of leachates within the landfill.

- *List (Yes/No/Unknown)*

Daily cover: this field specifies if a daily cover was used during landfill operation, the type of cover (geomembrane, mineral cover, soil, waste) and its thickness.

- Use of daily cover - *List (Yes/No)*
- Type of cover - *List (Geomembrane/Mineral cover/Soil/Waste)*
- Origin of cover products -*Text*
- Percentage: percentage of the waste volume occupied by the cover (0 if synthetic) : *Number*

[37] Sources may be medical radioactive elements, or some lightning rods with an head containing Radium 226 or Americium 241, produced in the 80s.

Waste composition: we assume that the landfill can be described with maximum five contrasted layers, following the RDM "resource distribution model" designed by RAWFILL historical and geophysical survey. A 2D or 3D map should be included to identify the different zones for which a lot of properties are precised.
For each zone :

- Zone name : name of the homogeneous zone - *Text*
- Height (m): average height of the layer (m) - *Number*
- Volume (m^3) : volume of the layer (m^3) - *Number*
- Density (T/m^3): average density of the waste in the layer (T/m^3) - *Number*
- Tons buried (T) - *Number*
- Physical State : main physical state – *List (Solid/Powdered/Sludge/Liquid)*
- Homogeneity (macro): see below – *List (Homogeneous/Non homogeneous)*
- Homogeneity (micro): see below - *List (Only one stream/More than one stream)*
- Percentage of Fines : % fine materials (%) (i.e. materials having a grainsize diameter lower than 40 or 50 mm) - *Number*
- Main type : main type of waste - *Text*
- Gas content (%) : average gas content(%) - *Number*
- Water content (%) : average water content (%) - *Number*
- T° (°C) : average T° (°C) - *Number*
- Presence of a water table : presence of a water table within the landill - *List(Yes/No)*
- Begin landfilling – *Date (dd/mm/yy)*
- End landfilling – *Date (dd/mm/yy)*
- Estimated composition - *Text*
- Recyclibality potential : estimated recyclability potential (free text) - *Text*

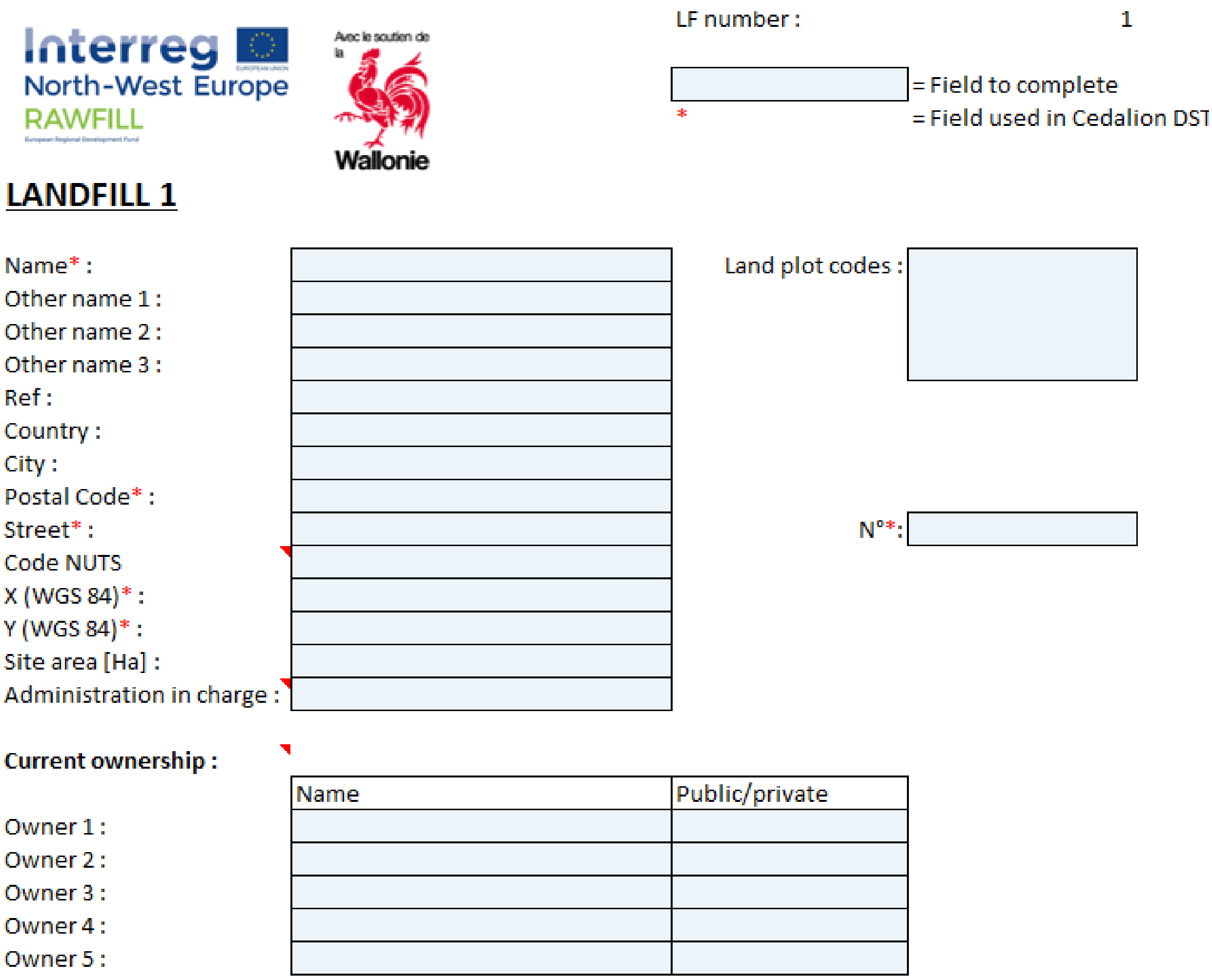
Waste homogeneity: this field specifies if each layer can be considered as homogeneous or heterogeneous, following the definition given in the RAWFILL SWOT analysis deliverable.

