WP T3.3.1. Lessons learned & recommendation report

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Introduction

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 enhanced landfill mining (ELFM) project 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 ELFM projects.

In addition, within the framework of the RAWFILL project, several tools and methodologies have been developed to facilitate the implementation and the development of the landfill mining project across Europe:

1. An evidence-based, cost-effective enhanced landfill inventory framework (ELIF). This inventory integrates all aspects related to landfills: administrative, environmental, social, technical and economical;
2. An innovative landfill characterization methodology by combining geophysical imaging and targeted waste sampling;
3. A two-step Decision Support Tool (DST 1-Cedalion and DST 2-Orion) to allow smart landfill mining project planning, prioritization and interim use.

During this four and half year project, RAWFILL project partners have faced and tackled some legislative and technical barriers. The aim of this report is to summarize the lessons learned during the RAWFILL project. A series of recommendations for the stakeholders and future landfill mining investors is also addressed. The lessons learned and recommendations are divided in subcategories to facilitate the reading : data collection, Enhanced Landfill Inventory Framework, Decision Support tools, desk study, geophysical investigations, waste sampling, building a resource distribution model, value for money of geophysical characterization, landfill mining operations, preliminary assessment of environmental and social impact and long-term effect. This report is aimed to anyone interested in landfill mining and sustainable waste management.

1. Data collection

1.1. Analyze of the current Landfill inventory structures within NWE regions & countries

The collection of landfill inventory structures revealed that it is more difficult to get information from private companies having landfill inventories than from public bodies. Some public bodies were very interested to participate to the study, especially when they were already involved in ELFM projects (for instance, the Département des Pyrénées-Atlantiques in France). The analyze of the current Landfill inventory structures showed that the development of the ELIF structure was a real need as none of them contained ELFM information.

1.2. Benchmark of existing ELFM initiatives

It was very difficult to get detailed information as most of the ELFM projects were considered as confidential. In addition, private companies were not keen to share their economic benefits related to ELFM project.

The benchmark performed in the framework of the RAWFILL project showed that the recovery of raw materials from landfills is not the only driver to start an ELFM project. Most of the time, it is not even the main driver. The identified drivers are multiple, they can be related either to reclaiming land (e.g., redevelopment project in a high land pressure area), environmental risk (e.g., flooding risk, pollution), health issues, landscape visual impact, or regaining void space (in case of a landfill still in operation), among others. As each landfill is quite specific on its own, it is highly recommended to have a deeper view into the landfill and its surroundings to find the most appropriate driver for ELFM project.

Regarding the economic benefits, the benchmark highlighted that the recovery of land (especially in areas characterized by high land value) and the implementation of redevelopment projects were the most effective way to ensure the economic viability of the ELFM project. For the moment, the promotion of ELFM only by focusing on material recovery or circular economic considerations has little impact. The benchmark identified a series of reasons explaining why the existing initiatives were not economically successful:

- Not assessing the presence of asbestos, therefore a lot of work precautions had to be taken during the excavation increasing the processing cost of waste materials. To solve this issue, the ELIF included the possibility to integrate asbestos quantities into the description of the waste mass.
- Bad estimation of volume due to soil irregularities and unexpected buried volumes of waste materials. For this issue, we recommend using multi-methods geophysical imaging combined with targeted sampling in order to improve the estimation of waste volumes (*see below for further information*).
- Bad estimation of waste composition based on too simplified historical studies illustrated the necessity to perform more detailed historical studies (when it is possible) and to describe the waste composition more precisely (*see below for further information*).
- The overestimation of the selling prices of metals and other materials. It was necessary to assess better the quality of metals and other materials in order to evaluate the profitability of the valorization. This data is now included in the business model.
- The percentage of "fine" materials that cannot be valorized was generally higher than expected (more than 40%).

The benchmark confirmed the interest to provide stakeholders with RAWFILL content: ELIF, DSTs, multi-methods geophysical imaging, and a standard waste description.

1.3. SWOT analysis of landfill content characterization methods

Using geophysical imaging methods to characterize landfill content is not new. However, the results obtained by landfill managers were often not satisfying explaining why people were reluctant to use these methods. A stakeholder experience survey, performed by RAWFILL, showed that most of them only used mono-method geophysical imaging, which did not supply accurate information. The RAWFILL multi-methods approach in combination with targeted sampling is currently the only suitable methodology to fully characterize the landfill geometry and its waste content with precision.