	Homogeneous	Heterogeneous
At large scale (macro)	Only one layer of waste can be distinguished: - One single waste stream (monolandfill) - 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.

Appendix B: Screenshots of ELIF tool

LF description

The sheet of the ELIF tool, called "LF description", allows the user to encode general administrative information about the landfill.


LF number : 1

= Field to complete

* = Field used in Cedalion DST

LANDFILL 1

Name* :
Other name 1 :
Other name 2 :
Other name 3 :
Ref :
Country :
City :
Postal Code* :
Street* :
Code NUTS
X (WGS 84)* :
Y (WGS 84)* :
Site area [Ha] :
Administration in charge :

Land plot codes :

N°*:

Current ownership :

	Name	Public/private
Owner 1 :		
Owner 2 :		
Owner 3 :		
Owner 4 :		
Owner 5 :		

Waste description

The waste description tabs is design to encode information about the waste within the landfill. Depending on the level of information, it is possible to use a simplified waste description tabs, or a detailed waste description tabs. This sheet is also used to insert information about the main waste type, the specific waste stream, the presence of hazardous waste, the main physical state, the daily cover and the waste homogeneity.

Legend
= Desactivated fields
= Field to complete
* = Field used in Cedalion

Reset Waste Description form

Total surface of the site* :		m²	Data source :	
Surface occupied by waste :		m²	Data source :	
Total Waste Volume* :		m³		
Type of waste description :	Simplified waste description		Value of the waste materials :	0 €

Simplified waste description

Reset User's notes

Waste	Weight (T)	Cost (-) or Benefit (+) per tonne (€/T)	Total	User's notes
Construction waste			0 €	
Municipal solid waste			0 €	
			0 €	
			0 €	
			0 €	
			0 €	
			0 €	
			0 €	
			0 €	
			0 €	
			0 €	
			0 €	
			0 €	

	Valuable Void created [m³]	Void Value /m³	Total	User's notes
Relandfill/void space value			0,00 €	
		Total	0,00 €	