The survey also revealed that there was a lack of standardized waste description. Large variation in the waste description could occur depending on the enterprise/operator in charge of it, making difficult waste correlation and often providing incomplete data. Therefore, there was a need to provide a standardized waste description method integrating data that can be useful for ELFM project developers. Following this observation, the RAWFILL project developed a standardized waste description method (*see dedicated section in the Landfill miner guide*).

Value-for-money of the RAWFILL methodology vs. traditional investigation methods was demonstrated with the SWOT analysis. The methodology developed by the RAWFILL project, based on "preliminary information gathering, geophysical studies combining several methods, targeted sampling, calibration/validation and construction of resource models", is the most suitable for landfill characterization. The coupling between geophysical measurements and targeted waste samples provide a more accurate mapping of the landfill content, and is cheaper and faster. We recommend to always characterize the landfill content using at least the multi-method geophysical imaging combined with targeted waste samples.

2. Enhanced Landfill Inventories Framework (ELIF)

Enhanced Landfill Inventory Framework (ELIF) combines all aspects related to landfills: administrative, environmental, social, technical and economical. The added value of this landfill inventory structure is that it includes parameters regarding the economic potential and the social impact of landfill sites. It has been quite challenging to define and quantify the final list of relevant indicators but exchanges between partners led finally to a reliable result. Based on these indicators, an ELIF software was developed in Excel format. Numerous tests were necessary to fine tune indicators and the ELIF software. The software structure was designed to be as simple and useful as possible. The ELIF software contained several spreadsheets for each topic (i.e. administrative, environmental, social, technical and economical) with the relevant indicators. In order to compare the landfills and import the data in the Cedalion (DST 1), most of the indicators can be filled by using multiple choices (list box). In addition, some fields with free text were also necessary to allow the user to specify some indicators. For technical reasons, these “free text” fields cannot be imported in the DST 1-Cedalion. As it is important to quantity the level of knowledge (quantity and quality of the indicators completed in the ELIF) of each landfill before comparing them, the calculation of a completeness rate was included in the software.

The testing of the ELIF showed that the ELIF is a very complete and useful structure. Some indicators are, however, difficult for landfill owners to collect. As the structure is very complete and contain many indicators, it is totally normal if all the indicators cannot be completed directly. The completion of the ELIF is a long process that should be done at each step of the landfill mining project implementation (*see Deliverable T3.1.2. ELIF performance report for more information*).
The testing phase identified that the weakness of the ELIF is its format. Using an excel file is suitable for small landfill database. However, it is incompatible with large database as all the indicators should be completed manually. This is why we recommend to directly implement the ELIF indicators directly into the regional and national landfill database.

2.1. Integration of the ELIF structure into a database

In order to demonstrate that the ELIF structure could be coupled with an existing database, several indicators from each ELIF category were selected to be integrated into the Walloon database, Walsols. Before starting the integration, we strongly recommend translating the ELIF indicators in the language of the database (in this case, French). Reflexions were made on how to transform the ELIF excel files into a language compatible with the existing database and where to insert the ELIF indicators in order to make the database more performant.

For that purpose, we made visual screens. Then, these visual screens were translated into computer language. Here, the technologies used were :

- For the principal framework : ASP.NET MVC 5
- For the language : C#
- For the framework .NET : 4.7.2
- For the database : SQL SERVER
- To get access to the database : EntityFramework 6.4.4 & ADO.NET
- For user interface (front end): HTML 5, CSS, Javascript, LINQ, JSON, XML.

The development was done following the principle of the agile methodology. During the development, weekly meetings were done with the software developer team to present the new functionalities developed during the previous week, and to discuss and validate each integration. Weekly testing of the new implemented functionalities were also performed in order to either improve or validate them.
In this case, the database was linked with a GIS database. Therefore, after the integration of selected indicators into the database, some of them can be automatically filled, especially the ones linked with GIS layers (eg. land use, surface area, drinking protection zone). For the indicators which could not be filled automatically, it should be done manually. This step takes time and should be done regularly in order to keep the database updated with the new findings. In the future, new GIS module would be implemented to calculate the distance between the landfill to the waste treatment facilities to increase the number of indicators that are filled automatically. It is also important to implement a function to export the data directly into an excel file to import the data into the DST 1-Cedalion, which is currently still in Excel format. The structure of this file is already provided in the ELIF Excel software – spreadsheet "DST 1 Input".

Suggestions for future development of the ELIF:
In order to enhance the ELIF Excel software, a more powerful and more stable user-friendly software or web application should be proposed in the future, to supply a full autonomy tool for stakeholders. This would allow the exchange of data between users.
Another suggestion is to include carbon footprint indicators in the ELIF as climate change is one of the priorities for EU but the evaluation of greenhouse gas for landfills remains quite complex.

2. Decision Support Tools : DST 1-Cedalion and DST 2-Orion

2.1. Overall findings

From the perspective of a landfill owner, it made much sense to split the Decision Support Tool into two parts, one for a first rough ranking (DST 1-Cedalion) and the second for an in-depth decision-making process for experts (DST 2-Orion). In most cases landfill owners, stakeholders or authorities need a first guidance to make a decision into the right direction. DST 1-Cedalion was designed to be easily used by everybody (e.g., civil servants, landfill owners, etc.). The tool should be promoted in every region on the lowest administrative level that deals with (old) landfills in order to ensure a future use of the landfill site. The online field application was added to DST 1-Cedalion in order to create a better involvement of the local stakeholders. By delivering an easy to use application, the threshold of experimenting in the field is lowered. This creates not only more local involvement but also a better detection of opportunities in the vicinity of the landfills. Thereafter experts can take over and develop business cases.

The RAWFILL project provides landfill owners, stakeholders and authorities with a clear step by step methodology to find out about ELFM potential of the landfill site and the possibility of interim use of the site. The user should keep in mind that the DSTs only provides a static snapshot at a giving time. The results obtained should be reevaluated and revalidated after a while by running again the DSTs. The number of highly feasible ELFM project will be very low due to the content of the landfills and the current system conditions: low commodity prices (and demand) and limited environmental risks. The limitation of financial, technical and human resources also requires a prioritization of landfill sites where investigations should be executed. The RAWFILL ranking delivers valuable elements to set up such a long-term planning and provides guidance for a sustainable and profitable use in the meantime. This interim use of the site can be either for a relative short-term (energy crops) or long-term (solar panels, building new infrastructure, nature redevelopment). For some landfills such as the ones characterized by a large volume of non-valuable waste materials and limited environmental impact, ELFM would never be an option due to the prohibitive cost of the ELFM operations. For them, interim use might be the final option.

2.2. Case study: determining the potential for forestation of landfills in cooperation with local authorities in Flanders

2.2.1. Exploration

In Flanders, a large-scale application of the DST 1-Cedalion was set up, to support the project "Landfills and nature redevelopment opportunities". This project was related to the ambition of the Flemish Minister of Environmental Affairs to achieve 4,000 ha of additional forest by 2024. In Flanders, open space is scarce and hence, it is hard to find locations that can be used to create extra forest areas. Therefore, the RAWFILL project partner OVAM explored the possibilities of landfills contributing to this goal, as these are often abandoned areas that have no current societal value. In that way, a sustainable interim use with a high value for the society can be installed. In order to achieve this goal, OVAM implemented the knowledge and tools that were created within the RAWFILL project.

In a first step, the useful data from the Flemish landfill database were exported to the DST 1-Cedalion. In total, the Flemish Cedalion database contained 3,318 landfills to explore the theoretical possibilities of afforestation and nature development on landfills. This database was shared in GIS format with the Governmental Agency of Nature and Forest (ANB). They applied some criteria in order to determine the afforestation potential on all the landfills present in our database to estimate the potential contribution of landfills to the afforestation goal of the minister.

Furthermore, the Ruimtemodel Vlaanderen from VITO, which is also included in the DST 2-Orion, was used to determine the landfills with high potentials. They were identified by taking into account the land pressure of the land. When the land pressure is lower, the land value is also lower and the potential for afforestation increases.

2.2.2. Implementation

Based on the promising results of the first exploration with the RAWFILL tools, OVAM developed an implementation plan in cooperation with ANB to plant additional forest on landfills in Flanders. In the first place, there was decided to mainly aim the approach at the local authorities, as they have the best view on the actual possibilities on site. If a landfill appeared to have a high potential in the exploration phase, it does not mean that it is suitable for actual afforestation in practice. An on site check with owners and stakeholders is always necessary to affirm the actual potential of landfills for afforestation. Hence, it was decided to approach the local authorities, with the question to check the possibility of afforestation on the landfills that are in their property.