Detailed waste description

Waste	% (weight)	Volume (m^3)	Density (T/m^3)	Total weight (T)	Recovery factor (%)	Tonnes recovered	€ per tonne recovered (€/T)	Evacuation cost / tonne (€/T)	Cost (-) or Benefit (+) / tonne (€/T)	Total
Ferrous metals	5	500	3	1500	75	1125	50	10	40	45.000 €
Nonferrous metals	5	100	22	2200	75	1650	20	40	-20	-33.000 €
Cardboard/paper	0			0		0			0	0 €
Plastics	0			0		0			0	0 €
Glass/ceramic	0			0		0			0	0 €
Stone/concrete	0			0		0			0	0 €
Rubber	0			0		0			0	0 €
Textile	0			0		0			0	0 €
Wood	0			0		0			0	0 €
Organic	0			0		0			0	0 €
Hazardous waste	0			0		0			0	0 €
Fine matrix	0			0		0			0	0 €
Other waste 1 :	0			0		0			0	0 €
Other waste 2 :	0			0		0			0	0 €
Other waste 3 :	0			0		0			0	0 €
Other waste 4 :	0			0		0			0	0 €
Space		**Volume (m^3)**							**Void value $/m^3$**	**Total**
Relandfill/void space value										0 €
TOTAL	**10,00%**						**TOTAL**			**12.000 €**

Main waste type* :	
Monolandfill* :	

Specific waste stream	%	Data quality
Dredging sludge* :		
Construction waste* :		
Water purification sludge* :		
Gypsum :		
Fly ash* :		
Asbestos* :		
Slags* :		
Mining waste* :		
Lime* :		
Contaminated soils :		
Other : ...		
Total	**0,00%**	

Hazardous waste	
Radioactive waste* :	
Hazardous hospital waste* :	
Hazardous military waste*:	
Asbestos* :	
Other hazardous waste :	

Main physical state :	

Daily cover	
Use of daily cover :	
Cover Type :	
% of the waste volume occupied by the cover :	
Origin of cover product :	

Environmental form

The environmental form describes the impact of the landfill and a potential landfill mining project on the environment. It includes indicators about general risk evaluation, specific environmental issues, surface and ground water vulnerability, air emission, biodiversity, soil contamination and erosion.

ENVIRONMENTAL ASPECT

General Risk Evaluation

Assessment of the main specific potential hazard presented by the landfill. Please note that flooding may be evaluated regarding climate changes aspects. Risk related to groundwater are described hereunder in a specific field "Groundwater vulnerability".

- Flood* : ☐ Flooding Risk level :
- Fire : ☐
- Risk of landfill's collapse : ☐
- Person accident : ☐
- Direct exposition to waste, (bio)gas and/or leachate : ☐
- Other : ☐
- Unknown : ☐

Specific Environmental Issue :

Description of the Specific Environmental Issue

Impact of the LFM project

Surface Water :

Analysis :

Description :

Geological context :

Permeability

Groundwater vulnerability

Groundwater type (factor) :

Groundwater contamination :

Landfill include in a catchment protection zone* :

Average level of upper groundwater table [meter below ground level]:

Short description of the issue :

Landfill producing leachates :

Air emission (e.g., biogas, industrial gas, dust) :

Biodiversity

Valuable biodiversity on site :

Description of the valuable biodiversity :

Site located in Natura 2000 zone* :

Soil contamination :

Erosion * :

Social form

The social form describes the landfill on a social point of view. It provides answers to the following questions: Is there a risk for the neighbourhood linked to the landfill? Is there some Olfactory pollution? What is the use of the landfill and the surroundings? Is there a land planning that includes the landfill zone or a social support for removing the landfill?

SOCIAL ASPECT

General risk Evaluation
Severe risk for human health caused by the landfill : ☐
Olfactory pollution : ☐
Distance from nearest housing [m] :

Land planning :

Current use
Current use of the site of the landfill, regardless its official us
Specifications :
Presence of a touristic area nearby :

Territorial strategy aspects:

Surroundings
Main land use of land within a radius of 50 m around the boundaries of the landfill.

Natural* :	☐ Present	☐ Potential
Agricultural* :	☐ Present	☐ Potential
Forest :	☐ Present	☐ Potential
Residential* :	☐ Present	☐ Potential
Recreational/touristic* :	☐ Present	☐ Potential
Economical/services :	☐ Present	☐ Potential
Industrial* :	☐ Present	☐ Potential

Social support :
Wishes of local residents or associations to see the landfill removed or reduced.
Description of the social support :

Technical form

The technical form includes indicators that reflects the level of technical difficulty encountered to perform a landfill mining project. It contains indicators about status and dates, sampling, leachate treatment, biogas aerial collection system, landfill morphology, waste height/depth, stability the waste mass, as well as the characteristics of top and bottom layers of the landfill.

TECHNICAL ASPECT

Landfill status and dates

Main period of landfilling activities * :

Rehabilitation status :

Sampling :

Leachates treatment plant on site :

Description of the leachate treatment plant related to the landfill :

Leachates treatment plant nearby :

Description of the nearest operational treatment plant that could receive leachates from the landfill (<10, < 20, <50 Km) :

Biogas aerial collection system :

All information about a gas collection system placed in the landfill, especially if the aerial system can hinder geophysics surveys.

Pipes :
Status :
Start date :
End date :
Valorisation :

Description (number of boreholes, trenches, lines of pipes, etc.) :

Landfill Morphology :

Shape of the landfill and its integration in the surrounding area

Surface state* :

Waste height/depth :

Average thickness of the waste deposit [m] :

Maximal height of the waste deposit *(above ground level [m])* :

Maximal depth of the waste deposit *(below ground level [m])* :

Stability of the waste deposit

This information is related to the probability to encounter any issue related to the stability of the whole waste mass.

General slope* :
Water table :
Risk of collapse during future excavation works :

Top layer

Watertightness layer :
Rainwater drainage :
Gas drainage :
Type of cover* :

Bottom layer

Watertightness :
Leachate drainage layer :

Economical form

The economical form includes the indicators used to calculate the profitability of a landfill mining project. It considers the regional policy, the current value in terms of remaining space or the cost (landfill mining operations costs, aftercare costs, remediation costs), the land value and the landfill value content. Some indicators completed in the waste description form and used as economic indicators are automatically filled in the economical form to avoid completing the field twice.

ECONOMICAL ASPECT	
POLICY	
Regional policy encouraging ELFM :	
Regional incentives encouraging ELFM :	
Site specific ELFM facilitation procedures :	
Regional authorisation for in-situ relandfilling :	
Regional authorisation for relandfilling at another landfill :	
Ownership :	
Legal status of the landfill :*	
LANDFILL CURENT VALUE/COST	
Fence/site protection :	
Buried volume [m³] :	
Method used for obtaining the volume :	
Remaining volume before ELFM [m³] :	
Method used for obtaining the volume :	
New available volume :	
Estimation of volume available to receive new waste (i.e. ultimate waste from another ELFM project) or materials (i.e. soil for shaping the final landfill after ELFM operations). In some cases, a large volume can be used for other operations as well.	
New available volume :	
Method used for obtaining the data :	
ELFM costs (waste excavation and remediation costs)	
Estimation of LFM costs [€] :	1 €
Annual aftercare costs	
Estimation of annual aftercare costs [€/year] :	1 €
Start of aftercare procedure [date : dd-mm-yyyy] :	
End of aftercare procedure [date : dd-mm-yyyy] :	
Remaining aftercare duration [total years] :	
Total aftercare costs remaining [€] :	
LAND VALUE	
Territorial strategy aspects :	
Land pressure :	

Interreg North-West Europe RAWFILL

European Regional Development Fund

EUROPEAN UNION

Co-funded by the Walloon region

LANDFILL MINING COSTS

Evaluation of the accessibility conditions (for trucks and equipment) to the landfill. Distances are real distances and not as the crow flies.

Access for landfill mining operations

Paved roads* :
Heavy truck access (> 30T)* :
Distance to the main road :
Distance to the nearest harbour :
Distance to the nearest waterways [m]* :
Distance to the nearest train station [m]* :

Facilities for landfill mining operations

Distance to a waste treatment unit or another operational landfill that can receive ultimate waste from an ELFM project.

Incineration plant :
Cement factories :
Waste treatment plant (in general) :
Landfill for hazardous waste :
Landfill for non hazardous waste :
Mechanical biological treatment plant :

Leachates

Leachates treatment plant on site :
Leachates treatment plant nearby :
Landfill producing leachates :

Fragmentation :

WASTE

Main waste type :

Specific waste stream	%	Data quality
Dredging sludge* :	0	
Construction waste*:	0	
Water purification sludge* :	0	
Gypsum :	0	
Fly ash* :	0	
Asbestos* :	0	
Slags* :	0	
Mining waste* :	0	
Lime* :	0	
Contaminated soil :	0	
Other : ...	0	
Total	**0,00%**	

Hazardous waste

Radioactive waste* :
Hazardous hospital waste* :
Hazardous military waste*:
Asbestos* :
Other hazardous waste :

Main physical state :

Daily cover

Use of daily cover :
Cover Type :
% of the waste volume occupied by the cover :
Origin of cover product :

Waste composition (from table)

12.000,00 €

Waste homogeneity (for each layer)	**Homogeneity**	**Volume of the layer/landfill volume [%]**
Layer 1		20,00%
Layer 2		10,00%
Layer 3		10,00%
Layer 4		0,00%
Layer 5		0,00%
	Total	**0,00%**

Additional Information

The additional information sheet is used to encode additional information that are not directly related to the evaluation of the landfill mining potential but are useful either for dynamic landfill management or to perform a landfill mining project. It includes a series of administrative information: data about who was responsible for the filling of the ELIF file, regulatory context, historic, permits, studies and analysis.