In practice, a letter was sent to all local authorities for which OVAM documented old landfills in the Cedalion database. In total, there were 296 local authorities. Each local authority received: (1) a letter sent from the office of the Minister of Environmental Affairs, stating the purpose, conditions and benefits of the project and (2) a map with the identified landfills present in the Cedalion database.
On the map, the QR code of the Cedalion field application was included. In that way, the local civil servants are able to digitally share information on the landfills with OVAM by means of a simple smartphone device. This sort of civil servant science provides OVAM information on the interest of municipalities to set up nature conservation and/or forestation projects. Furthermore, the Cedalion database is validated and updated based on the local knowledge of the local authorities.
In the letter, also some financial aspects are included. According to the Flemish soil legislation, all landfills should be investigated by means of a Preliminary Soil Investigation (OBO) before 2024. If the local authorities intend to upgrade a landfill to a forest or other nature, and a Preliminary Soil Investigation is not performed yet, OVAM will perform the investigation at its expense. During that investigation, OVAM will also analyze the afforestation potential from an environmental technical point-of-view. Namely, for some landfills afforestation will not be possible due to certain characteristics of the landfill (eg. hazardous waste, capping of the landfill). To determine this potential, a flow chart[1] was developed in order to determine that (1) afforestation is possible, (2) afforestation is possible under certain conditions or (3) afforestation is not possible. Thereby, also specific advice is given on measures that should be taken when you afforest a specific landfill and which prevention measures should be taken to guarantee the safety of the users.

Two months after the letter was sent, we received a reaction from 126 of the municipalities (42%). From 126 local authorities, 34 signed up to the project with specific landfills for which they see an opportunity for afforestation. 43 local authorities responded negatively to the proposal, indicating that no landfill is suitable for the project proposal. However, the majority of the local authorities (49) asked for more information on the specific location and the characteristics of their landfills.

In response to the large demand for more information, OVAM decided to share the Cedalion database with the local authorities. However, because of the GDPR, it is not easy to find a suitable strategy to share data on such a large scale. It was not possible to share the whole dataset of 3,318 records with all the local authorities. Therefore, it was needed to find a way to share the specific data of the local communities in a way that is not too time consuming. In Flanders, the local authorities have access to a specific municipal web-based platform, where we can share GIS files with the civil servants. Therefore, the data from the Cedalion were transferred into the attribute table of a GIS format. In that way, the local authorities can consult the specific location as well as the Cedalion data for their specific area. Moreover, they can now consult the data concerning the landfills that is available at OVAM, and validate/update this information. With the GIS file, a descriptive document was added,

[1] https://www.nweurope.eu/media/14342/wp_t231_afforestationdecisiontree_dst2.pdf

explaining the different criteria present in the attribute table of the GIS layer. In that document, they can find the QR code as well to upload the data.

2.2.3. Lessons learned and recommendations

As it can be seen in the response rate of the local authorities, the approach did not miss its goal. The local authorities are not only informed on the policy on afforestation, but they are also reminded of the number of old landfills that they have in their municipality. By means of this communication, some awareness has been created on the existence of these landfills and the opportunities for Dynamic Landfill Management – a reminder to tackle the challenges that are linked to old landfills.

Unfortunately, many local authorities were not motivated to share information by means of the QR code. Based on the questions that we received from local authorities, we noticed that the first questions "DLM ID?" and "Landfill Name" were not entirely clear. In the map of the letter, we communicated the ID as "Identification number of landfill". However, the link with DLM ID was not clear enough. Hence, denominations should be used very consistently in the communication process with possible users. Further, the "Landfill Name" could be any name related to the landfill. The user expects that it should be a specific predetermined name. This can be solved by appending a specific, short and comprehensive manual, where each step of the field application is briefly explained. For the local authorities in Flanders, a manual is available in Dutch on YouTube.

The local authorities often asked for more information on the exact location of the landfills. Although the GPS coordinates were present in the Cedalion database, the exact areas of the landfills were not known. Hence, it would be interesting to couple the Cedalion dataset or field application with landfill data present in a Geographic Information System (GIS). In that way, spatial analyses can be performed and the right cadastral parcels can be determined.

It was also notable that the local authorities preferred to share information with us by means of a different data format than the QR code. Some shared information by means of an Excel file, some shared information by email, some by means of a short note. In that way, it was more difficult to standardize the received information and included it in our Cedalion database. However, the fact that local authorities were sharing their information, interests and initiatives was already an important step forward a Dynamic Landfill Management in Flanders.

3. Geophysical investigations performed on landfill sites

3.1. Desk study and prior information collection

An analysis of the landfill, its surroundings and its historical activity – when it is available – is required prior to the geophysical investigations in order to select the most suitable geophysical methods to characterize the selected landfill. However, the historical activity of the site is not always documented. Discussions with the local population can provide valuable information but further investigations should be done in order to verify it.
The analysis of satellite images taken in different periods of time can also be interesting:

- to detect the main landfilling activities on site;
- to predetermine the landfill lateral extension;
- to identify different layers of waste deposits;
- to detect the potential presence of unexploded WWII bombs.