Avec le soutien de la Wallonie

Additional information

Reset this form

GENERIC INFORMATION

ELIF datasheet responsible
Name: Function :

Creation date [dd-mm-yyyy] :

Date of updating [dd-mm-yyyy] :

REGULATORY INFORMATION

Regional policy encouraging ELFM:

Regional incentives encouraging ELFM:

Dates of landfill ban:

Name of the stream (metals, organics, hazardous waste, EOL vehicles...)	Regional code of the restricted stream (when it exists)	Date of applicability of the restriction	Type of restriction:

Site specific ELFM facilitation procedures
Reference :
Signature date :
Expiration date :
Summary :

Regional authorisation for in-situ relandfilling:

Regional authorisation for relandfilling at another landfill :

Landfill ID card

Permits

Reference	Date of autorisation	Expiration date	Nature of permit	Permit Holder

Landfill operator(s)

	Name	Start date	End date
Operator 1 :			
Operator 2 :			
Operator 3 :			
Operator 4 :			
Operator 5 :			

Landfill type (EU Directive) :

Landfill status and dates

Usage status :

Landfill operation :

Start date : End date :

Rehabilitation

Start date : End date :

Aftercare period

Start date : End date :

Landfill monitoring

Monitored :

Company in charge of the monitoring :

Start date : End date :

Warranties given

Cost *(€ excluding taxes, VAT, etc.)* :

Studies

Reference	Title	Date	Main author(s)	Confidentiality

Sampling

Reference	Date	Author	Sampling method	Analysis

Historical Information

Date	Historical activities/Description/Historical data

Resource Distribution Model

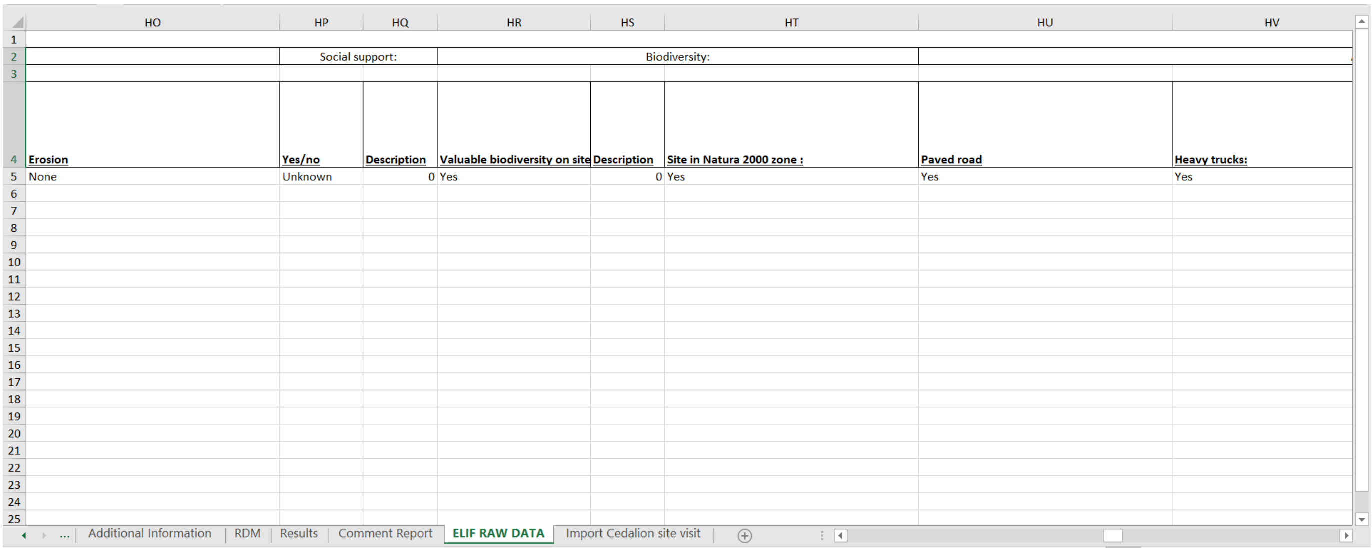
A dedicated sheet is used for the resource distribution model (see **Chapter 4.7**) for more information). The resource distribution module helps to describe the different homogeneous waste layer identified by the RAWFILL characterization methodology.