The presence of bomb craters can be clearly identified with satellite images. Particular attention should be done if the landfill is older than 1944 and located close to train stations or other well-known targeted structure during WWII, and/or if circular depressions identified as bomb craters are present on the satellite image. Statistic studies showed that in average 10% of the bombs did not explode (UXO or unexploded ordnance). The landfill mining activities on this type of site are still possible but extra caution should be taken during the different phases of the project (mainly for the waste sampling, waste excavation).

Before any geophysical investigation study, a site visit is necessary to identify potential disturbances/noise sources on the landfill (e.g. fences, metallic objects on the surface) and to check the accessibility (vegetation, etc.). In some cases, site clearance could be necessary to perform geophysical measurements on site.

3.2. Geophysical survey

Before starting a geophysical survey is important to identify the needs (e.g., definition of volume, lateral extension of the landfill). This evaluation coupling with the a priori data collection will serve as a base to define the most suitable geophysical measurements to apply on a specific site. For instance, if the landfill surface is covered with a geomembrane, electrical resistivity tomography (ERT) would not work properly as the electrical signal would be blocked by the geomembrane. Therefore, this method will not be chosen. A summary of the geophysical measurements with their strength and weakness is provided in **Table 1**.

		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

Table 1 - 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.

Geophysical characterization could be carried out in two steps. First, a quick survey of the landfill should be conducted using geophysical mapping methods (electromagnetic induction or magnetic) if the aim is to identify the lateral zonation of waste. In a second step, in order to investigate identified zones in more detail, profiling methods (such as electrical resistivity tomography or induced polarization) providing better vertical resolution can be applied.

Estimation of waste thickness using geophysical methods has been successful in most of the cases investigated within the RAWFILL project. The best results were obtained when the contrast of physical properties between the waste material(s) and the host geology was high (e.g. when the waste lies directly on the bedrock). However, in all cases, the larger the waste thickness, the more difficult it is to estimate with geophysical methods (due to their inherent loss of resolution with depth and the generally limited space available to deploy equipment). In that respect, only passive seismic can provide valuable information, but it absolutely requires calibration points as well as a sufficient impedance contrast between the waste and the natural ground.

Among the profiling methods tested, seismic refraction tomography (SRT) which, in theory, is well suited to retrieve landfill structure did not provide good results on the RAWFILL landfill pilot sites, except for the landfill of Onoz where the impedance contrast between the bedrock and the waste material was sufficient enough. The reasons for this are multiple: high noise levels, lack of contrast between the waste and the natural ground, too low acoustic velocity in the waste material.

Another lesson learned is that a good communication and coordination are required during the geophysical survey with the landfill manager especially if the landfill is still in operation or other works are carried out simultaneously in order to ensure the safety of the operators on site.

The RAWFILL project focus mainly on Municipal Solid Waste (MSW). More diversity in the type of waste studied would have been beneficial to the project.

5. Waste sampling

On municipal solid waste landfills, sampling data from boreholes are not necessarily well correlated with geophysical data. The main reason is that the volumes studied with the two approaches are not the same. A borehole will provide high-resolution images very locally (punctual information), whereas geophysical methods incorporate a larger volume but with a lower resolution. Borehole data are not representative of the heterogeneity found in these landfills. Moreover, too small borehole diameter might not provide representative samples since waste items with a larger diameter could be "pushed to the side". However, boreholes can still be used to detect interfaces between distinct waste facies. In this particular case, they are very useful for geophysics. Otherwise, in general, preference should be given to trenches and trial pits that incorporate a larger volume (with the disadvantage of a limited depth of investigation). For each waste sample/borehole/trial pit/trench, it is important to document it with spatial location, scale, photographs material fractions and describe it using the standardized waste description method (*see dedicated chapter in the Landfill Miner guide*).

Ideally, every detected geophysical anomaly should be sampled in order to provide a detailed correlation analysis. Properties of interest must be quantified (e.g. wet/dry or material fractions) to correlate/calibrate it with the geophysical measurements and translate it into a resource distribution model.

Concerning the temperature measurements of the waste samples which provide useful information regarding the biodegradation process, it was impossible to do it for the waste samples collected from the boreholes as the drilling technique tends to heat up the waste materials. Therefore, we recommend performing temperature measurements only for the waste samples recovered from trenches or trial pits.

6. Building of a Resource Distribution Model

For the building of a resource distribution model (RDM), data collected on the RAWFILL pilot sites with geophysics and targeted waste sampling did not allow to separate and quantify materials composing the waste deposits (e.g. ferrous material = X tonnes, plastic = X tonnes). This would have required further laboratory analysis but would also have taken much longer. Moreover, as most of the studied sites consisted mainly of municipal solid waste, the heterogeneity of the waste composition did not guarantee to obtain better results.
It should be noticed that the geometry of old landfills is seldom well known due to various reasons (no archives, limited data available, fraud …). In those cases, even a simple RDM which only describes the top layer, the landfilled waste body and the delineation with the environment is already an improvement and lowers uncertainties on volume and type of materials. Building of a resource distribution model using machine learning can be a good method helping to bring all data (having different resolutions) into one model. To go further with the data interpretation and the RDM, we recommend including uncertainties in it.

7. Value-for money of HADESS methodology

Within the RAWFILL project, an innovative landfill content characterization methodology, called HADESS (High-performing Acquisition of landfill Data by using a geophysical Exploration and Surveying Strategy), was developed. This methodology is based on the coupling between multi method geophysical investigations and targeted waste samples. More information regarding the methodology can be found in the Landfill Miner guide. The cost benefit analysis performed on two RAWFILL pilot sites showed that by using HADESS, saving costs up to 39% could be expected in comparison with tradition investigation methodology. Moreover, HADESS methology is also min. 20% faster than with the traditional landfill characterization on site. Detailed results of this cost benefit analysis are presented in the Deliverable WP T3.2.1. Cost and benefit analysis. These results can be extended to all mixed waste landfills, thicker than 5 m depth and having a surface area around 10,000 to 15,000 m^2. However, for shallow documented monolandfills, it might be not always the case. For this specific type of landfill, we recommend doing a cost benefit analysis prior to the beginning of the landfill investigations.

8. Elaboration of a business model

Elaboration of a business case for a landfill site is the key to assess if the landfill is suitable to launch profitable ELFM project. The business case should take into account not only the material, energy and land recovery but should also assess the economic values of social and environmental benefits of such a project. First estimation can be done using online tools such as OnTOL (included in the DST 2 – Orion) or the business model template available on the RAWFILL website.

This business model template was developed within the framework of the RAWFILL project. The structure of the business model is divided in three main parts : (1) Costs of landfill mining characterization; (2) Pre-operational costs (which includes the different studies which are generally required by regional authorities); (3) Landfill mining operations costs. Its aim is to help private/public investors and relevant stakeholders to assess the economic viability of any ELFM project. The prices that are provided in the business model template are based on the evaluation of the Walloon market price over the last six years (from 2014 to 2020). Prices were difficult to obtain as private companies involved in ELFM project are not keen to share their substantial financial revenues. It should be noted that these prices are indicative and could potentially vary depending on the region. An update of the market price should be done regularly.

Regarding operational cost calculations, the business model only provides a first estimation of the ELFM costs. The main expenditure items are staff costs, waste transportation and treatment costs. Staff costs directly depends on the duration of the ELFM project. This is why prior to the design of a business model, it is highly recommended having a clear view of the ELFM project and correct estimations of the volume of the landfill as well as its characteristics. For the ELFM activities planning, we recommend dividing the project into different phases of work by taking into account the operational feasibility, the vicinity of the landfill and the legal obligations. Working by phases also help to avoid the saturation of the waste treatment/valorization facilities.

If the first assessment is positive, we strongly recommend doing a detailed analysis with an expert. It is also important to note that a business case is only valid for a short time span and should be updated regularly based on the current market price. If the business case shows that the ELFM project is not profitable and if the balance between social/environmental benefits and economic benefits is not demonstrated, short and long-term interim use can be developed on site instead such as energy crops, solar panels, nature conservation, afforestation, recreative area, among others.