Comment Report

In the comment report sheet, the button *"Generate a User's note report"* creates a report containing all the user's notes of the 11 sheets.

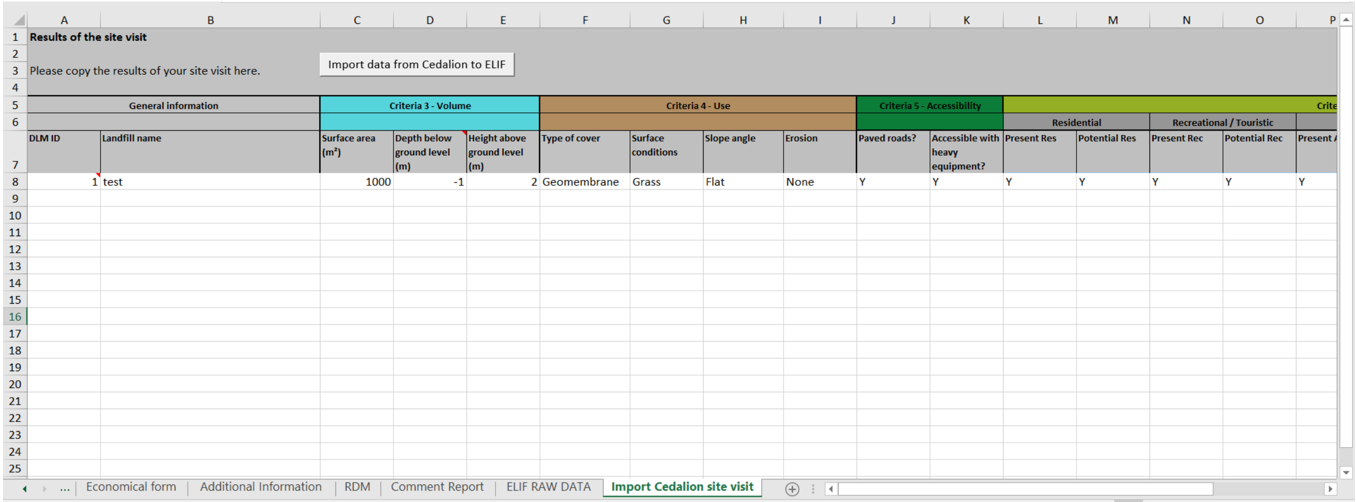
ELIF RAW DATA

The ELIF RAW DATA tabs summarizes all the information of the *RAWFILL LF#.xlsm* file in a single table. This table can then be exported to an existing database. To export data about multiple landfills (i.e. more than one *RAWFILL LF#.xlsm* file*)*, the user should instead use the ELIF RAWDATA sheet of the *RAWFILL ELIF.xlsm* file.



Import Cedalion site visit

ELIF can be automatically filled with the site visit report of the field tool of DST1- Cedalion. In order to do that, the user can copy/past the result of the field visit in this sheet and click on the button *"Import data from Cedalion to ELIF"*. **<u>Caution:</u>** this process may overwrite previously encoded data.



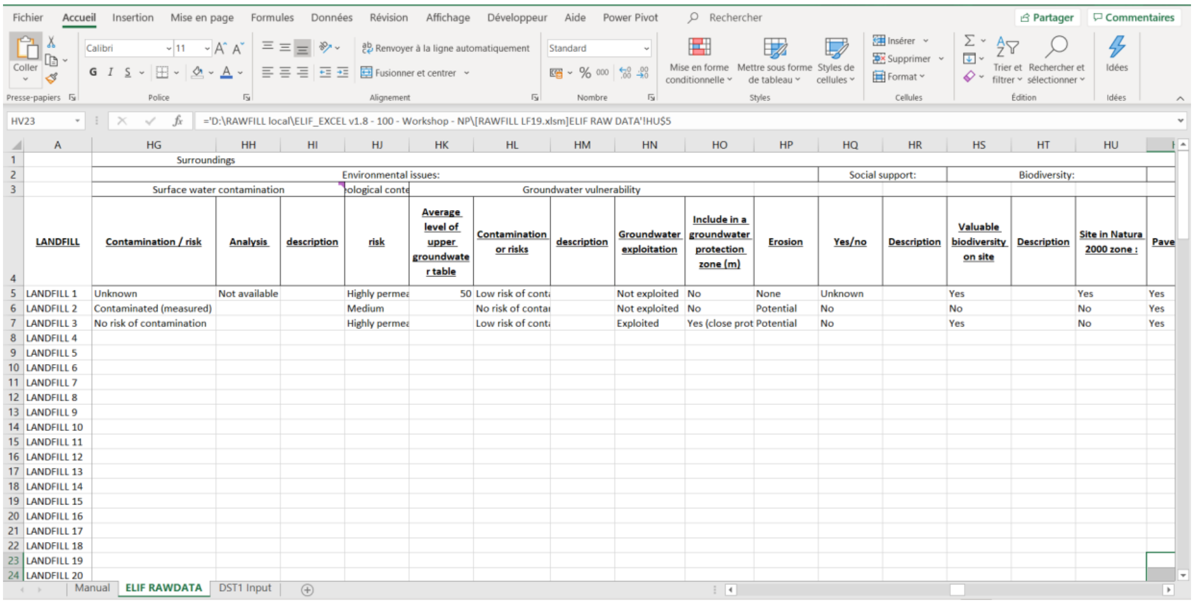
2. RAWFILL ELIF file

The *RAWFILL ELIF.xlsm* file consists of three sheets:

4. Manual: this page describes how to use the tool.
5. ELIF RAW DATA
6. DST1 INPUT

ELIF RAW DATA

The ELIF RAW DATA sheet contains a table that summarizes the information of all *RAWFILL LF#.xlsm files.* This table can then be exported to an existing database.



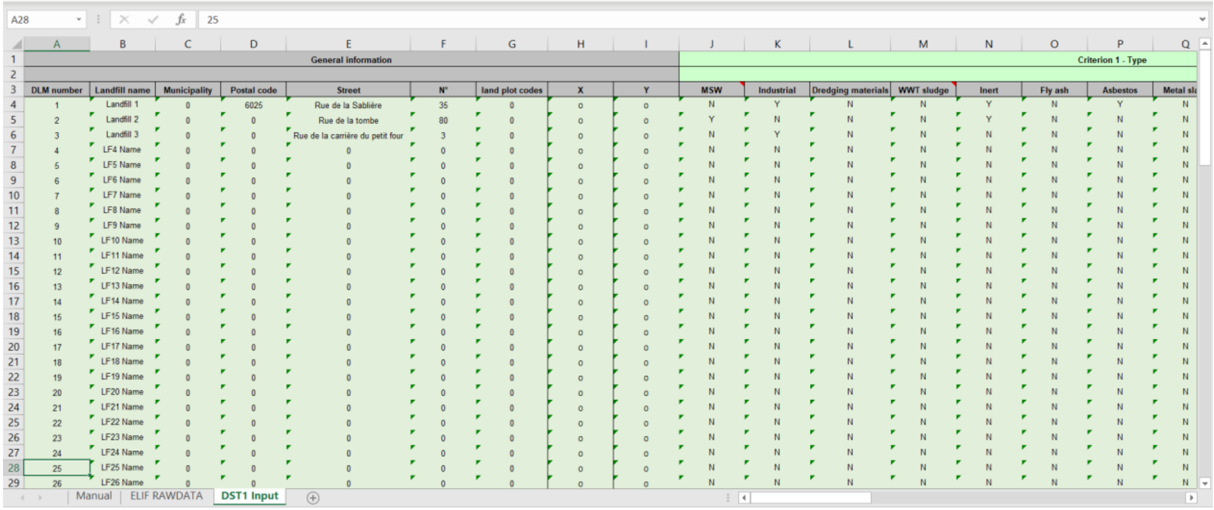
HV23 | ='D:\RAWFILL local\ELIF_EXCEL v1.8 - 100 - Workshop - NP\[RAWFILL LF19.xlsm]ELIF RAW DATA'!HU$5