Based on this business model template, business cases were developed for two of the RAWFILL pilot sites: Onoz and Meerhout landfills. Regarding the industrial landfill of Onoz, the RAWFILL tools have predicted that the landfill would be suitable for profitable ELFM project. By contrast, the RAWFILL tools have forecasted that Meerhout would probably not suitable for ELFM project due to its large volume of non-valuable waste materials. Results also showed that main revenues highly depend on the excavated material quality and quantity, along with socio-economic, environmental and health benefits during and after the project. The two business cases confirmed the prediction of the RAWFILL tools. On the one hand, the ELFM project at Onoz landfill would be highly profitable as most of the waste materials (fly ashes and staked lime) could be valorized and sold. An ELFM project at Onoz landfill has started in 2021 for a duration of 13 years. On the other hand, the business case of Meerhout landfill showed that an ELFM project would not be economically viable and would generate an economic loss of at least 17 million euros. However, the development of an interim use such as the implementation of a solar panels farm would be profitable in the long run. The installation cost was estimated at around 4 million euros and the annual revenues at approximately 372,000 €.

9. Landfill mining operations

The scope of the RAWFILL project was to provide useful tool to characterize landfill content in order to ensure the economical profitability of the landfill mining project. Thus, we did not concentrate our effort on the optimization of landfill mining operations. During our discussion with stakeholders or landfill mining managers, we highlighted a major problem. Although there is a lot of efforts that have been done to characterize the waste content of the landfill and maximize the recovery of waste material through several European projects (e.g., NEW Mine, Smartground, RAWFILL, Minea), there are still some knowledge gaps which require further studies. For instance, there is currently no scientific publication regarding how to prepare a landfill prior to waste excavation in order to avoid explosion risk related to the presence of biogas within the landfill. Another issue is related to the presence of leachate which can contaminate the waste material and therefore devalue the resource that can be recovered.

10. Preliminary assessment of the environmental and social impact

In the RAWFILL project, the environmental and social impacts were assessed for two scenarios for each RAWFILL pilot site: (1) during the landfill mining operations, (2) after the completion of the ELFM project. This preliminary assessment was done based on the scientific literature available and the RAWFILL project partner's experience (see *Deliverable WP T3.2.3. Preliminary environmental and social impact assessment report*). The positive and negative impacts are summarized in **Table 2.** Despite the negative impacts generated by the ELFM operations on site, substantial benefits on several aspects (i.e. human health, land, soil, air, water, biodiversity, landscape and climate) are expected after the completion of the ELFM project.

Aspect	Impacts during the ELFM operations	Impacts after the completion of the ELFM project
Human health/Social aspect	• (+) Increase employment opportunities. • (-) Health risks for workers. • (-) Increased noise, odor and transport.	• (+) No risk of person accident due to aftercare of the landfill. • (+) Increase well-being of the neighbors. • (+) Depending on the redevelopment project, it will either improve the development of the local economy/ nature conservation/residential area. • (-) Unemployment in the sector of landfill aftercare.
Land		• (+) Increase of the land value surrounding the site. • (+) Limitation of the urban sprawl on greenfield. • (+) Limitation of greenfield use for new redevelopment project. • (+) Creation of a protected natural area (in some cases).
Soil	• (-) Risk of soil contamination.	• (+) Minimization of long-term risk of soil contamination due to landfill liner failure.
Air	• (-) Risk of explosion or fire. • (-) Emission of dust during excavation.	• (+) No more landfill gas emission. • (+) Improvement of the air quality.
Water	• (-) Risk of surface and groundwater contamination. • (-) Risk of leakage.	• (+) Minimization of long-term risk for surface and groundwater contamination due to landfill liner failure. • (+) No more risk of leakage of contaminants directly to the groundwater and the surface water • (+) Improvement of the groundwater quality.
Landscape	• (-) Negative visual impact.	• (+) Reduced prominent shape of the landfill → less or no disruptive landscape. • (+) Restoration of a natural dune complex. • (+) Reshaping of the site and slope stabilization.
Biodiversity	• (-) Disturbance of the fauna and flora.	• (+) Diversification and increasing of the biodiversity on site. • (+) Eradication of invasive species (eg. the Japanese Knotweed).
Climate	• (-) Generation of CO_2 during the ELFM operations (excavation, waste transport, etc.).	• (+) Avoids methane emissions → Reduction of the greenhouse effect. • (+) Revalorization of the metal content and other materials recovered from the landfill → Avoid CO_2 production. • (+) Valorization of the combustible fraction → substitution of fossil fuels.

Table 2 – Preliminary environmental and social assessment - Advantages and disadvantages of an ELFM project.