	A	HG	HH	HI	HJ	HK	HL	HM	HN	HO	HP	HQ	HR	HS	HT	HU	
1		Surroundings															
2		Environmental issues:										Social support:		Biodiversity:			
3		Surface water contamination			ological conte	Groundwater vulnerability											
4	LANDFILL	Contamination / risk	Analysis	description	risk	Average level of upper groundwater table	Contamination or risks	description	Groundwater exploitation	Include in a groundwater protection zone (m)	Erosion	Yes/no	Description	Valuable biodiversity on site	Description	Site in Natura 2000 zone :	Pave
5	LANDFILL 1	Unknown	Not available		Highly permea	50	Low risk of conta		Not exploited	No	None	Unknown		Yes		Yes	Yes
6	LANDFILL 2	Contaminated (measured)			Medium		No risk of contai		Not exploited	No	Potential	No		No		No	Yes
7	LANDFILL 3	No risk of contamination			Highly permea		Low risk of conta		Exploited	Yes (close prot	Potential	No		Yes		No	Yes
8	LANDFILL 4																
9	LANDFILL 5																
10	LANDFILL 6																
11	LANDFILL 7																
12	LANDFILL 8																
13	LANDFILL 9																
14	LANDFILL 10																
15	LANDFILL 11																
16	LANDFILL 12																
17	LANDFILL 13																
18	LANDFILL 14																
19	LANDFILL 15																
20	LANDFILL 16																
21	LANDFILL 17																
22	LANDFILL 18																
23	LANDFILL 19																
24	LANDFILL 20																

Manual | ELIF RAWDATA | DST1 Input

DST1 Input

The DST1 input sheet converts the RAWFILL ELIF table into a table that can be directly copy/past into DST 1 - Cedalion. The DST 1 - Cedalion is then used to provide a quick ranking and select the best use for each landfill. More details about the DST 1 – Cedalion are provided in the following chapter.



General information									Criterion 1 - Type							
DLM number	Landfill name	Municipality	Postal code	Street	N°	land plot codes	X	Y	MSW	Industrial	Dredging materials	WWT sludge	Inert	Fly ash	Asbestos	Metal sla
1	Landfill 1	0	6025	Rue de la Sablière	35	0	0	0	N	Y	N	N	Y	N	Y	N
2	Landfill 2	0	0	Rue de la tombe	80	0	0	0	Y	N	N	N	Y	N	N	N
3	Landfill 3	0	0	Rue de la carrière du petit four	3	0	0	0	N	Y	N	N	N	N	N	N
4	LF4 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
5	LF5 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
6	LF6 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
7	LF7 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
8	LF8 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
9	LF9 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
10	LF10 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
11	LF11 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
12	LF12 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
13	LF13 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
14	LF14 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
15	LF15 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
16	LF16 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
17	LF17 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
18	LF18 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
19	LF19 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
20	LF20 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
21	LF21 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
22	LF22 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
23	LF23 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
24	LF24 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
25	LF25 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N
26	LF26 Name	0	0	0	0	0	0	0	N	N	N	N	N	N	N	N

Appendix C: Questionnaire for Stakeholders

Questionnaire as per Einhäupl *et al.* (2019):

- What is a landfill to you?
- Can you, in general, describe what advantages and/or disadvantages having landfills comes with?
- When you think about the landfill site, do you have positive or negative associations?
- Are you familiar with the concept of LFM/ELFM?
- Do you think LFM/ELFM should be done?
- What projects about LFM/ELFM are you involved with?
- What are the main advantages/opportunities you see in LFM/ELFM projects?
- According to you, which are the main environmental benefits of LFM/ELFM?
- What main disadvantages/risks do you see with the realization of an LFM/ELFM project?
- According to you, which are the main negative environmental impacts/risks of LFM/ELFM projects?
- According to you, which are the main challenges for the realization of LFM/ELFM projects?
- What economic drivers and/or barriers can you identify?
- What regulatory instruments do you know affecting LFM/ELFM projects?
- Where do you see markets for the products/outcomes of LFM/ELFM?
- What societal challenges do you expect/have you experienced in LFM/ELFM projects?
- According to you, which are the most influential actors when it comes to the planning and realization of LFM/ELFM projects?
- Who do you think is/ should be responsible for regulating and/or communicating LFM/ELFM?
- How do/does the authorities/your institution deal with uncertainties concerning LFM/ELFM projects?
- How happy are you with the role of institutions/authorities when it comes to LFM/ELFM?