10. Long-term effect of the RAWFILL project

Organizing workshops has been a key practice to generate interest from stakeholders in the project. This is evidenced by the large fraction of website views related to pages about the midterm event and other workshop events. In particular the novel use of geophysics within landfill management has been a strong attractor of external interest. Organizing site visits with geophysical demonstrations or training sessions really allows stakeholders to grasp the benefits of using geophysics on landfills. There was a great interest of the people involved in landfill management for non-intrusive characterization techniques. Before participating at a RAWFILL event (i.e. RAWFILL conference, workshop, kick-off, midterm, final event, training days, site visit), most of the people we met in RAWFILL had only a vague idea (or no idea at all) of what geophysics is. The organization of multiple events increased awareness of using the RAWFILL methodology to characterize the content of a landfill. Throughout the engagements with stakeholders, their needs have been further identified within the context of the RAWFILL project. Items such as a need for a diversified suite of surveying methods (i.e. the presented geophysical methods) and a standardization for waste description (as part of the ELIF framework) have been actively addressed throughout the RAWFILL project. This addressing of stakeholder expectations will ensure a continued relevance of the project's deliverables for those managing waste and landfills. Despite the early alignment with stakeholders, there are certain expectations which have not been able to be incorporated. Notably there is the lack of scientific material on how to prepare a landfill for excavation. As these needs were identified during the later stages of the project, it is recommended to dedicate specific projects to address them.

Concerning the landfill mining in NWE, no country has currently specific national/regional frameworks or legislation that encourage ELFM projects. Only the region of Flanders (Belgium) has enacted specific regulations: environmental permit code for ELFM projects, exemption of waste taxes, specific calls for brownfields with landfills. We recommend continuing what has been started during the RAWFILL project by implementing an interregional policy platform for the exchange of experience and a long-term perspective for a NWE or EU-wide consensus/strategy on ELFM.

During the time life of the RAWFILL project, ELFM was a European interest and quite a lot of stakeholders were already engaged in this topic, either by trying to set up ELFM projects in different scales, or by discovering the ELFM potential of their landfills and preparing for next steps. At the beginning of RAWFILL, it seemed as if in every country there were people that were already engaged in ELFM in different ways making their experiences on their own. Interregional knowledge and experience exchange during RAWFILL events help stakeholders to avoid pitfalls and speed up a constructive planning procedure for ELFM projects.

However, the renewed Landfill directive has no specific regulations on ELFM and is focusing on the currently operational landfills. As part of the EU waste management, it is the least favorable way of dealing with waste. RAWFILL is fully in line with this EU policy and is not promoting more landfilling. The objectives are different in a sense that the RAWFILL practices were mainly developed for closed landfills. At the moment, no specific rules were enacted at the EU level and member states apply various legislative frameworks to facilitate ELFM. Due to the fact that most ELFM projects are at the level of a pilot, nor the need nor the experience of a comprehensive legislation is in place. However, if ELFM reaches the next level, the legal aspects will become a necessity in order to avoid risky business cases. Legal uncertainty may jeopardize valuable projects.

10.1. Greendeal in Wallonia

Like most of the NWE regions, there was no legal framework for ELFM project in Wallonia. In order to launch landfill mining project across Wallonia, a Green deal was signed between the Walloon Region, SPAQuE, the local authorities and the private investors for an ELFM project at Onoz landfill. This Green deal was the first one signed in Wallonia. Its concept was inspired by the Green deal from the Netherlands. By signing the green deal, all parties are committed to doing what is within their capabilities to realize the project. It is important to note that the covenant is an obligation of best efforts, not an obligation of result. To succeed in the development of this ELFM project, a working group was created and met on a monthly basis to discuss technical and legislative issues. The permits to start the ELFM operations at Onoz landfill site was delivered by the regional authorities at the beginning of 2021. This project has served as leverage for other landfill mining initiatives in Wallonia. Promotion of the greendeal was broadcast through conferences and presentations. Other local authorities have expressed their interest to start at least two other landfill mining project in Wallonia. Discussions are currently ongoing. The results in Wallonia are very promising and we strongly encourage other regions to follow the same path in order to develop ELFM across NWE regions.

Contact

Feel free to contact us.

Local contact details:

BELGIUM	ATRASOL	renaud.derijdt@atrasol.eu
	Cleantech Flanders / VITO	alain.ducheyne@vito.be
	OVAM	ewille@ovam.be
	SPAQuE	c.neculau@spaque.be
	Université de Liège	f.nguyen@ulg.ac.be
FRANCE	SAS Les Champs Jouault	champsjouault@gmail.com
GERMANY	BAV	pbv@bavmail.de
THE UK	NERC	jecha@bgs.ac.uk

Coordination office:

BELGIUM	SPAQuE Avenue Maurice Destenay 13 4000 Liège	c.neculau@spaque.be